THE INFLUENCE OF DESIGN PARAMETERS ON GLIDER TRAILER TOWING BEHAVIOR

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Summary

A computer engineering model simulation can predict the dynamic lateral-sway behaviors of various combinations of tow vehicles (trucks, autos, vans, motorhomes, etc.) and trailers.

A model has been developed to analyze various combinations of trucks and trailers owned by the U.S. Forest Service and operated by a diversity of personnel. A method of selecting the correct combinations of trucks and trailers was needed by, and developed for, the U.S. Forest Service to make trailer use and selection most efficient within the limits of safety and practicability.

This model has also been used by the author to analyze the in-motion lateral-sway behavior of vehicle/trailer configurations typically used to convey and store gliders and is the subject of this paper.

The effects of the key design parameters (such as trailer wheelbase, weight and yaw inertia, weight distribution, hitch weight, tire lateral stiffness, and tow vehicle weight and geometry) have been analyzed to determine their influence on trailer lateral-sway behavior. These may be used to provide a rational basis for the decisions that are eventually made in the trailer design process. Recommendations for changes of current designs of trailers are made which will enhance the safety and dynamics of trailer towing.

Glider trailer configurations with weights over 800 Kg. and hitch-to-CG lengths of less than 5m (which includes most of today's configurations) are marginally safe when towed by medium and small vehicles (under 1800 Kg.), regardless of

whether front-wheel or rear-wheel drive. Improvements of lateral sway dynamics will result from the following changes to the trailer:

(1) Increase: Hitch length, hitch weight, tire size, or
(2) Reduce: Speed, yaw inertia, weight.

A. Introduction

Glider trailers serve a variety of functions, including service as a portable hangar for the disassembled glider, a rigging platform with convenient fittings for assembling the glider, and a convenient conveyance that can be towed safely by a variety of vehicles.

Over the last 10 years or so, in the U.S., trailer characteristics have become more uniform as a result of the importations of numerous trailers designed and purchased in Europe. The most common loading of a glider in these designs is with the wing roots and fuselage loaded forward; glider assembly is performed on the trailer's tail gate, and appears to be one of the key design criteria.

Over the past three years, the author has conducted analytical studies and field tests for the U.S. Forest Service to evaluate and to determine the suitability of various combinations of trucks and trailers for safe and economical towing, and to facilitate tow vehicle selection by personnel. Some of the analytical techniques developed and validated in the Forest Service study are used here to evaluate the lateral-sway dynamics of combinations of trailers and tow vehicles most commonly used to convey gliders.

For the purposes of this paper only, the key equations of motion from Reference (1) are included herein. This presentation emphasizes results of the evaluation of particular vehicle/trailer combinations and then draws conclusions concerning the handling characteristics of today's trailers.

B. Analysis techniques

Two sets of equations are presented:

(I) The simple case of a trailer only with no lateral hitch motion possible, which is equivalent to a trailer being towed by an infinitely large and rigid tow vehicle (Equations 1 through 4); and

(II) The case of a trailer loaded in a way that results in no dynamic forces at the trailer hitch of the towing vehicle (Equation 5). This case results when the wheels are located at the center of percussion.

Analysis of these two simple cases gives insight into the relationships of the design parameters which are applicable to a range of real-world combinations.

The equations of motion which formed the basis of the analytical results subsequently presented consider the tow vehicle and the trailer as rigid bodies connected at the hitch. The equations of motion used for the computer solutions include degrees of freedom for the truck yaw, and lateral motion, and the trailer/truck articulation angle. The forward speed was constant, the tires had linear lateral stiffness (no skidding).

Equations of Motion

(Case I) Trailer only dynamic equations of motion

The trailer is analyzed as a one degree of freedom system (yaw only). Based on the nomenclature of Figure (1), the equation of motion, for the trailer only, is written in the yaw direction for the case in which the hitch is considered frozen from lateral motion.

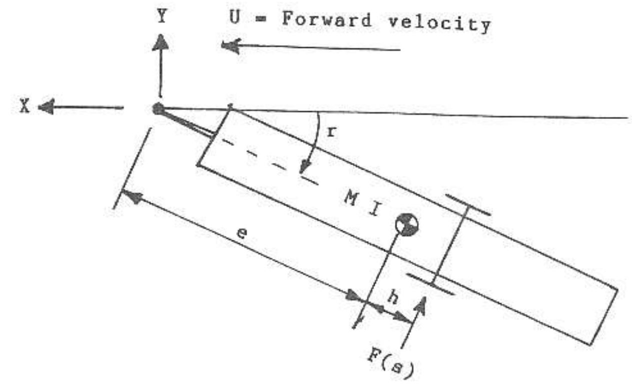

FIGURE 1. Trailer schematic for deriving equations of motion.

$$I'*\ddot{r} + F(s)*(e+h) = 0.0 \quad (1)$$

Where:

I' = $I_o + M*e^2$ (Yaw inertia about hitch)
I'_o = Trailer yaw inertia about its CG
r = Trailer sway (articulation angle with truck)
$\ddot{r}$ = Rotational acceleration
F(s) = Lateral force at tire due to tire side slip angle F(s) = C*s
C = Tire lateral force coefficient as a function of sideslip, units of N/rad

The sideslip angle, s, can be expressed in terms of the sway (r) and sway velocity ($\dot{r}$):

$$s = (e+h)*\dot{r}/U + r$$

then, the equation of motion (1) can be re-written as:

$$O = I'*\ddot{r} + (C*(e+h)^2/U)*\dot{r} + (C*(e+h)*r \quad (2)$$

From the above equation, the expressions for trailer response resonant frequency, f_n, and for the damping ratio, B, as a percent of critical can be written. Critical damping is the smallest damping for which perturbations do not oscillate but return gradually to zero.

$$f_n = \sqrt{C*(e+h)/I'}$$
$$B = C*(e+h)^2 / [2*U*\sqrt{C*(e+h)*I'}] \quad (3)$$

$$B = \frac{1}{2*U} \sqrt{\frac{C*(e+h)^3}{I'}} \quad (4)$$

These equations give an initial assessment at trailer behavior. Figure (5) tabulates the rigid-hitch lateral damping of the trailer configurations used in this paper. Equation (4) gives straightforward insight of the parameters that affect lateral stability and their relative importance. The most critical factor is hitch length since damping is proportional to the 1.5 power of the hitch length.

Speed is the second most critical factor with damping varying inversely to the speed. Larger tire lateral stiffness increases damping, and larger yaw inertia decreases damping, by the square root of the change.

With a practical tow vehicle, the influence of the parameters (hitch length, speed, tire stiffness) is often even more pronounced.

(Case II) No hitch dynamic loads

By adjusting the weight distribution and geometry, a tongue weight can be determined, which will result in no lateral dynamic hitch force at all. This is achieved by solving for the hitch lateral dynamic force in terms of the other parameters of the trailer and setting it equal to zero. If the pitch inertia is equal to the yaw inertia, a side benefit of setting the lateral dynamic hitch forces equal to zero is that the vertical hitch dynamic forces will also be zero. A very happy situation results since the pounding induced on the hitch and the jerking of the tow vehicle by the trailer, especially heavy ones are totally avoided.

Setting up equations for the lateral forces at the hitch and rearranging yields the optimum tongue weight ratio.

$$T/W = 0.5 - \sqrt{(0.25 - (R/(e+h))^2} \qquad (5)$$

Where:

- T = Tongue weight
- W = Trailer weight
- R = Trailer radius of gyration $\sqrt{(I_0/M)}$
- M = Trailer mass (W/g)

The merit of designing and building a trailer to satisfy equation (5) is that the size of the tow vehicle, small or large, does not matter, as there are no lateral or vertical dynamic loads at the hitch.

D. Criteria for trailer behavior evaluation

Sway damping of at least 25% at a speed of at least 100 Km/hr is considered necessary for satisfactory overall towing performance. While 100% damping is possible (highway semi-trucks, for example), it is not very practical for glider trailers; 25% damping decays to less than 5% of the perturbation in two cycles. Figure (2) shows the decay behavior of various values of damping.

Values of damping lower than 25% can be occasionally tolerated, but safe behavior mandates conservatism in order to cover cases of unusually adverse circumstances, such as loose gravel, slick or rutted roads, or traffic surprises.

Equation (6) is an expression for the decay of motion per cycle as a function of the damping. Figure (2) provides a visual representation of the decay of motion as a function of time for three different damping values.

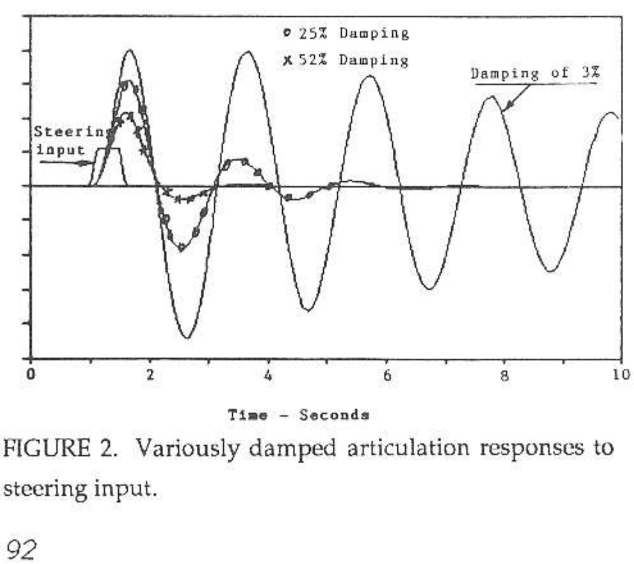

FIGURE 2. Variously damped articulation responses to steering input.

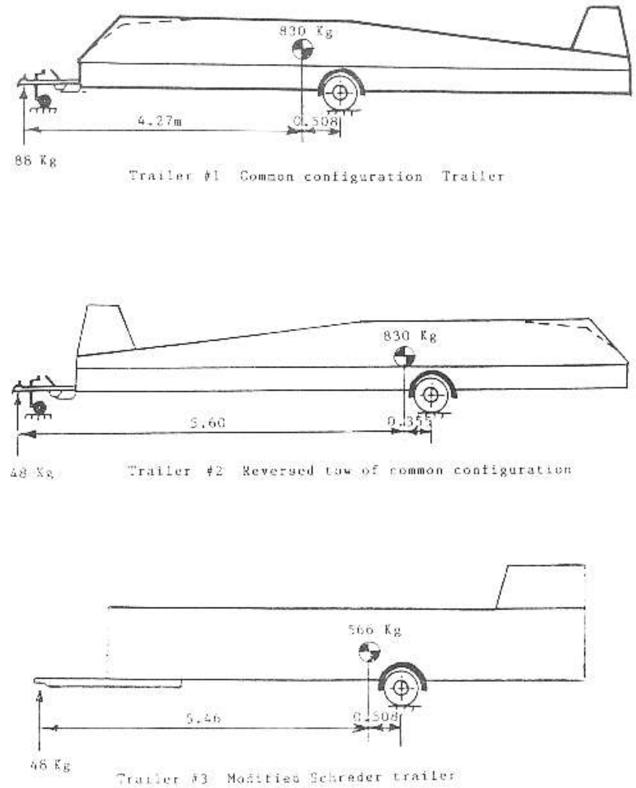

FIGURE 3. Schematics of glider trailers used in this study.

$$Y_n = Y_0^* e^{(-2*\pi*B*n)}$$

Where:

- Y_n = Is the amplitude of the n-th cycle after an initial perturbation of Y_0
- B = The damping ratio
- e = Base of natural logarithms

E. Vehicles and trailers analyzed

Three diverse tow vehicles depicted figure (3) in combination with these specific trailers depicted in figure (4) were selected for this study: (Car #1), a 950 Kg small front wheel drive automobile, (truck #2) a 1590 Kg small-size truck, and (truck #3) a 3800 Kg medium-size truck loaded with a camper.

The trailers were picked to demonstrate particular points: hitch weight, trailer wheelbase and weight distribution, trailer weight, and tire influence. Trailer #1 is a typical manufacturer's glider trailer, 830 Kg. (loaded), with a short wheelbase. Trailer #2 is a typical glider trailer, 830 Kg., and towed from the opposite end. Trailer #3 is a Schreder glider trailer modified to reduce weight (566 Kg.) and to lengthen the tongue.

F. The influence of analysis parameters

Hitch Weight

Hitch weight is a powerful parameter and the easiest parameter to vary in order to control lateral sway dynamics. Figures (6) and (7) are plots of the influence of tongue weight on sway damping for several different tow vehicle and trailer combinations. If the tow vehicle is able to handle any amount of tongue weight, sway damping can always be controlled.

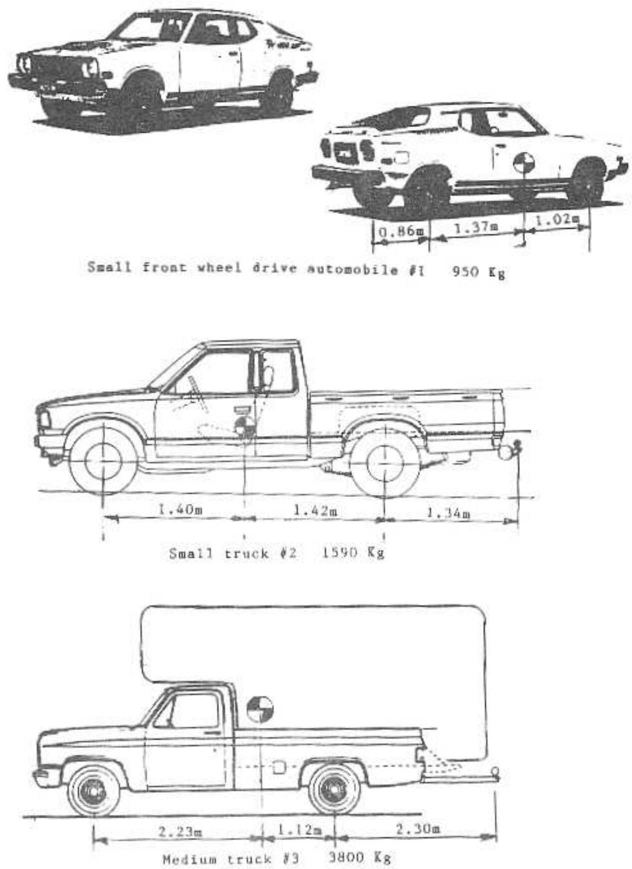

FIGURE 4. Schematics of tow vehicles used in this study.

Trailer Wheelbase and Weight Distribution

Trailer weight distribution can significantly influence the amount of tongue weight required to control sway damping. Figures (6) and (7) are for the three different vehicles towing short and longer wheelbase trailers, respectively. At heavier tongue loads, little difference results between a small tow vehicle (950 Kg.) (car #1) and a larger tow vehicle (3800 Kg.) (truck #3). Also, tongue weight is not as critical or as sensitive a parameter for large tow vehicles as for small cars.

TRAILER PROPERTIES

		Weight Kg	I_0 Yaw Inertia $Kg-m^2$	CG to Hitch m	Tire Stiff deg^{-1}	* Damp % Cr	** Hitch Load
#1	Typical Trailer	830	3500	4.27	0.135	0.29	240
#2	Reversed Trailer	830	3680	5.60	0.135	0.35	120
#3	Modified Schreder	566	2520	5.46	0.135	0.36	.84

* Damping for 100 Km/hr speed with "infinite" mass truck
** Hitch load for zero dynamic hitch forces - Kg

TOW VEHICLE PROPERTIES

	Weight Kg	I_0 Inertia $Kg-m^2$	Wheel Base m	Weight Distr. Dry	Over Hang m	Tire Stiff deg^{-1}
#1 Small Car	950	1200	2.39	58/42	0.86	0.165
#2 Small Truck	1590	1800	2.81	50/50	1.34	0.165
#3 Heavy Truck	3790	5890	3.34	33/67	2.30	0.140

FIGURE 5. Physical properties of study vehicles.

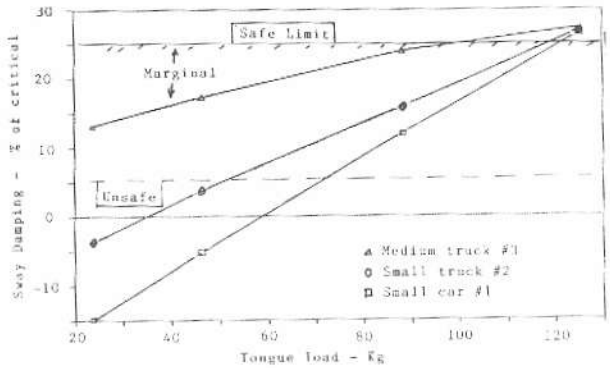

FIGURE 6. Sway damping of trailer #1 towed by three vehicles at 100 km/hr.

The sway dynamics of trailers with the longest wheelbase provides the most benign towing characteristics. By keeping the weight as far aft as possible and/or using a long tongue, benign conditions are produced with a lighter tongue weight, especially for small cars. The ultimate trailer typifying this condition in the U.S. is a compact gravel and sand box with a small yaw inertia placed directly over the trailer wheels connected to a long tongue. The result is a trailer with high damping of over 100% with a low tongue weight of less than 5%.

Trailer Weight

Weight is best kept to a minimum; however, weight is not a major culprit by itself in relation to lateral sway. However, heavy loads put a greater stress on brakes and power plant. Adding weight to a trailer ahead of the wheels can improve the lateral damping. For example, basic trailer #1 towed by small car #1 at 100 Km/hr has a basic damping of 3%. By adding 70 Kg of weight at various locations ahead of the wheels, the damping is improving from 3% to 6% with the weight over the wheels and to 8% with the weight placed half way between the hitch and the wheels.

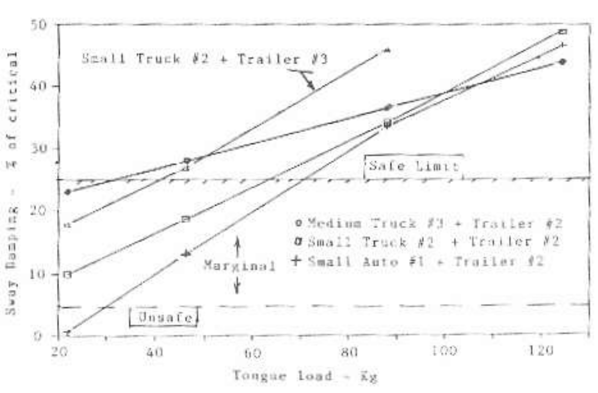

FIGURE 7. Sway damping of trailer #2 towed at 100 km/hr.

Yaw Inertia

Yaw inertia aggravates lateral sway. Since glider payloads are long in relation to their weight, not much can be done about this high inertia except to keep the total weight of the trailer as low as possible and not to add mass to the ends of the trailer. "Extra" weight such as spare tires and tool boxes should be placed near the wheels.

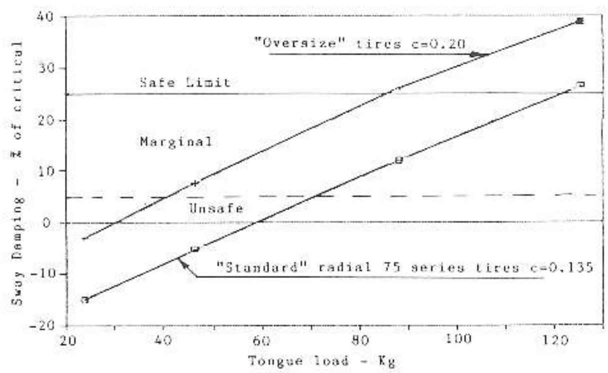

FIGURE 8. Influence of trailer tire stiffness on sway damping, small car #1 towing trailer #1.

Tire Influences

Tire data for this paper were taken primarily from Reference (4). Tire lateral stiffness has a significant impact on trailer lateral sway. Figure (8) is a plot of the articulation angle damping for car #1 pulling trailer #1 at 100 Km/hr at various tongue loads with both standard P165/75R13 tires (c=0.135) and high stiffness low profile tires, perhaps 220/55R390 (c=0.2). The higher stiffness (low profile) tires improve the sway damping by a nearly constant value of 12% across the entire tongue load range. This is especially significant if the damping is near zero in the first place.

By contrast, changing to higher stiffness tires on the tow vehicle has very little effect on trailer lateral sway. However, tire stiffness and weight distribution have a significant impact on the oversteer tendency of the tow vehicle. Low tire stiffness and/or overweight on the rear wheels can cause a dangerous oversteer condition independent of the trailer. (Tow vehicle oversteer is not addressed by this paper in detail.)

Of the three tow vehicles analyzed, the medium truck (3) has a high rear-to-front load ratio and is marginal at 100 Km/hr from an oversteer standpoint. If the stiffness of the rear tires is reduced 15%, the vehicle is unstable. The front wheel drive automobile (car #1) is the most stable because of its weight distribution. For this reason and for the short hitch overhang behind the rear wheels, front wheel drive automobiles make the best tow vehicles assuming other factors are equal.

Tire lateral stiffness for typical tires is plotted in Figure (9). The lateral force generated by a tire is plotted as Kg side force per Kg of vertical force per degree angle of attack. In the normal load range of 50% to 100% of loaded range, low-profile (55 and 60 series) tires have lateral stiffness of up to 40% higher than standard 75 or 80-series radials. Bias ply tires generally have 25% to 30% lower lateral stiffness than radials and are not recommended for use on glider trailers. There is

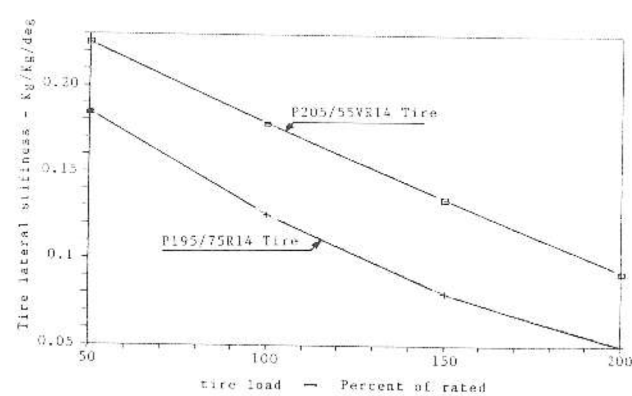

FIGURE 9. Lateral stiffness of two types of tires as a function of load.

no point in giving up that much lateral sway damping for such a small price.

Speed

Figure (10) plots the influence of speed on trailer lateral-sway damping. Reduction of speed always improves sway damping. For the case of light truck #2 pulling trailer #1, reducing speed to 82 Km/hr allows the damping criteria of 25% of critical to meet at 88 Kg tongue loading or 66 Km/hr at 46 Kg tongue load.

G. Conclusions and recommendations

The major factors affecting trailer lateral stability are;

(1) Hitch length to the trailer CG
(2) Tongue weight (position of the wheels aft of the CG)
(3) Speed
(4) Yaw inertia of the trailer
(5) Trailer tire lateral stiffness
(6) Ratio of trailer to tow vehicle weight

Glider trailer configurations with weights over 800 Kg. and hitch-to-CG lengths of less than 5m (which includes most of today's configurations) are marginally safe when towed by medium and small vehicles (under 1800 Kg.), regardless whether front-wheel or rear-wheel drive.

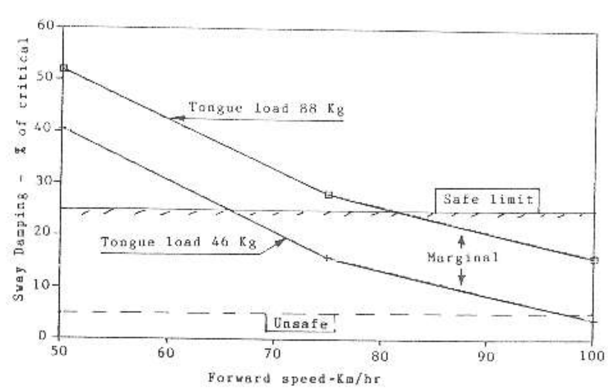

FIGURE 10. Influence of speed on sway damping, small truck #2 towing trailer #1.

Techniques for improving trailer lateral-sway dynamics include:

(1) Redesign the trailers to tow from the "long" end (i.e., with the glider tail stored forward)

(2) Use a longer hitch on existing designs

(3) Make the trailers lighter, keep mass near the CG

(4) Use larger tires and/or low profile tires

(5) Increase tongue weights

(6) Tow with larger trucks

(7) Drive more slowly

The choice of compromises is left to the designer, manufacturer, and the pilot or user.

H. References

(1) Ellis, J.R. 1969 Vehicle Dynamics, London Business Books

(2) Funston, Nelson E. Girard, Joseph D. 1984 Gooseneck and Pole Trailer Study, Structural Dynamics, Contract No. 53-9JA9-3-398, U.S. Dept. of Agriculture Forest Service, (1984)

(3) Funston, Nelson E. Hodges, Henry C. Jr. 1984 Safe Tow Load Tests of Truck/Trailer Combinations, Nevada Automotive Test Center, Contract No. 53-9JA9-4-487, U.S. Dept. of Agriculture Forest Service

(4) Tapi, George A. 1983 Extending Tire Testing, Calspan Corp., Contract No. DTNH22-81-C-07100, U.S. Dept. of Transportation.