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STABILITY AND CONTROL PROPERTIES OF SADDLE-MOUNTED TRUCK COMBINATIONS

R. Ervin
A. Mathew

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16. Abstract

Newly manufactured, heavy-duty trucks are often transported over the highway in a combination of units comprising the so-called "saddle-mount" configuration. In this study, the braking, roll stability, and performance of such configurations in rapid evasive steering maneuvers was examined by means of computerized simulation. The results established that (a) the braking performance was relatively poor, but no worse than that of an empty five-axle tractor-semitrailer combination, (b) the roll stability level was quite high, falling between that of empty and fully loaded tractor-semi-trailers, and (c) the rapid steering behavior showed that the rear unit in the combination approaches the degree of lateral amplification which is seen in conventional five-axle doubles combinations--but other details of the vehicle's makeup render the overall stability in such maneuvers quite high. One specific recommendation for improved operation of saddle-mounted truck combinations is to avoid connection of the brakes on the rearmost unit in the train.

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1.0 INTRODUCTION

This document presents the results of computerized simulations of the dynamic response of saddle-mounted truck combinations. This "piggy-back" type of vehicle configuration is employed for the highway transportation of newly manufactured trucks. The work has been sponsored by the Western Highway Institute as part of a broader study of overall safety considerations of such vehicle combinations.

The study included examination of three basic properties of the vehicle, namely, (1) braking efficiency, (2) static roll stability, and (3) the rearward amplification response to rapid steering reversals. Each of these properties was selected for study on the basis of an initial hypothesis of potential safety problems. The respective sections of this report describe the vehicles of interest, explain the simulation methods for obtaining performance measures, and present the computed results.

2.0 DESCRIPTION OF THE STUDY VEHICLE

Shown in Figure 1 is a photograph of a typical combination of new trucks which have been "triple-saddle-mounted" so as to form a vehicle train which is towed by the leading vehicle. From a conceptual point of view, this combination constitutes the equivalent of a tractor vehicle towing three "semitrailers." That is, each of the three saddle-mounted trucks constitutes the equivalent of a passive semitrailer. The hitch device is called a "saddle" and provides the equivalent degrees of freedom normally achieved with a "fifth wheel" hitch such as couples tractor-semitrailer combinations in normal commercial service. The saddle hitch, shown in Figure 2, bolts to the frame of the leading unit and grasps the following unit by means of simple clamping bolts fastened to the front, or steering, axle of each trailing truck. By means of this hitch, the trailing truck is able to yaw and pitch relative to the towing unit. The hitch is nominally rigid in terms of transmitting roll moments between coupled units. (It will become clear later that the actual roll compliance of the saddle hitch is not of significance to the performance of the vehicle combination.)

Shown in Figure 3 is a side-view diagram of a triple-saddle-mounted combination with geometric and weight parameters identified. Four cases of saddle-mounted trucks were identified in terms of variations in the illustrated geometric parameters. One of the vehicle combinations was of the dual-saddle-mounted configuration, with only two trailing units, and three were of the triple-saddle-mounted variety. Listed in Table 1 are values for the geometric and inerial parameters used in describing each of the four cases. In each case, the basic truck element weighs 16,000 lbs. The pitch pivot established by the saddle hitch was 60 inches above the ground in all cases.

Shown in Figure 4 is a side view of a coupled unit occupying an intermediate position in the train of vehicles. The figure establishes that only the rear tandem axle on the unit contacts the ground such that other axles are being carried as sprung weight. Note, for example, that the front axle of the trailing truck is rigidly clamped to the leading unit such that the mass of that axle assembly becomes part of the sprung mass of the leading

Figure 1. Triple saddle-mount combination

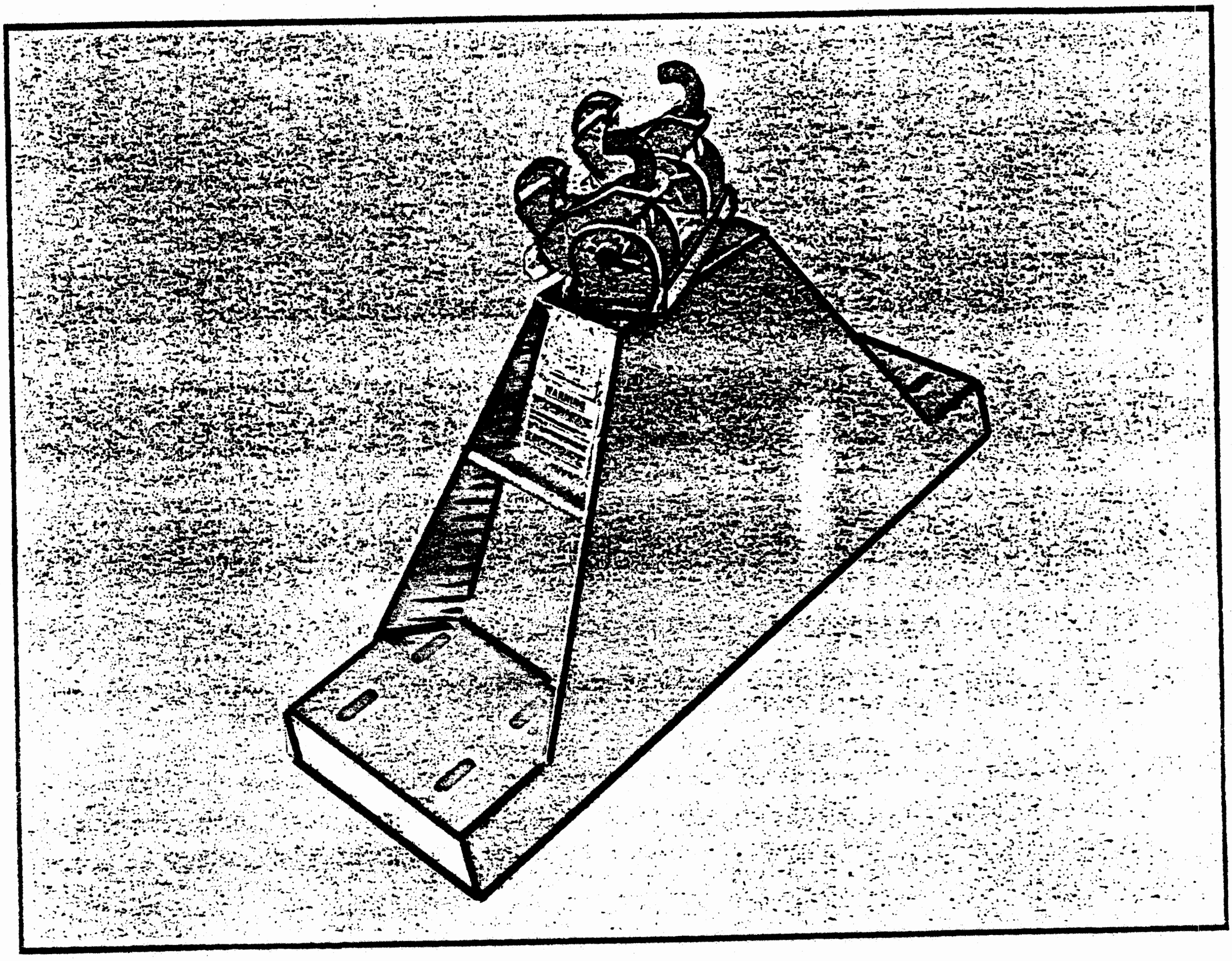

Figure 2. Saddle-mount hitch that is connected by U-bolts to the towing truck's frame and which grasps the front axle of the trailing unit by means of clamping fingers.

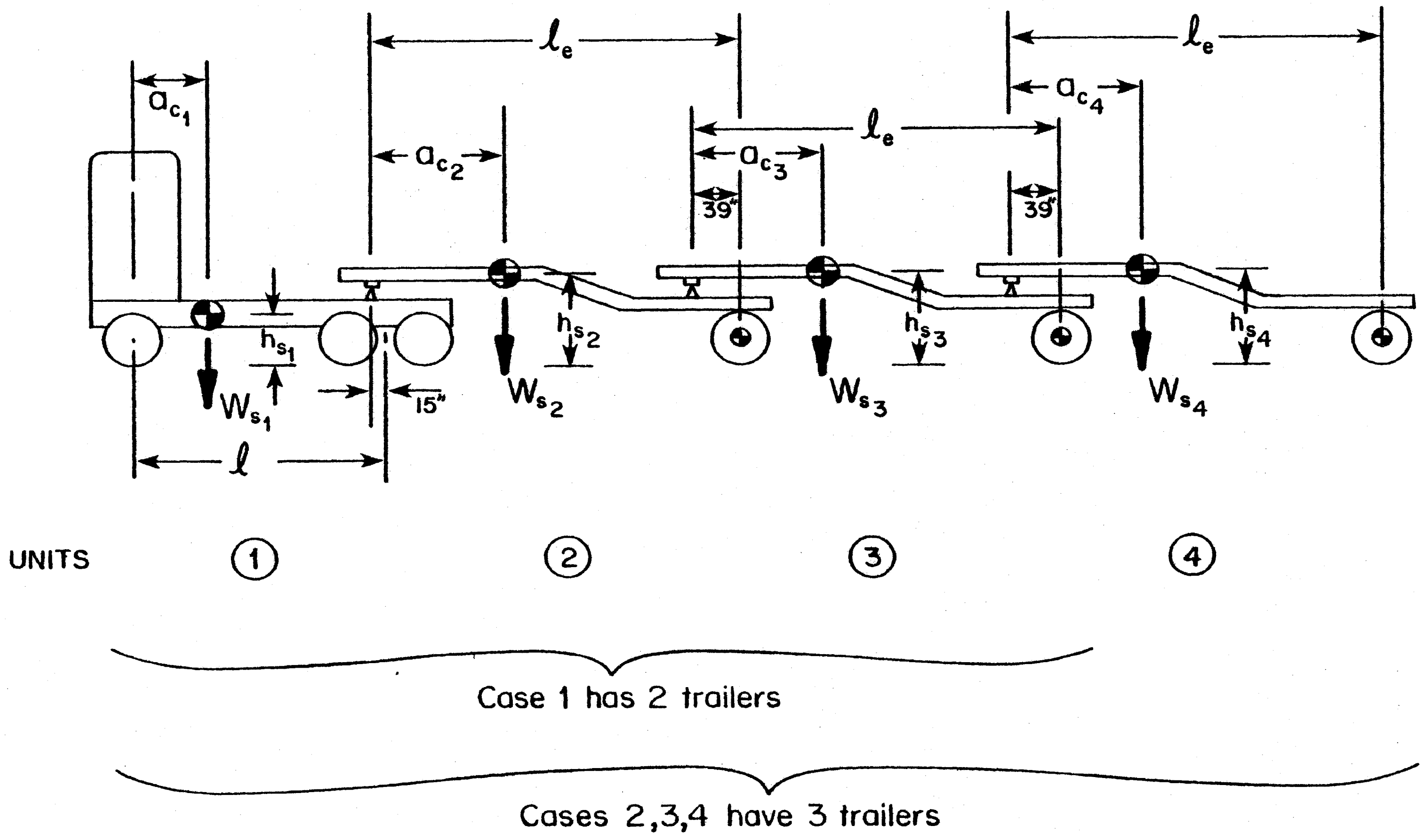

Figure 3. Parametric definitions.

Table 1. Parametric values for saddle-mount combinations.

Case	Basic Wheelbase in	Eff. Trailer Wheelbases in	Sprung Weights lbs				Sprung Mass Heights in				Longitudinal c.g. Locations in				$I_{yy} = I_{zz}$ (in-lb-sec^{2}x1000) Unit Number			
	ℓ	ℓ_c	W_{s_1}	W_{s_2}	W_{s_3}	W_{s_4}	h_{s_1}	h_{s_2}	h_{s_3}	h_{s_4}	a_{c_1}	a_{c_2}	a_{c_3}	a_{c_4}	1	2	3	4
1 DSM-215	215	226	11400	13700	12500	0	46.8	71.7	71.1	-	78.0	97.0	87.0	-	136 (19)	229 *(23)	172 (19)	-
2 TSM-174	174	193	11400	13700	13700	12500	46.8	70.1	70.1	69.3	72.2	85.3	85.3	78.2	104 (19)	151 (23)	151 (23)	121 (19)
3 TSM-189	189	207	11400	13700	13700	12500	46.8	70.9	70.9	70.2	74.2	86.9	86.9	81.4	113 (19)	177 (23)	177 (23)	139 (19)
4 TSM-204	204	222	11400	11400	13700	12500	46.8	71.4	71.4	70.7	76.4	93.8	93.8	84.7	124 (19)	206 (23)	206 (23)	157 (19)

*I_{xx}'s in parentheses

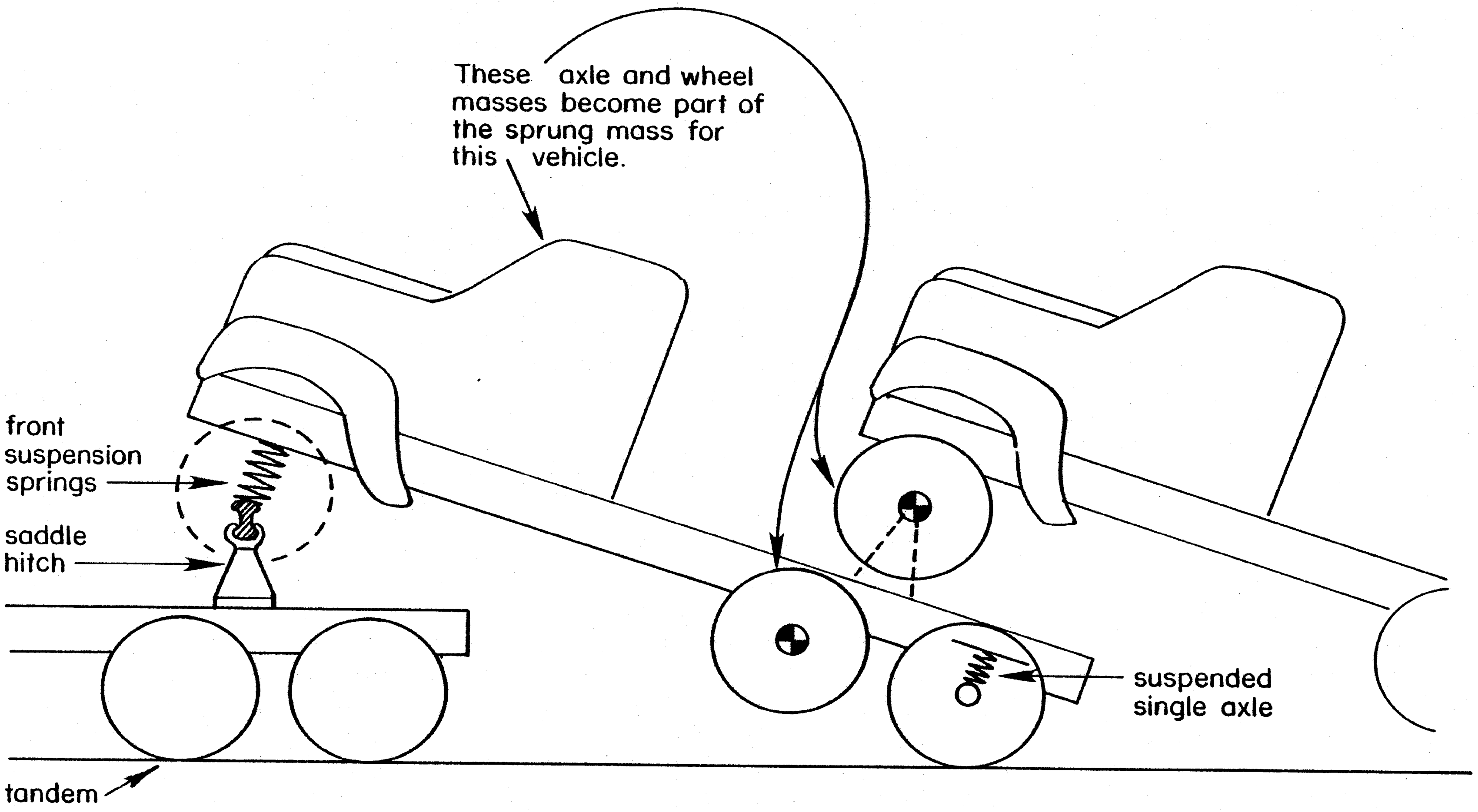

Figure 4. Side view of saddle-mount arrangement.

unit. Similarly, the leading tandem axle of the intermediate truck, as well as the front axle of the next trailing unit, are considered to be additions to the normal sprung mass of the intermediate truck. It follows, also, that the last unit in the combination has a sprung mass which is comprised of the truck's frame/engine/cab mass plus only the leading tandem axle on that unit.

Additionally, Figure 4 illustrates that each trailing unit is coupled to the saddle hitch through the front axle suspension. Thus, the trailing unit experiences compliance at the hitch connection according to the stiffness properties of its own front springs. Also, the rear of each trailing unit is supported on the suspension of only the rear tandem axle.

To represent the brake torque distribution for each vehicle, a convention was adopted in which the steering axle of the leading unit achieved a total brake force (longitudinal force at the tire/road interface) equal to 100 lbs per psi of brake line pressure. Similarly, all axles aft of the steering axle were represented with brake force levels equal to 150 lbs per psi. This convention was taken as the baseline arrangement and was supplemented by an additional case in which the rear brakes on the rearmost unit were disconnected, having a brake force gain of zero. The latter case was examined upon having reviewed the results for the baseline arrangement which showed that the rearmost axle is so lightly loaded that its "overbraked" status is detrimental to overall performance.

3.0 SIMULATION OF VEHICLE RESPONSE

The multiply saddle-mounted combinations were represented in two different types of vehicle simulations in order to obtain the desired measures of response. One model was employed to describe a simple braking performance limit and the other model was used to determine both a rollover stability level and a measure, called "rearward amplification," describing the tendency to whip the last trailing unit, laterally, during a rapid steering reversal.

The first model entailed a simple treatment of the static braking performance by which the apportioned brake torques and vertical wheel loads at each axle are compared during steady deceleration. The purpose of this type of calculation is to establish, over the range of effective tire/road friction limits, the maximum braking level which can be sustained without wheel lockup. Ideally, the maximum deceleration level achievable will be equal, in units of g, to the nondimensional value for friction level. For example, an ideal vehicle which brakes on a slick wet surface having a friction level of 0.4 will be able to attain a deceleration level of 0.4 g's. Real vehicles exhibit lower deceleration capabilities than the ideal level, however. That is, the general finding is that some axle in the vehicle combination is found to be "overbraked," with an excessive level of brake torque being applied given the prevailing wheel load, such that wheel lock occurs at a deceleration level below the ideal. Since wheel lockup generally portends a loss of directional control, this "premature lockup" condition is used to define the performance limit of the vehicle. In this report, the performance limit will be expressed in terms of the "braking efficiency" measure, which ratios the deceleration capability to the tire/road friction level. A braking efficiency value of 50 percent, for example, is achieved on a surface with a friction level of 0.4 when no more than a 0.2 g deceleration level can be attained without wheel lockup.

A rather comprehensive simulation of the cornering response of truck combinations was employed in determining both the roll stability and rearward amplification performance levels. The simulation model is termed the UMTRI Yaw/Roll Model and provides for articulation and roll freedom of each element of the combination. Tires and suspensions are represented in a nonlinear fashion. Also, the hitches employed between respective units are modeled to represent compliances as well as kinematic constraints.

To compute roll stability in a nominally steady curve, the vehicle was operated at 55 mph around a gradually sharpening turn until rollover was observed. The sharpening turn was achieved by inputting steering at a linear rate of 0.25 degrees of front wheel angle per second. This very slow rate of steer input permits examination of the rollover limit in a single extended simulation run, without the need to iterate to find the limit in successive runs. The performance limit is defined as that maximum level of lateral acceleration, in g's, which the vehicle will tolerate without rolling over. This measure is called the "static rollover threshold."

To compute the rearward amplification measure, the vehicle is operated initially in a straight line, at 55 mph, and then a single sine wave of steering is applied. A 2.0-second period for the steering sine wave was selected to provide a basis for comparison of results with prior findings obtained for other types of vehicles. The amplitude of the steering input wave was selected such that the towing unit of each combination acheived a peak value of lateral acceleration equal to approximately 0.2 g's. In response to this steering input, the vehicle excecutes an abrupt lateral displacement maneuver, such as in avoiding an obstacle. The trailing elements in the combination, however, indicate increasing peak values of lateral acceleration toward the rear of the train of elements. The rearward amplification measure simply ratios the peak value achieved at the mass center of the last trailing unit to that achieved at the mass center of the tractor, or towing unit. In conventionallly coupled multiple-trailer combinations, with pintle hitch connections to the dolly unit, higher levels of rearward amplification directly indicate a tendency for premature rollover of the last unit in rapid steering maneuvers. With the saddle-mounted configuration, however, the hitch mechanism does provide for roll coupling of the successive trailing units such that the rearward amplification measure does not so directly predict a premature rollover outcome. In the presentation of results, in Section 4.0, the conservative nature of the rearward amplification measure for application to saddle-mounted configurations will be noted.

4.0 PRESENTATION OF RESULTS

The results of the braking, rollover, and rearward amplification calculations will be presented in turn, and discussed in terms of their apparent implications for the safe operation of saddle-mounted trucks.

4.1 Braking Efficiency Results

Shown in Table 2 are the numerical values of braking efficiency for each of four saddle-mount cases and for each of four operating conditions. Braking efficiencies have been computed for deceleration levels of 0.1 and 0.4 g's which represent light and heavy braking levels, respectively, for trucks. At each deceleration level, the braking efficiency value is presented both for the "all axles" case in which brakes are connected at all axles and the "all but last axle" case in which the brakes on the rearmost axle are considered to be disconnected. Light and heavy braking levels are distinguished in recognition of the fact that the light braking applied when operating, for example, on long downgrades and very slippery surfaces, generally involves a significantly different braking efficiency level than applies to heavy braking. Further, the 0.4 g selection for the "heavy" braking level reflects the rather low braking capabilities which are generally seen with heavy-duty commercial vehicles. (We recognize that a 0.4 g deceleration level is not considered a "heavy" braking condition, for example, with passenger cars.)

Table 2. Braking Efficiency Values for Saddle-Mount Combination and a Reference 3-S2 Tractor-Semitrailer

Case	Brakes: Light Braking, 0.1 g — All Axles	Light Braking, 0.1 g — All But Last Axle	Heavy Braking, 0.4 g — All Axles	Heavy Braking, 0.4 g — All But Last Axle
1 DSM-215	66	64	58	59
2 TSM-174	62	64	52	58
3 TSM-189	61	64	52	59
4 TSM-204	60	63	51	58
Reference Empty 3-S2	62		59	
Reference Loaded 3-S2	96		88	

Braking Efficiency,

The results show the following:

-Comparing the braking performance of saddle-mounted trucks with that of a conventional 3-S2 tractor-semitrailer combination, we see that the braking efficiency levels of the saddle-mount combinations are approximately equal to that of the empty tractor-semitrailer. In particular, a very close match in performance between empty semis and saddle-mounted trucks is obtained when the rearmost axle of the saddle-mount combination is unbraked. On the other hand, the saddle-mount combination shows a large contrast relative to the loaded tractor-semitrailer, for which the brakes are more properly proportioned to the loads carried. While the braking efficiency of the saddle-mount units with rearmost axle unbraked can be looked upon as "no worse than" that of the empty tractor-semitrailer, the drivers of saddle-mount vehicles should be advised that this combination is relatively poor in stopping performance and care should be exercised, especially on slippery surfaces.

-The removal of brakes from the rearmost axle of the saddle-mount combination is advantageous to braking efficiency in all cases but the light braking condition with the double-saddle configuration. These results argue strongly that braking performance will be generally benefitted, and the hookup procedure simplified, if the rearmost brakes are simply left disconnected. The reason for this anomaly, of course, is that the rearmost axle is peculiarly underloaded and thus suffers from a substantial degree of overbraking. In the double-saddle configuration, the removal of the rearmost brakes provides little or no improvement simply because the loss of the additional braking at that axle approximately counterbalances the benefit of eliminating the strongly overbraked axle.

As noted above, a small reduction in performance, upon eliminating the rearmost brakes, was seen in the case of light braking on the double-saddle configuration. Unless some other factors may prevail which impinge upon other than braking efficiency considerations, however, the author's judgment is that the rearmost axle should be left unbraked in all double- and triple-saddle combinations.

-When the rearmost axle is unbraked, the critical axle set in the combination becomes the tandem rear axles of the towing unit. Thus, the likely limit condition which will result with a saddle-mount vehicle having no brakes on the rearmost axle will be a tandem lockup, with probable jackknife of the towing unit.

4.2 Rollover Threshold Results

Listed in Table 3 are the rollover threshold values determined for each of the four selected cases. The results represent rollover threshold levels which fall between that of typical loaded and empty truck combinations. Fully loaded tractor-semitrailers, for example, exhibit rollover threshold values between approximately 0.24 and 0.40. Since it is known that rollover accident involvement rises exponentially as rollover threshold declines, the 0.54 value exhibited by the saddle-mount configurations suggests that rollover involvement with such vehicles is likely to be very low.

The roll compliance which appears effectively at the saddle hitch point, deriving from the front axle suspension of the saddle-mounted truck, becomes a moot issue since the effective mass center of the trailing element is approximately at the height of the hitch point. Thus, the front axle suspensions of the trailing units do not become appreciably deflected in roll as the rollover threshold is approached. Moreover, the static roll stability of saddle-mounted truck combinations poses no peculiar safety problems, especially when considered relative to general trucking practice.

Table 3. Rollover Threshold Values for Saddle-Mount Combinations and Reference 3-S2 Tractor-Semitrailers

Case	Rollover Threshold, g's
1 DSM-215	.547
2 TSM-174	.543
3 TSM-189	.546
4 TSM-204	.542
Reference Loaded 3-S2	.24 to .40
Reference Empty 3-S2	.70

4.3 Rearward Amplification Results

The ratio of the peak amplitude of lateral acceleration at the rearmost unit to that of the towing unit in response to a rapid steering reversal is expressed as a nondimensional term which is ideally around 1.0. Values above 1.0 suggest that some exaggeration in rear trailer response is occurring and premature rollover may be threatened, accordingly. Listed in Table 4 are the rearward amplification values for the saddle-mount cases as well as a reference value computed for a conventional five-axle double trailer combination comprised of two 28-foot trailers. We see that all cases of the saddle-mount combinations register rearward amplification values which are well above 1.0, although none of the examined cases achieved the 2.55 level of the conventional double. In this sense, we might say that the saddle-mount configurations are no worse than one other popular vehicle type which is in use across the U.S. Closer interpretation of the saddle-mount cases, however, suggests that the actual risk of premature rollover due to rearward amplification, per se, is much less with saddle-mount combinations than the mere comparison of values in Table 4 would indicate. There are two reasons for saddle-mount combinations to be less susceptible to rollover deriving from rearward amplification, namely,

Table 4. Rearward Amplification Values in Response to a Two-Second Sine Wave of Steering at 55 mph.

Case	Rearward Amplification at 55 mph
1 DSM-215	1.53
2 TSM-174	2.13
3 TSM-189	2.09
4 TSM-204	1.95
Double-28 ft Combination	2.55

a) The fact that the nominal rollover threshold level of saddle-mounted trucks is very high relative to loaded commercial vehicles for which rollover is a general concern. That is, saddle-mounted trucks are difficult to roll over under any circumstances, either static or dynamic, in comparison to loaded commercial vehicles generally.

b) The fact that the saddle-mount units are hitched with a roll-coupled connection, and that the hitch point will react lateral forces at or somewhat above the center of the sprung mass of the trailing unit, suggests that the preceding units in the saddle-mount vehicle will "help to hold up" the rearmost unit when it reaches its peaking lateral acceleration response. As a result, saddle-mount truck combinations are not prone to the "rear trailer rollover" anomaly that occurs with conventionally coupled doubles or triples combinations. This same feature has been identified as one of the peculiar advantages of the Canadian doubles configuration called a "B-train." The B-train essentially constitutes a tractor, semitrailer, semitrailer combination in which all of the elements are roll-coupled together by means of fifth wheel hitches. The roll-rigidity of the fifth wheel device affords a ready means for the tractor and leading trailer to work together in resisting the roll over of the rear trailer when it manifests a peaking, rearward-amplified, lateral acceleration response. The fact that the saddle-mounted truck configuration exhibits this same behavior suggests that rearward amplification response of this vehicle is essentially a moot issue.

5.0 CONCLUSIONS

The simulation results have shown that saddle-mount truck configurations exhibit braking, roll stability, and rearward amplification characteristics which are as good as, or better than, other vehicles in common service. The least advantageous among these characteristics is the braking performance of the saddle-mount vehicle. In this regard, the braking efficiency levels of the saddle-mount combinations were seen to be comparable to that of empty tractor-semitrailers. Also, the braking results support a general recommendation that double- and triple-saddle-mount vehicles be transported with the brakes on the rearmost axle disconnected.

With regard to rollover threshold levels and rearward amplification behavior, the saddle-mount combinations should fare considerably better than many vehicles in common service. The roll stability levels were much higher than those found among virtually all loaded truck combinations. Although the computed values of rearward amplification were found to be relatively high, approaching that of the conventional five-axle doubles combination, the saddle-mount hitching arrangement renders the net potential for rear unit rollover problems rather low. Moreover, saddle-mount configurations appear to exhibit generally acceptable performance characteristics over a broad range of the wheelbase values which comprise the truck market. Additionally, the influence of wheelbase, itself, is not strong such that saddle-mount combinations covering a broad range of wheelbase values behave quite similarly.