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THE YAW STABILITY OF TRACTOR-SEMITRAILERS DURING CORNERING

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SUMMARY REPORT
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16. Abstract

The yaw stability of tractor-semitrailers in steering-only maneuvers is examined by means of computer simulation and full-scale tests. The tests included as-designed vehicles as well as vehicles modified with frame and front suspension stiffening elements installed. Results show that while tractor yaw instability can occur well below the rollover threshold for certain vehicles, modified stiffness parameters can eliminate such premature yaw instability.

Simulation study of the influence of design and operating variables on tractor yaw stability served to classify the relative importance of different suspension stiffness options, as well as tire mix, fifth wheel placement, and trailer loading practices. Results show that remarkably low levels of tractor yaw stability are possible with certain combinations of design and in-use variables.

A set of measurements of tractor-semitrailer ride vibrations is also reported as an add-on task to this study.

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SUMMARY REPORT

This study examined the yaw stability of tractor-semitrailers under pure cornering conditions, with no braking. The particular stability mode which was of interest could be called the jackknife mode, although the divergent response which can occur is much less violent than that which occurs when tractor rear wheels are braked to the point of lockup. If the overall domain of cornering responses can be usefully broken down into "normal" and "emergency" maneuvers, the subject study has addressed maneuvers of the high level variety which occur only rarely and which represent an emergency domain of operation. Particularly, it is under conditions of high lateral acceleration that a potential arises for losing control due to a "yaw instability," which phenomenon is the special interest of this study.

Although the possibility of a yaw instability is a pertinent safety issue with any class of pneumatic-tired vehicle, a recent NHTSA-sponsored project [1] has revealed that there is a special basis for concern in the case of heavy trucks and tractor-trailers. In that project, it was found that a yaw instability could arise at a maneuvering level which was well below the rollover threshold. Thus, it is possible that the usable maneuvering range of the heavy truck and tractor-trailer could be much narrower than that already-narrow range which had been previously accepted as the status quo with such vehicles. Further, it was established (in the earlier study) that certain peculiar aspects of the construction of truck frames and suspensions were the primary determinants of vehicle yaw stability in the emergency domain of operation. Whereas the previous work explored these relationships for the case of straight trucks, the present study has expanded the findings to tractor-semitrailers.

The objectives of this study were to:

1) identify the maneuver conditions in which tractor-semitrailer yaw stability is challenged,

2) examine the propensity for unstable yaw behavior among different vehicle combinations,

3) identify the primary mechanisms by which vehicle design and operating variables combine to degrade yaw stability,

4) modify actual vehicles in a fashion which defeats the destabilizing mechanisms, demonstrating stable performance in full-scale tests.

In this research project, the issue of tractor-trailer yaw stability, as a determinant of vehicle controllability, was studied by means of laboratory measurements and full-scale tests, producing results which were generalized through supporting mathematical analysis and computerized simulations. Laboratory measurements concentrated upon the direct evaluation of design parameters affecting the manner in which the combination vehicle reacts the roll moment that arises during cornering. The basic questions, here, pertained to the manner in which the normal loads on the tires change when a vehicle is in a turn. A long-understood axiom in passenger car design has been that the distribution of lateral load transfer among tires on fore- and aft-located axles will determine the yaw stability of the vehicle at higher maneuvering levels. On the heavy trucks and road tractors examined in this study, conventional measurements of suspension roll stiffness and roll center heights were supplemented with measurements of the torsional stiffness of the vehicle frame to permit calculation of load transfer distributions and, ultimately, yaw stability characteristics.

Two tractors and two semitrailers were measured and prepared for full-scale testing. Each vehicle combination was outfitted with an instrumentation package to provide recordings of dynamic response variables. In addition, each tractor was fitted, as shown in Figure 1, with additional mechanical elements which provided a major rear-to-front redistribution of effective roll stiffnesses.

These mechanical devices included a "sway bar" type of front suspension stiffener and an external structure which stiffened the tractor's frame in torsion. As seen in the photograph, these elements were added simply to examine the concepts of suspension and frame stiffening while not attempting to resolve the packaging issues. Each stiffening element introduced a five- to seven-fold increase in the respective baseline

Figure 1. Ford two-axle tractor coupled to Fruehauf van-type semitrailer. Photo shows front suspension stiffener (transverse pipe structure nearest to the ground), frame-stiffening structure, and anti-rollover outriggers.

stiffnesses of the vehicle. Taken together, they constituted one "check condition" at which the basic hypothesis of the study could be validated. Further, when both stiffening modifications were engaged, the vehicle achieved a balance in the front-to-rear distribution of roll stiffness which was comparable to that of passenger cars, given the typical differences in weight distribution between cars and heavy road tractors. Full-scale tests were conducted during the project to determine the levels of yaw stability yielded by both the "baseline" and "modified" vehicle configurations.

Through mathematical analysis, the groundwork was laid for applying certain classical presentations of passenger car yaw response to the articulated commercial vehicle, including configurations with tandemized axle sets. Computerized simulations were employed to identify the range of vehicle configurations which can exhibit yaw instability prior to reaching the rollover threshold. Additional simulation runs were devoted to exploring the extent to which roll stiffness modifications serve to eliminate the potential for such yaw instability.

Shown in Figure 2 is an example of the "handling diagram" type of data presentation which has been chosen for summarizing the results of the study. The diagram presents lateral acceleration versus the difference between front and rear tire slip angles on the tractor. Per these response variables, the typical steady-state steering response for a road tractor is seen to make a transition from understeer to oversteer at a low level of lateral acceleration. Of particular importance to this study, however, the flattening positive slope of the example curve reveals a continually increasing level of oversteer, such that tractor yaw stability may be threatened before the rollover threshold is reached.

A basic axiom of linear vehicle mechanics holds that an oversteer vehicle will indeed become yaw unstable at some critical speed, V_{crit}. Shown in Figure 3, critical speeds have been evaluated at various points along the example handling curve, pointing up the fact that the declining slope at higher levels of lateral acceleration provides for an unstable yaw response at ever-lower speeds. Thus, if the example vehicle were coming off of a sharply-curved exit ramp, say, at 55 mph, the tractor would begin a divergent spin-out type of response when the 0.5 g level was

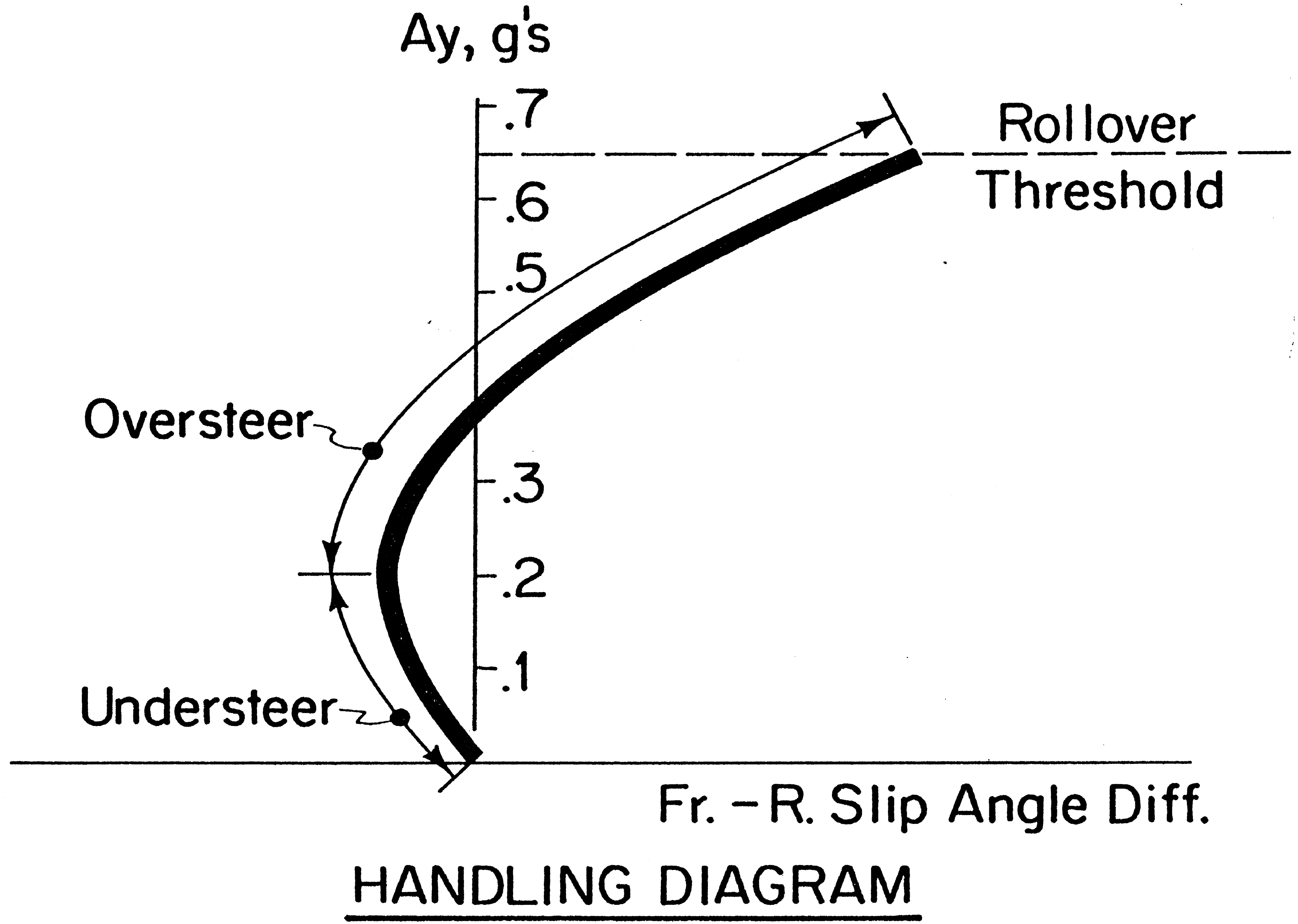

Figure 2. Example handling diagram for a heavy road tractor.

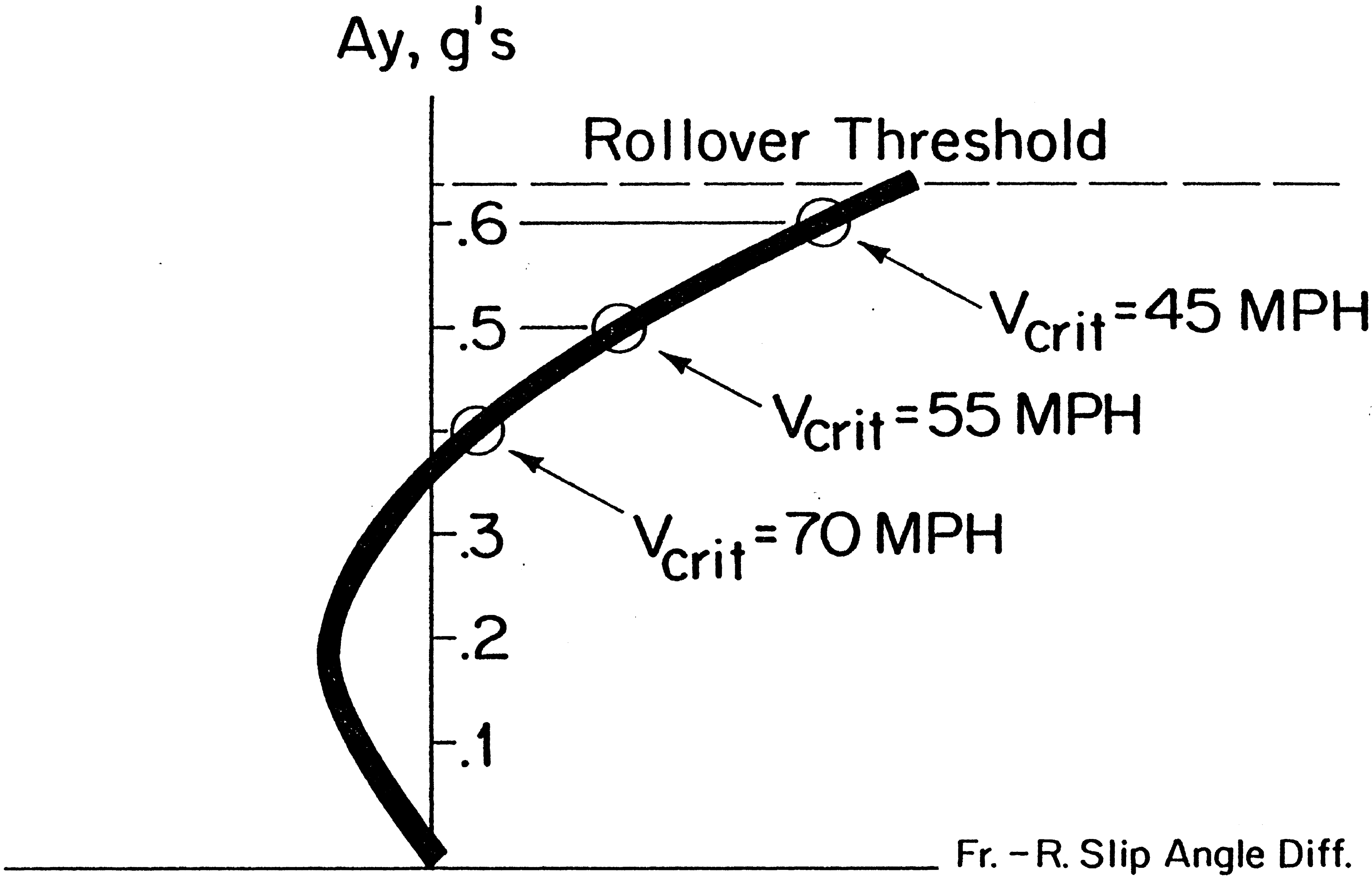

Figure 3. Example handling diagram, with critical velocities evaluated at each of three lateral acceleration levels.

attained. Without such a yaw behavior, the same vehicle would have been fully controllable up to the .65 g level of the rollover threshold. Computerized simulations in this study have shown that yaw instability from a speed of 50 mph may be possible in certain contemporary vehicles at 0.3 g or lower.

Noting that the handling diagram demonstrates the potential for a yaw instability through a declining positive slope, the generalized results of full-scale tests and simulations can be summarized and interpreted.

Two types of parametric variations were considered; namely,

1) the addition of large levels of auxiliary torsional stiffness to the tractor frame and front suspension (that is, providing changes to the vehicle which are not done in common practice today), and

2) the variation of those parameters which are commonly varied in the trucking industry, including selection of tractor and semitrailer suspension load rating, mixing of tires on the tractor, placement of the fifth wheel, and placement of the center of gravity of the payload on the semitrailer.

Taking the influences of auxiliary stiffening modifications first, we see in Figure 4 that increased torsional stiffness of the tractor frame, alone, produced negligible changes in tractor yaw behavior, with respect to a typical baseline performance. On the other hand, Figure 5 reveals that progressive increases in front suspension roll stiffness, alone, cause a dramatic improvement in yaw response by producing negative slopes, or understeer responses, throughout the maneuvering range. Further, Figure 6 illustrates that combined increases in both frame torsional stiffness and front roll stiffness constitute a powerful means of securing even more substantial levels of understeer over the operating range of the vehicle.

These results support a basic hypothesis of the study, namely, that roll stiffness distribution is a primary determinant of tractor and truck yaw instability.

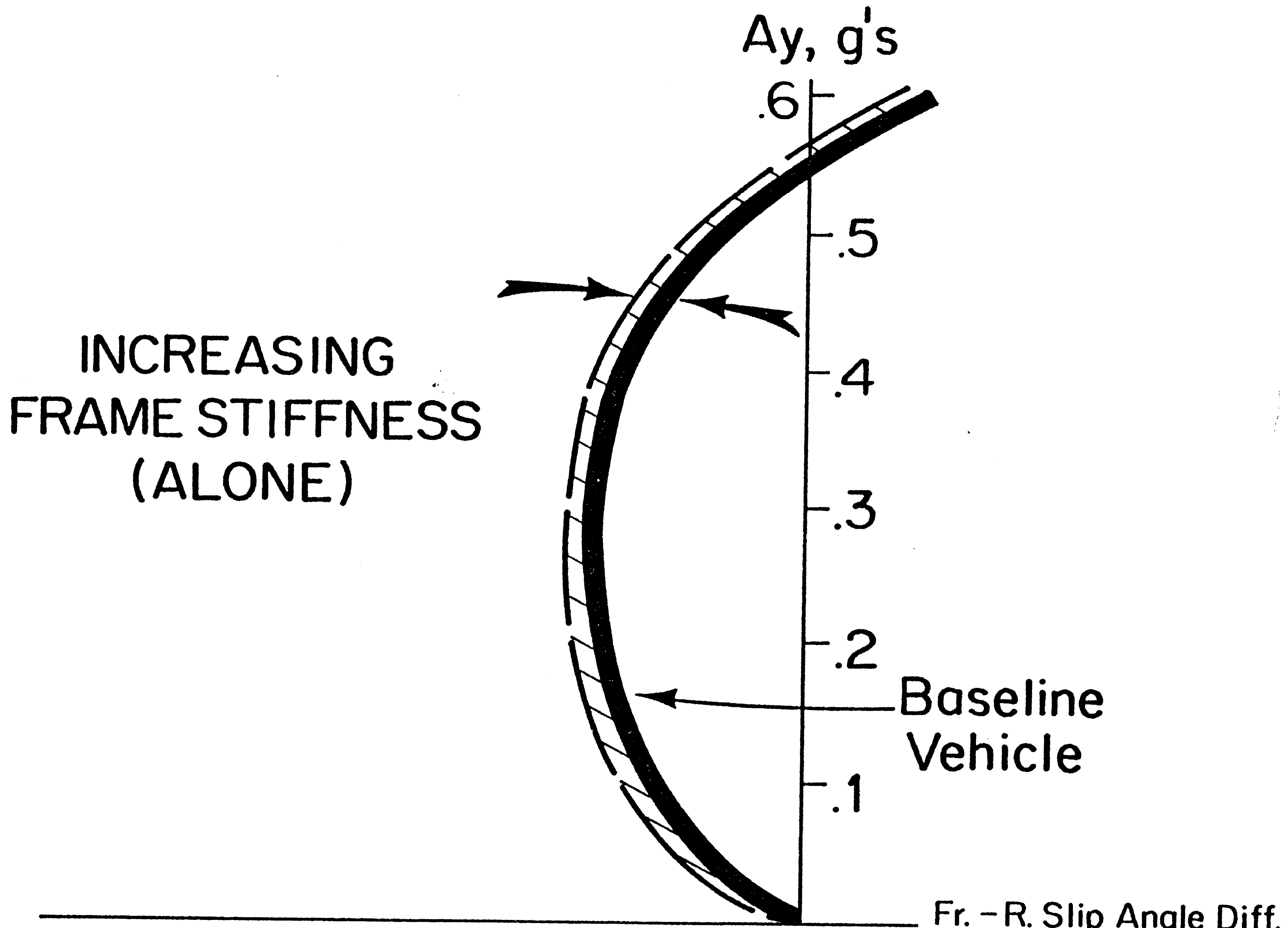

Figure 4. Typical change in handling curve for a two-axle tractor deriving from sevenfold increase in frame torsional stiffness.

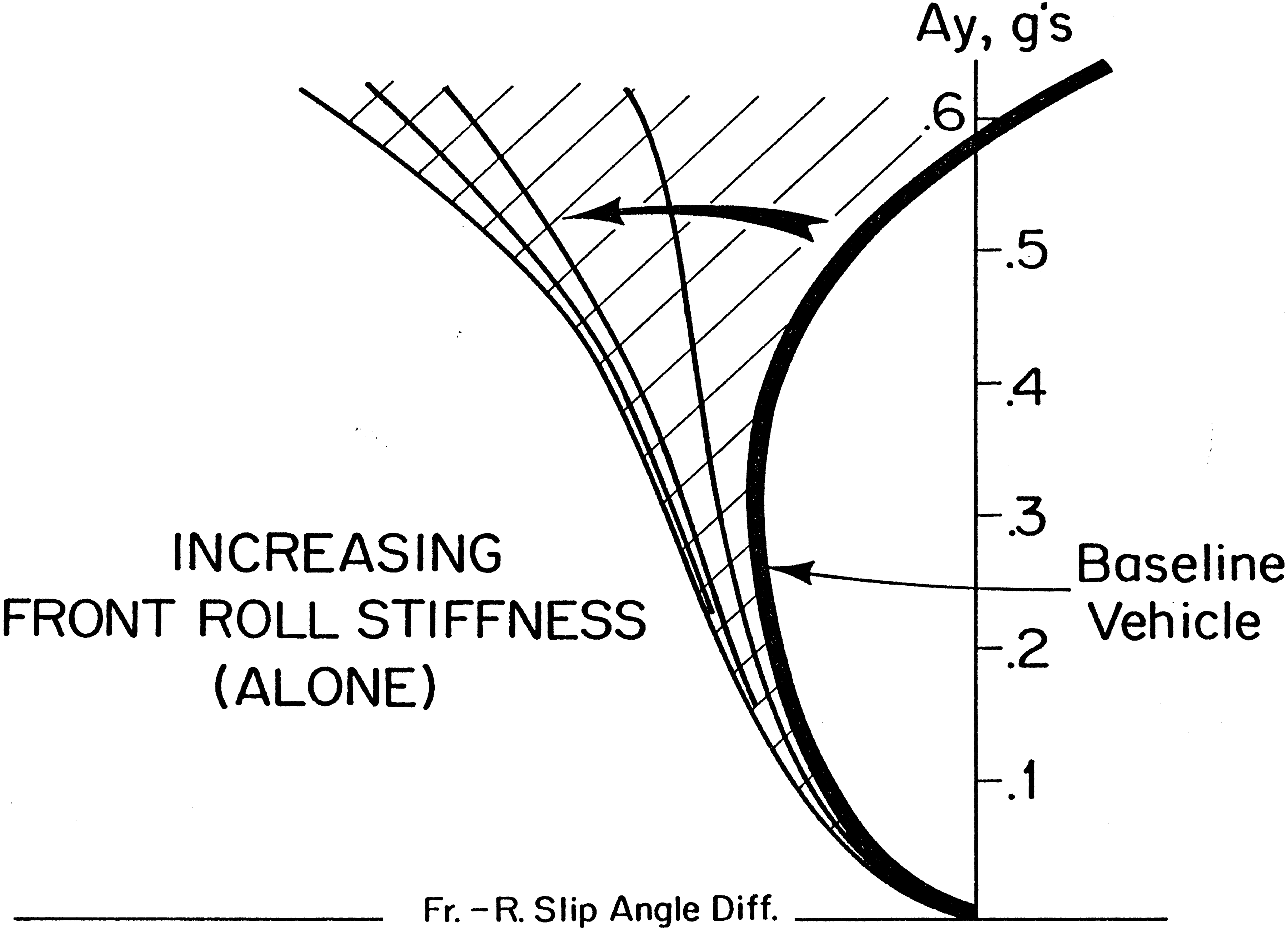

Figure 5. Typical change in handling curve for a two-axle tractor deriving from sequential increases, up to five-fold, in front suspension roll stiffness.

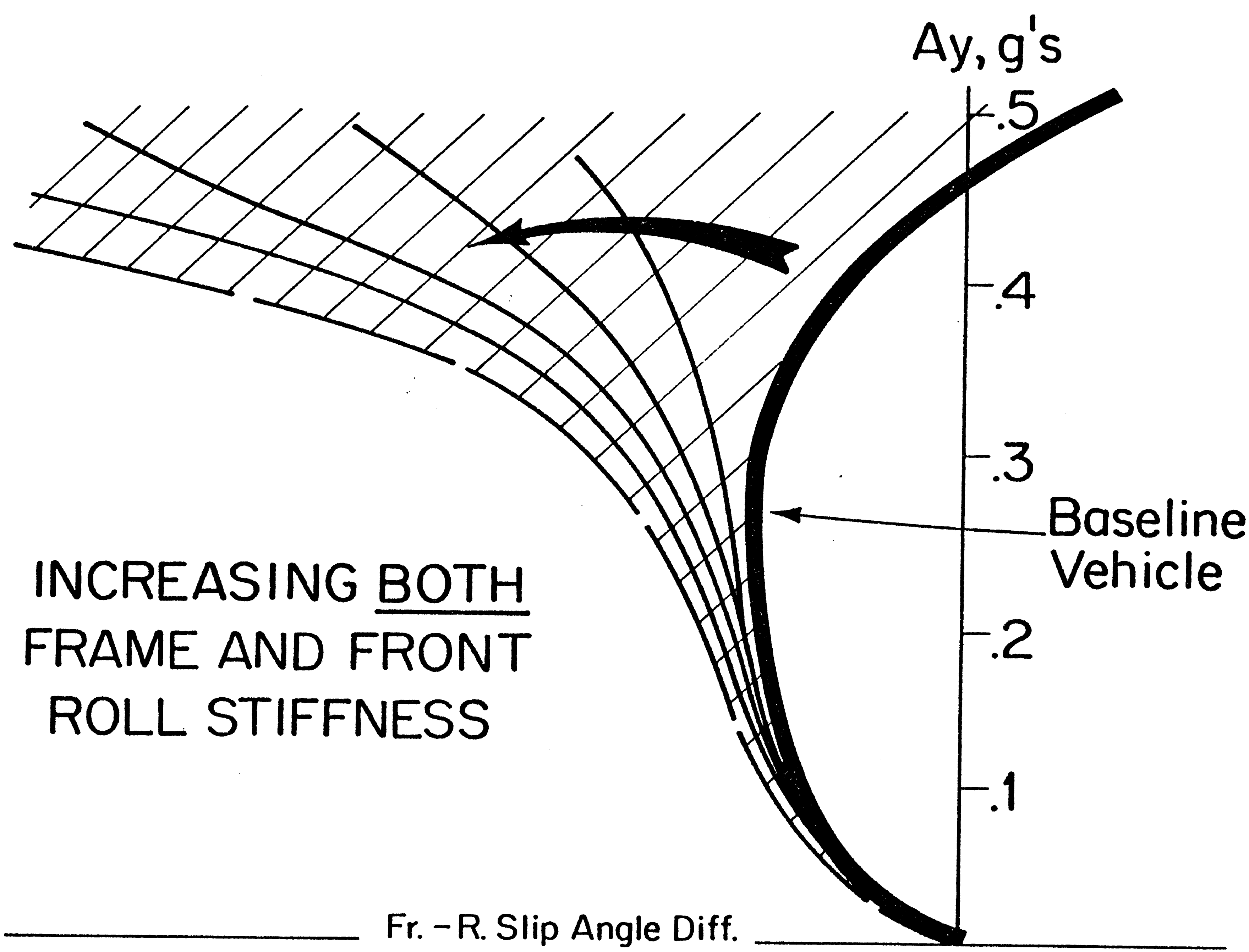

Figure 6. Typical change in handling curve for a two-axle tractor deriving from combined increases in both frame and front roll stiffness.

Computer simulations were also performed to determine the extent to which different operating conditions and basic vehicle design configurations may render typical tractor-semitrailers capable of unstable yaw behavior in their fully-loaded condition. A matrix of runs was defined to cover the cases of two- and three-axle tractors coupled, respectively, to one- and two-axle trailers with which five selected parameters were varied to realistic degrees and in the directions which are hypothesized to degrade yaw stability. The baseline state of each vehicle was configured to incorporate typical values of those parameters which were expected to influence yaw stability. No parametric variations were made in the directions expected to improve stability since the goal was to identify the states in which stability is compromised. Thus, the results do not constitute an estimate of the yaw stability characteristics of the U.S. fleet of tractor-semitrailers but, rather, represent only that portion of the fleet which lies on the "unstable side" of the more typical configurations. As will be shown, the results of this set of calculations suggest that the unexamined portion of the tractor-semitrailer spectrum can be presumed to be largely incapable of yaw divergence prior to reaching the rollover limit, since the baseline vehicles are seen to be only marginally unstable at the examined condition of 50 mph.

Shown in Figure 7 is the range of handling curves exhibited by a two-axle tractor as a result of the combined variation of roll stiffness, tire mix, c.g. height, etc., parameters described earlier. We see that a substantial lessening of the positive slope can occur at higher levels of lateral acceleration, suggesting a pronounced reduction in yaw stability, with respect to the baseline curve. The two-axle tractor was seen to lose 37% of its stable maneuvering range at 50 mph, due to combined parametric variations.

Similarly, for the case of the three-axle tractor, in Figure 8, we see that the more stable baseline yaw behavior becomes degraded to a large degree by the combined parameter changes. Stated numerically, the three-axle tractor loses 40% in its stable maneuvering range, at 50 mph, due to the combined variations. Moreover, this parameter sensitivity study has revealed that the yaw stability of a tractor-semitrailer can be reduced to a remarkably low level through variations in operating

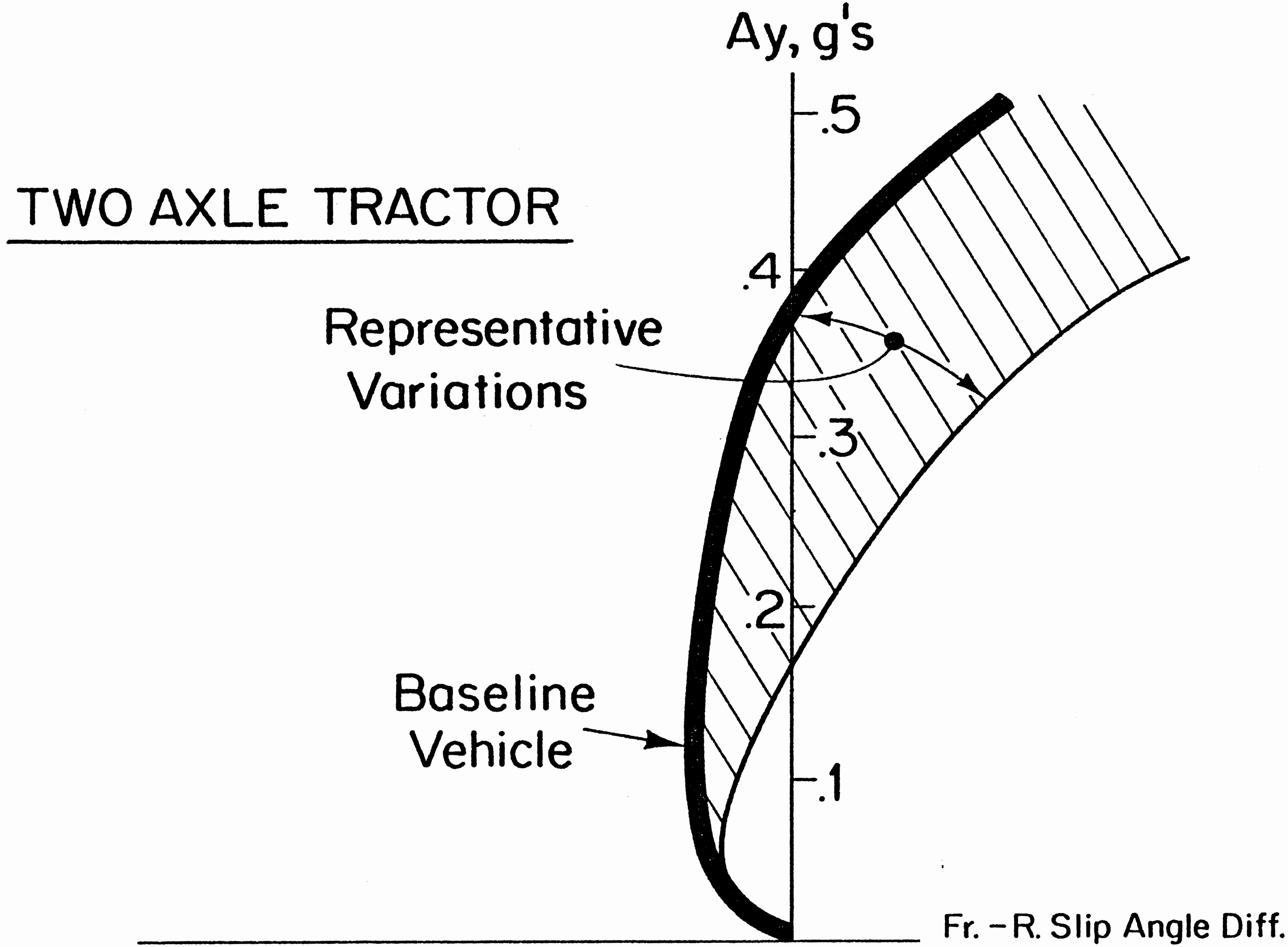

Figure 7. Change in handling curve of typical two-axle tractor deriving from common variations in design and operating parameters.

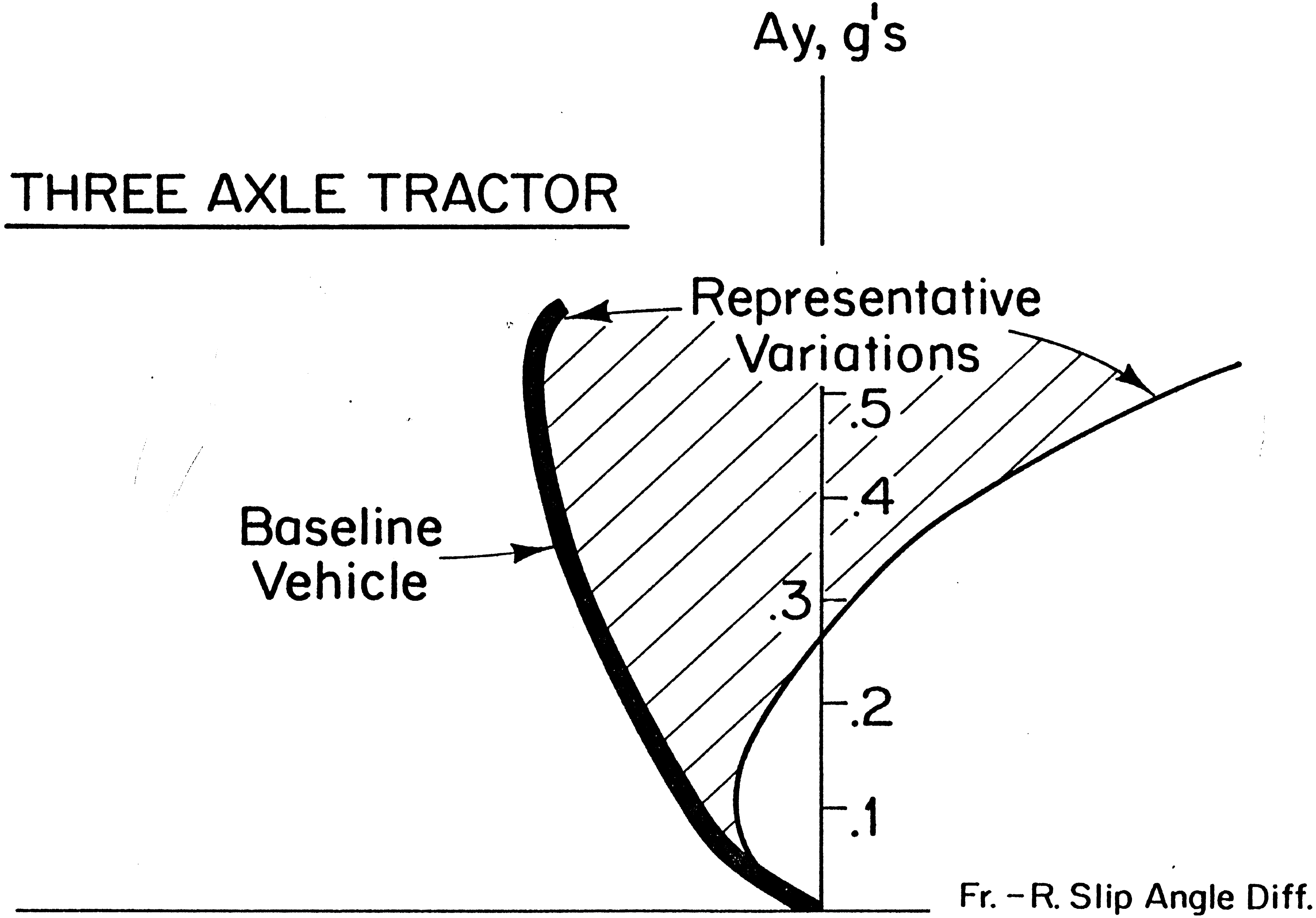

Figure 8. Change in handling curve of typical three-axle tractor deriving from common variations in design and operating parameters.

conditions and design variables which are known to be relatively commonplace.

In line with each of the objectives, the following findings were made:

1) Tractor yaw stability in an articulated combination was found to be most challenged in steady-turn maneuvers at elevated levels of lateral acceleration. In transient maneuvers, the potential for an unstable yaw response is reduced as the duration of the transient is reduced. In quick transients, the lagging response of the semitrailer delays and reduces the roll moments being borne by the tractor—thus promoting a stable response.

2) Many types of tractor-semitrailer combinations exhibit a yaw instability prior to reaching their rollover thresholds. This instability occurs primarily with loaded vehicles and is degraded by the following conditions:

   a) A forward bias in the distribution of tire cornering stiffnesses. (Radial construction-front mixed with bias construction-rear or rib tread type-front and lug tread type-rear are combinations tending to degrade yaw stability.)

   b) Rearward placement of the fifth wheel coupling.

   c) High c.g. location of the trailer payload.

   d) Low roll stiffness of the trailer suspension.

   Design parameters of the tractor seen to degrade yaw stability were:

   a) Excessively rear-biased distribution in suspension roll stiffness.

   b) Torsionally compliant frame.

   c) Short wheelbase configuration.

   d) Single drive axle (rather than a tandem axle arrangement).

3) The most significant vehicle characteristic promoting yaw instability, by far, is the rear-biased distribution in suspension roll stiffness. The mechanical properties of the pneumatic tire are such that the rear-mounted tires (which typically bear the largest transfer of load during cornering) experience a greater net reduction in lateral force, thus providing for a destabilizing yaw moment to be developed.

4) Full-scale tests in this study confirmed that large increases in (a) front roll stiffness and (b) frame torsional stiffness can, indeed, eliminate the possibility of an unstable yaw response occurring below the rollover limit.

The significance of these findings lies in their potential application to the improvement of vehicle design and operating practices. Knowing that vehicle response can be improved through certain suspension modifications, it remains to be established whether such modifications can be practically implemented, given the host of other considerations which actual vehicles must satisfy.

Concerning the current state of traffic safety, it can be simply said that the potential for divergent yaw behavior occurring within the rollover limit constitutes a factor which degrades the controllability of heavy commercial vehicles. Further, it is clear that such behavior can be mitigated in the short term through the adoption of favorable operating practices and, perhaps, eliminated in the long term through the development of practicable design modifications.

Additional Ride Measurement Task

At the request of NHTSA, an additional task was undertaken to obtain measurements of ride vibrations on two road tractors in both the bobtail configuration and when coupled to a loaded, van-type semi-trailer. The ride measurements were obtained on a selection of local expressways and urban streets. Data were collected using analog tape recording of the outputs of six accelerometers located on the tractor frame rails and inside of the cab. The recorded signals were then processed using a digital spectrum analyzer to obtain power spectral density (PSD) displays and phase angle spectra from which the simpler vibration modes could be identified. Shown in Figure 9 are the power spectra of the vertical and fore/aft accelerations at the driver's seat for a cab-over-engine tractor at 55 mph on a smooth asphalt section of interstate highway. The figure shows six spectral peaks in the vertical PSD labeled (a) through (f), four of which are also evident in the fore/aft spectrum.

Peaks (a) and (b) have been identified as predominantly "bounce" and "pitch" modes of motion of the sprung mass, as diagrammed in Figures 10 and 11. Since the pitch mode, peak (b), involves primarily a rotation about a point well below the driver's seat, a peak in the fore/aft acceleration spectrum is observed at the pitch frequency, 5.2 Hz. Peaks (c), (e), and (f) have been identified as comprising the responses to tire and wheel nonuniformities, appearing at the fundamental wheel rotation frequency, 7.5 Hz, and at the first two harmonic frequencies, 15 Hz and 22.5 Hz. The large peak seen at (c) presumably indicates a resonance between the wheel rotation fundamental and a flexural mode—perhaps the first frame beaming mode. Finally, the peak labeled (d) constitutes a vertical bounce mode of the cab on its rubber mounts.

Such spectral breakdown was performed on each of the test vehicles test site, and speed combinations. Although this exercise in no way constitutes an original treatment of truck ride phenomena, it does serve as an introduction for NHTSA into the rudiments of commercial vehicle ride vibrations. The measurements and subsequent analysis demonstrated that the ride response of a heavy road tractor:

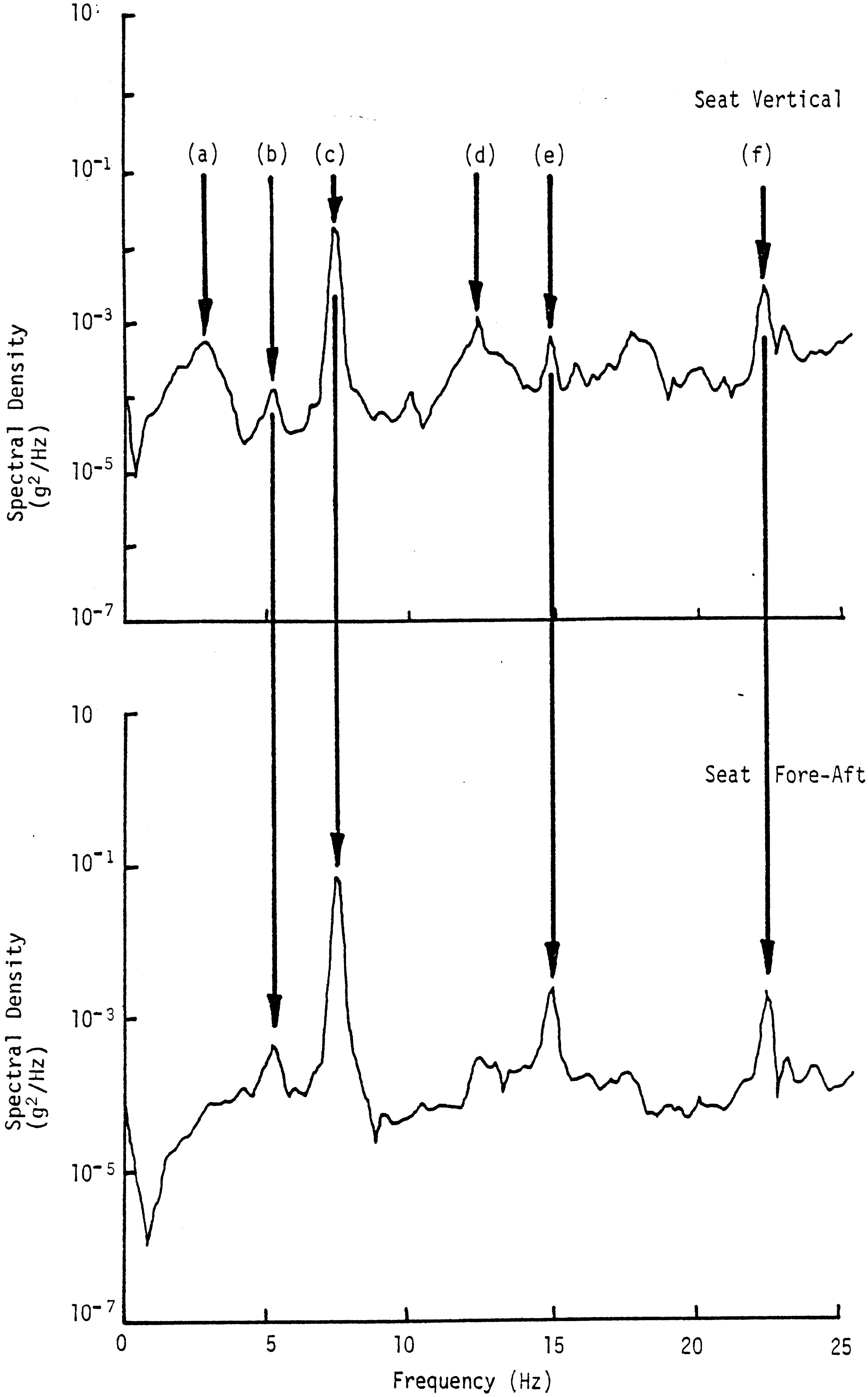

Figure 9. PSD's for vertical and fore/aft vibration of driver's seat - COE tractor, bobtail, 55 mph, test site No. 1.

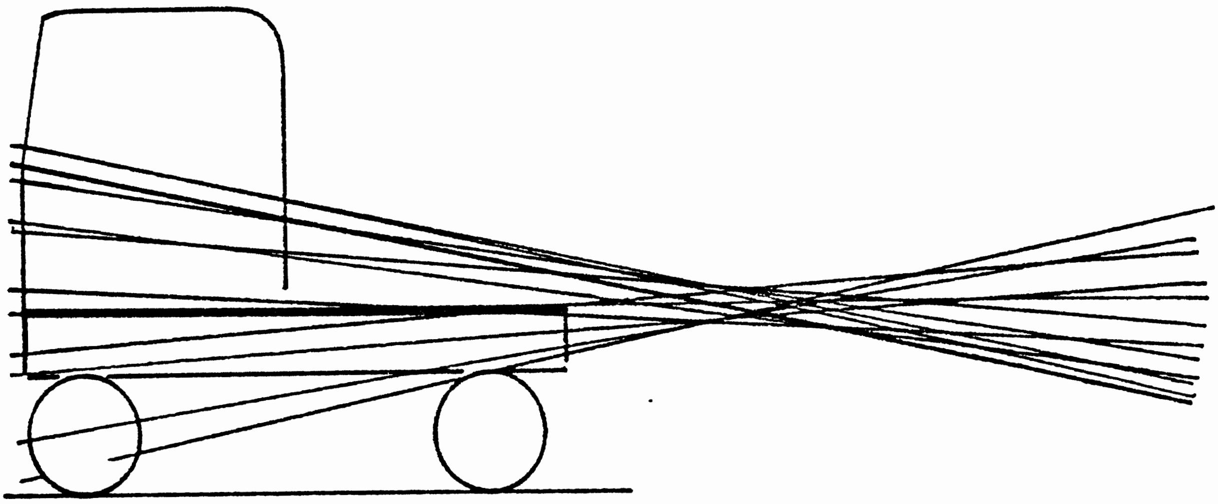

Figure 10. Predominantly "bounce" mode shape at 3 Hz (peak a).

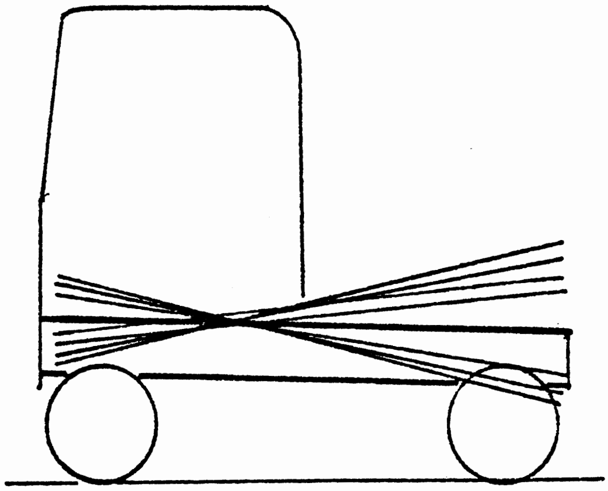

Figure 11. Predominantly "pitch" mode shape at 5.2 Hz (peak b).

1) is comprised of responses whose energy level is highest in the 0 to 15 Hz range

2) is comprised of simple (though, perhaps, coupled) "rigid-body" modes of motion (e.g., pitch and bounce) in the range of 0 to 6 Hz, followed by more complex modes (including those involving structural flexing) at higher frequencies.

4) can exhibit high energy responses on smooth road surfaces, simply due to wheel and tire nonuniformities

5) is heavily influenced by road surface condition, both in terms of overall absorbed power level and in terms of the resonant match between the peculiar design properties of the vehicle and the spectral content of the road profile

6) is heavily influenced by road speed, especially insofar as the wheel rotation frequency can become matched with lightly damped natural modes of vibration

7) is heavily influenced by the loading condition such that, for example, the bobtail tractor configuration can exhibit much higher energy levels in certain modes of response while being devoid entirely of other modes that prevail when a trailer is attached.