SHORT PAPER PCB 3 - 2007

AIR BRAKE DESIGN & SAFETY

PART TWO

TRACTOR - TRAILERS

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1.0. INTRODUCTION

This publication presents the second paper of our computer-based air brake system design and safety analysis addressing articulated tractor-trailer combinations. All major input data and parameters relative to the foundation brakes are discussed in Short Paper PCB 2 – 2007, Air brake Design and Safety, Part One, Straight Trucks. Only additional input data pertinent to articulated vehicle will be discussed.

Most over-the road tractor-semi-trailer combinations have air springs on the tractor, and either air springs or leaf springs on the trailer. The leaf spring suspension is of particular interest since it exhibits significant inter-axle load transfer and may be of particular interest to the brake engineer as well as accident reconstruction expert.

In the past in many accidents involving tractor jack-knifing the tractor rear brakes locked up first causing the tractor to rotate and the front of the tractor (without any steering by the driver) to either invaded the opposite traffic lane or to spin off the road to the right with the trailer simply following the fifth wheel. Frequently the front brakes were not properly adjusted, and for the lightly loaded condition, the deceleration of the combination was severely reduced due to the fact that the most heavily loaded axle (front) could not utilize its traction coefficient due non-adjusted front brakes.

2.0. PARTICULAR CONSIDERATION FOR TRACTOR-SEMITRAILERS

For a straight truck or a car the axle loads, either static or dynamic, are always equal to the weight of the vehicle. For a tractor-semitrailer the axle loads of the tractor are not equal to the weight of the tractor, since some load transfer occurs from the trailer unto the tractor statically or during braking.

For simplicity, we consider a 2-S1 tractor-semitrailer combination, that is, neither the tractor nor the trailer are equipped with tandem axles. For a given tractor-semitrailer geometry all longitudinal dimensions are specified or measured at the accident vehicle. Consequently, the following data are either measured or known: Fifth wheel location ($L_1 – l_{l5}$), trailer wheelbase (L_2), tractor wheelbase (L_1), tractor (without trailer attached) longitudinal center-of-gravity location (l_1) (generally known or can be obtained from measured loads of axle 1 and axle 2).

Assume the static axle load F_{z3meas} of the third axle of the accident tractor-semitrailer was measured. This measurement with all other dimensions known automatically determines the static axle loads F_{z1st} and F_{z2st} of the tractor. For 3-S2 combinations with air/air or air/walking beam suspension knowing the total axle load of the trailer rear axles is sufficient to calculate the axle loads of the tractor. For a 3-S2 combination with leaf rear spring suspension different axle loads of axle #4 and axle #5 will affect the static tractor axle loads differently. The data required from the subject vehicle are as follows:

1. 2-S1: Measure static load F_{z3sta} of axle #3
2. 3-S2: air/air or air/WB: Measure loads of axle #4 and axle #5, either combined (or individually).
3. 3-S2: air/leaf spring: Measure loads of axle #4 and axle #5 individually
4. 2-S1-2: Measure load of axle #3; measure loads of axle #4 and axle #5 of the pup-trailer (they do not affect the axle load(s) of the semitrailer or the tractor.

1.0. LIMITING AND PROPORTIONING VALVES

The front brake line pressure-limiting valve used for straight trucks is also used for combination vehicles. The brake line pressure curve is illustrated in Figure 1. Up to the limit pressure p_{k1} the front pressure is reduced by the reduction factor k_1. For greater pressures, the front pressure equals the brake line pressure demanded by the driver's pedal effort.

For any other axles the brake line pressure follows proportioning valve characteristics illustrated in Figure 2. For pressures less than the knee-point pressure, the brake line pressure to the wheel brake equals the pressure demanded by the driver's pedal effort. For greater pressures, the pressure increase is reduced by the slope factor k_2.

3.0. 2-S1 TRACTOR-TRAILER COMBINATION

The tractor-trailer schematic is illustrated in Figure 3. Both tractor axle weights are included in the tractor weight. The trailer axle weight is included in the trailer weight.

The axle normal forces of the tractor and semi-trailer are:

$$F_{z1} = W_1 + Y - F_{z2}; \text{ lb} \tag{1}$$

$$F_{z2} = (W_1 l_1 - aW_1 h_1 - Xh_5 + Yl_5)/L_1; \text{ lb} \tag{2}$$

$$F_{z3} = W_2 - Y; \text{ lb} \tag{3}$$

The king pin/fifth wheel forces are:

$$X = F_{x1} + F_{x2} - aW_1; \text{ lb} \tag{4}$$

$$Y = (aW_2 h_2 + W_2(L_2 - l_2) - Xh_5)/L_2; \text{ lb} \tag{5}$$

where: a = deceleration, g-units ($\Sigma F_i/(W_1 + W_2)$

F_{xi} = braking force of i^{th} axle, lb

h_{1cg} = vertical distance ground to tractor center-of-gravity, ft

h_{2cg} = vertical distance ground to trailer center-of-gravity, ft

h_5 = vertical distance ground to fifth wheel, ft

L_1 = tractor wheelbase, ft

L = trailer wheelbase, ft

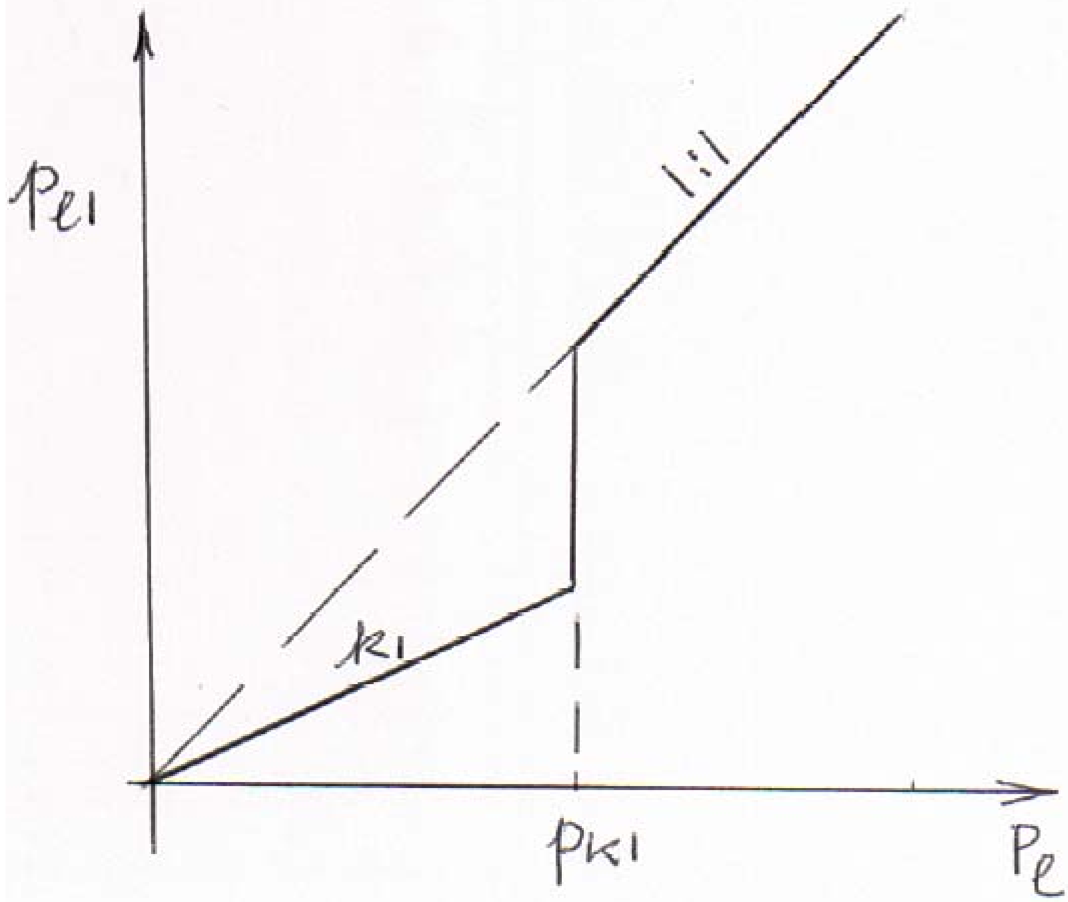

Figure 1: Axle #1 Limiting Pressure Valve

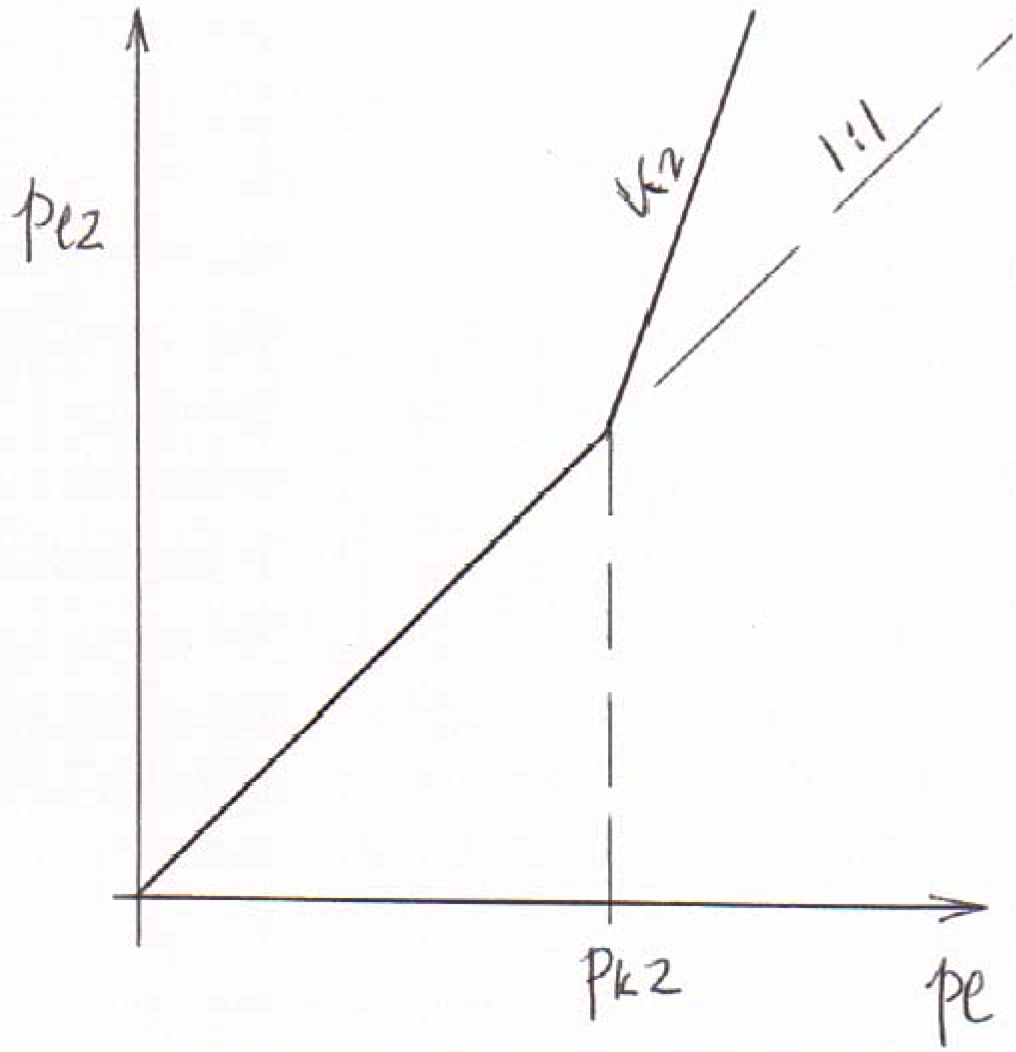

Figure 2: Axle #2 Proportioning Valve

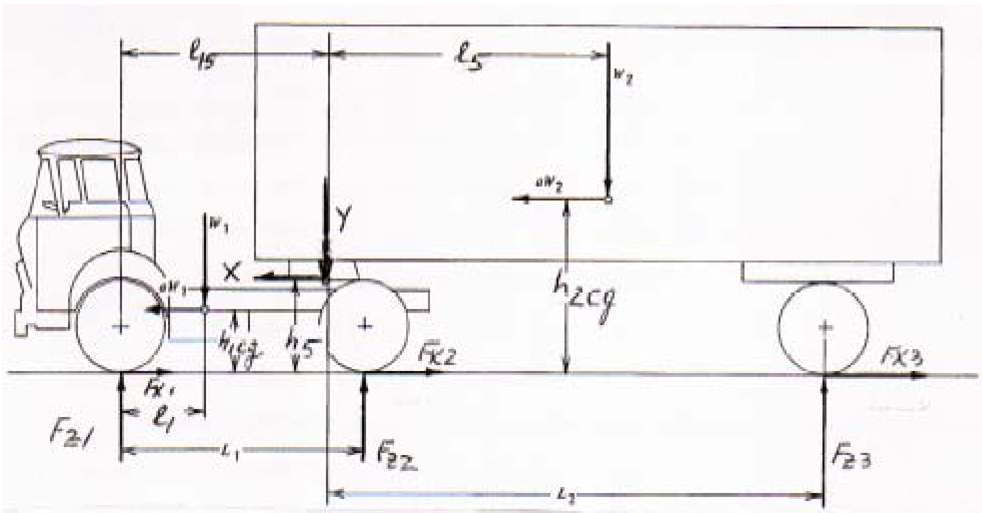

Figure 3: 2-S1 Tractor-Semitrailer – Forces and Dimensions

l_1 = front axle to tractor cg, in.
l_5 = fifth wheel to trailer cg, in.
l_{15} = front axle to fifth wheel, in.
W_1 = tractor weight, lb
W_2 = trailer weight, lb

The normal forces as a function of deceleration for a 46,000 lb 2-S1 combination are shown in Figure 4. As expected, axle #1load increases, while the others decrease. The axle # 2 load does not decrease as much as that of axle #3, since it experiences both a load transfer onto it from axle #3, as well as load transfer off itself onto axle #1.

The friction utilization curves for all three axles are shown in Figure 5. Inspection of Figure 5 reveals an excellent brake force distribution among all three axles. Axle #1 (UT1) will lock up first for decelerations below approximately 0.45g, thus rendering the tractor-semitrailer stable for most decelerations. The detailed analysis of the table data (not shown) showed an associated brake line pressure of approximately 65 psi.

For decelerations higher than 0.45g, and assuming a tire-road friction coefficient of 0.6, axles #2 and 3 will lock up at approximately 85 to 95 psi, followed by axle #1 at 105 psi. Since all brakes are locked, the associated deceleration is 0.6g. It should be noted, that the entire tire-road friction is utilized for deceleration because of the excellent brake force distribution as well as brake torque capacity designed into the foundation brakes.

4.0. 3-S2 TRACTOR-TRAILER COMBINATIONS

4.1. AIR SPRINGS ON BOTH TANDEM AXLES (3-S2-AA)

Since there is no inter-axle load transfer among the individual axles of the tandem axles, the weights of the rear axles are included in the tractor and trailer weights, respectively. The three axle normal forces carrying the tractor frame are mathematically indeterminate (unless a complicated deflection relationships is used). We made the (reasonable) assumption that the normal forces are distributed according to their static normal axle loads. Frequently, flat bed and other semitrailers have two rear air suspensions with an axle spread much greater than the usual 50 in. These designs can also be analyzed with the PC-BRAKE AIR AA (two-air spring) software.

The forces and dimensions are illustrated in Figure 6.

The axle normal forces of the tractor and semi-trailer are:

$$F_{z1} = W_1 + Y - (F_{z2} + F_{z3});\ \text{lb} \tag{6}$$

$$F_{z2} = ((W_1 l_1 - aW_1 h_1 - Xh_5 + Yl_5)/(L_1))((F_{z2st}/(F_{z2st} + F_{z3st}));\ \text{lb} \tag{7}$$

$$F_{z3} = ((W_1 l_1 - aW_1 h_1 - Xh_5 + Yl_{15})/(L_1)((F_{z3st}/(F_{z2st} + F_{z3st}));\ \text{lb} \tag{8}$$

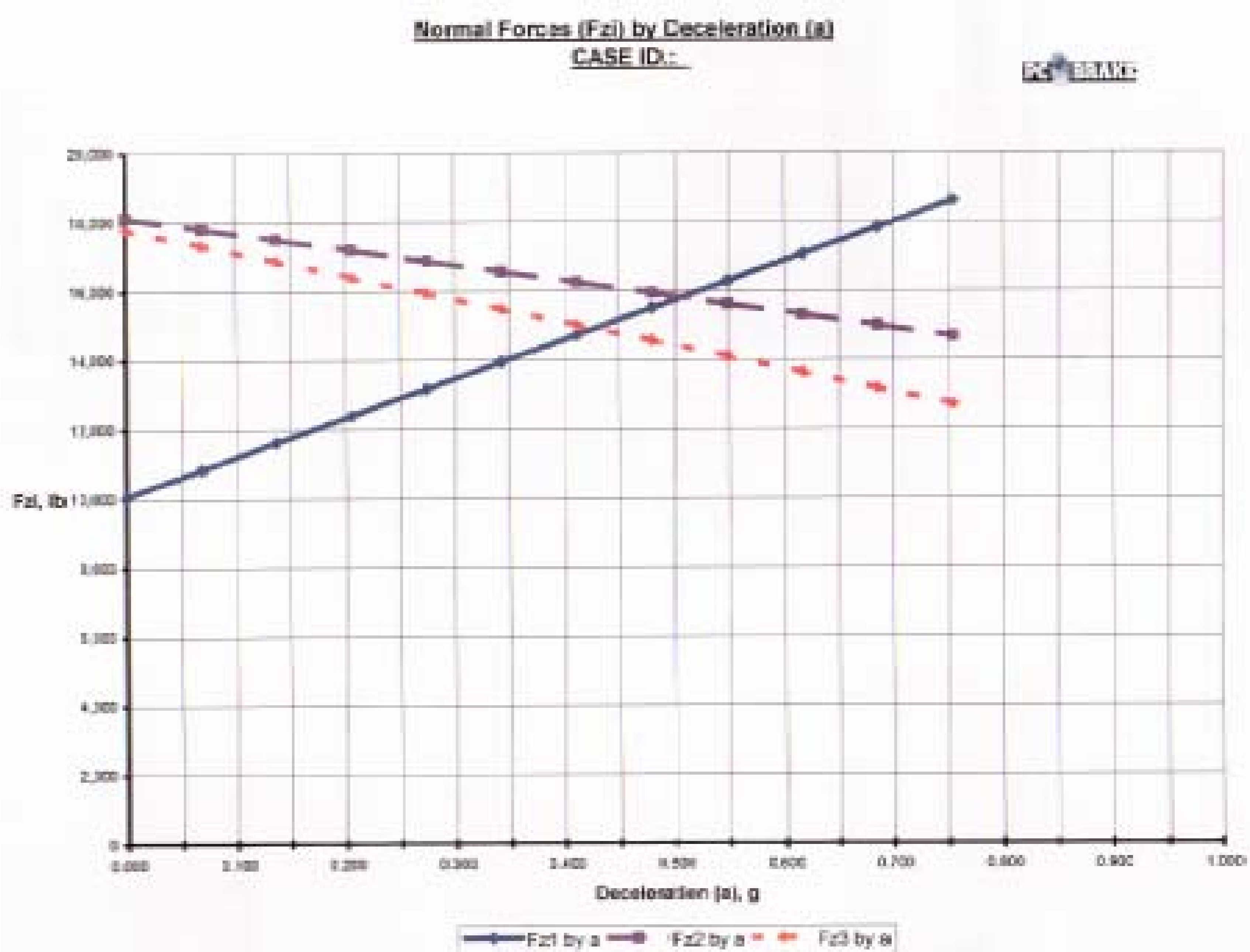

Figure 4: 2S-1 Combination at GVWC – Axle Loads as a Function of Deceleration

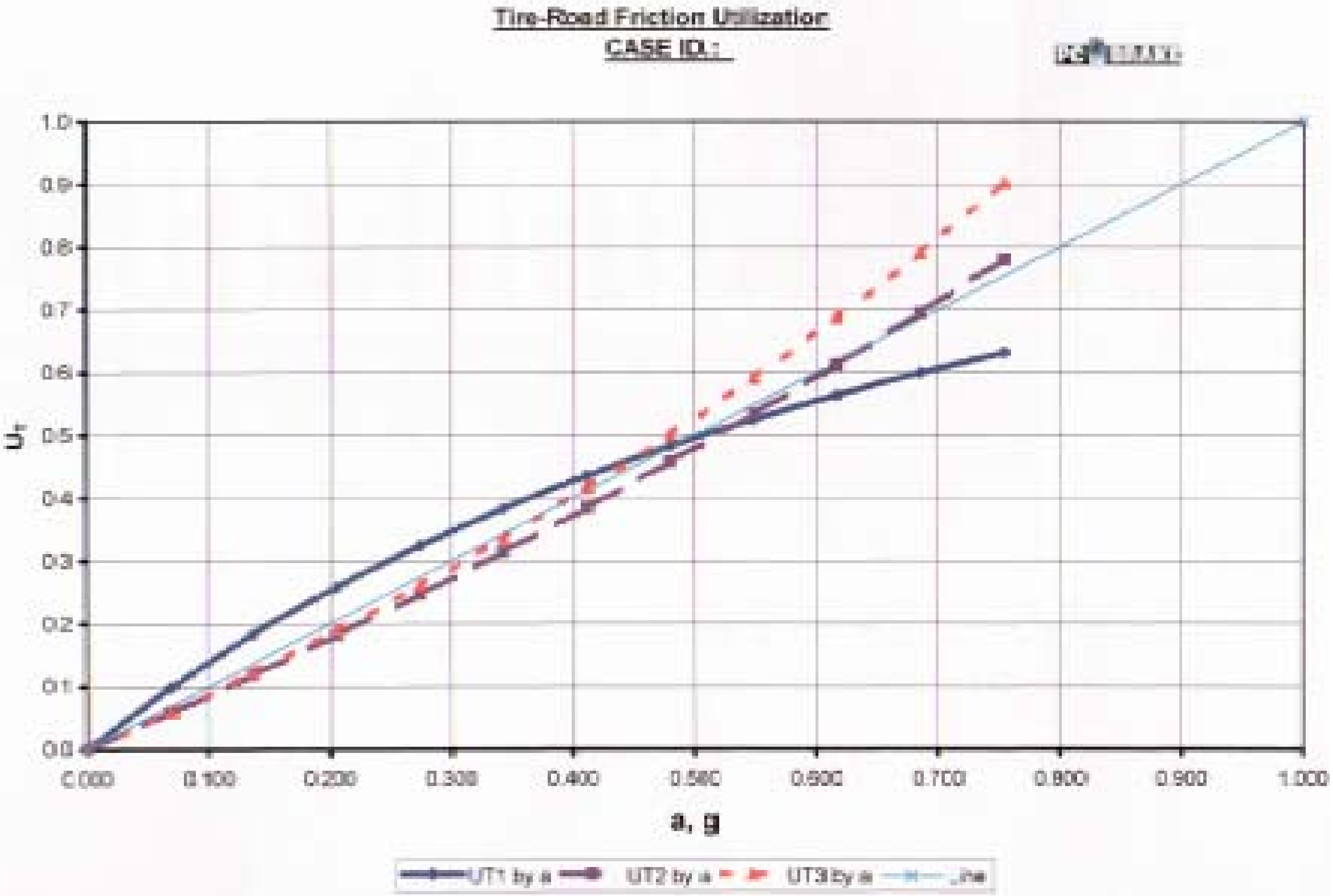

Figure 5: 2-S1 Combination a: GVWC – Tire Road Friction Utilization

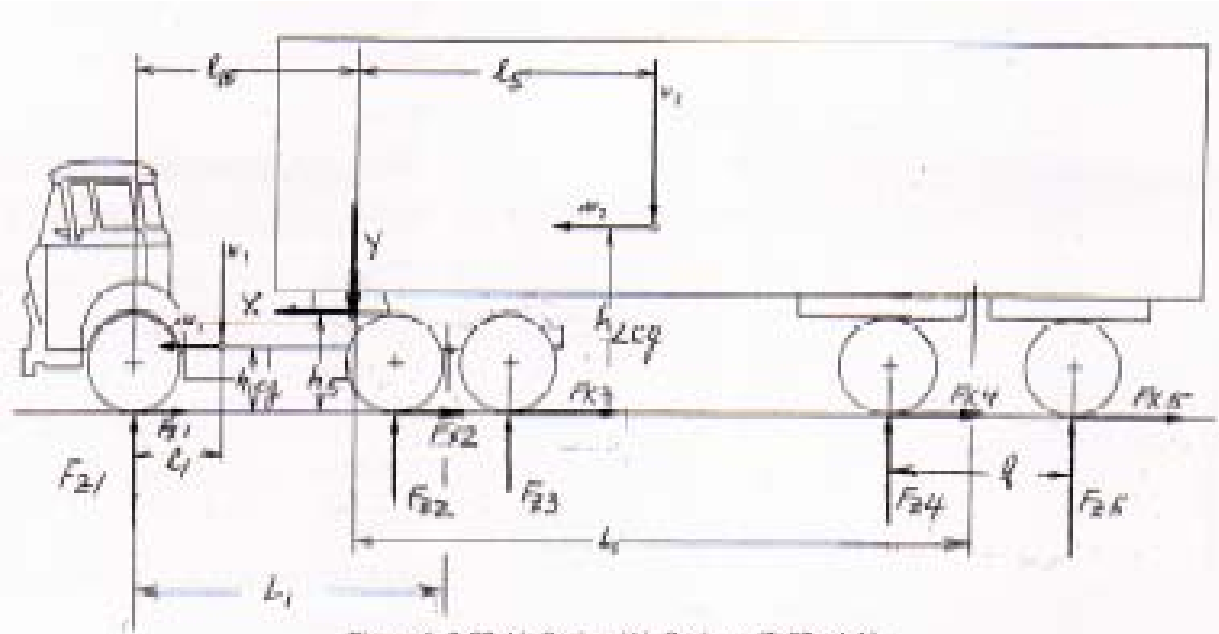

Figure 6: 3-S2 Air Springs/Air Springs (3-S2 –AA)

$$F_{z4} = (W_2 - Y)(F_{z4st}/(F_{z4st} + F_{z5st}); \text{lb} \qquad (9)$$

$$F_{z5} = (W_2 - Y)(F_{z5st}/(F_{z4st} + F_{z5st}); \text{lb} \qquad (10)$$

where: $X = F_{x1} + F_{x2} + F_{x3} - aW_1$; lb (11)

Y = Equation 5 with X from Equation 11.

4.2. TRACTOR AIR SPRINGS – TRAILER WALKING BEAM (3-S2-AWB)

The forces and dimensions are illustrated in Figure 7. The normal forces of the 3-S2 tractor-trailer are:

$$F_{z1} = W_1 + Y - F_{z2} - F_{z3}; \text{lb} \qquad (12)$$

$$F_{z2} = (W_1 l_1 - Xh_5 + Yl_5 - aW_1 h_{1cg})/(L_1)(F_{z2st}/(F_{z2st} + F_{z3st}); \text{lb} \qquad (13)$$

$$F_{z3} = (W_1 l_1 - Xh_5 + Yl_5 - aW_1 h_{1cg})/(L_1)(F_{z3st}/(F_{z2st} + F_{z3st}); \text{lb} \qquad (14)$$

$$F_{z4} = Y_2 + w_4 + w_5 - F_{z5}; \text{lb} \qquad (16)$$

$$F_{z5} = (1/2)(Y_2 + 2w_5 - X_2 v_1/(q_2/2) - a(w_4 + w_5)u_1/(q_2/2)) \quad ; \text{lb} \qquad (17)$$

where: $Y = (aW_{S2}(h_{S2} - v_1) + W_{S2}(L_2 - l_{S2}) - X(h_5 - v_1)/L_2$; lb (18)

$$X = F_{x1} + F_{x2} + F_{x3} - aW_1; \text{lb} \qquad (19)$$

$$Y_2 = W_{S2} - Y; \text{lb} \qquad (20)$$

$$X_2 = aW_{S2} - X; \text{lb} \qquad (21)$$

$h_{S2} = (W_2 h_{cg2} - (w_4 + w_5)u_1)/W_{S2}$; in. (sprung trailer weight cg-height) (22)

$l_{S2} = ((F_{z4st} - w_4)(L_2 - q_2/2) + (F_{z5st} - w_5)(L_2 + q_2/2))/W_{S2}$; in (23)

(horizontal distance fifth wheel to sprung trailer cg-location)

F_{xi} = braking force of i^{th} axle; lb
F_{zist} = static axle weight of i^{th} axle; lb
w_i = un-sprung weight of i^{th} axle; lb
W_1 = tractor weight; lb
W_{S2} = sprung weight of trailer; lb
q = walking beam axle spread, in.
v_1 = walking beam pivot height, in.
u_1 = walking beam un-sprung weight height, in.

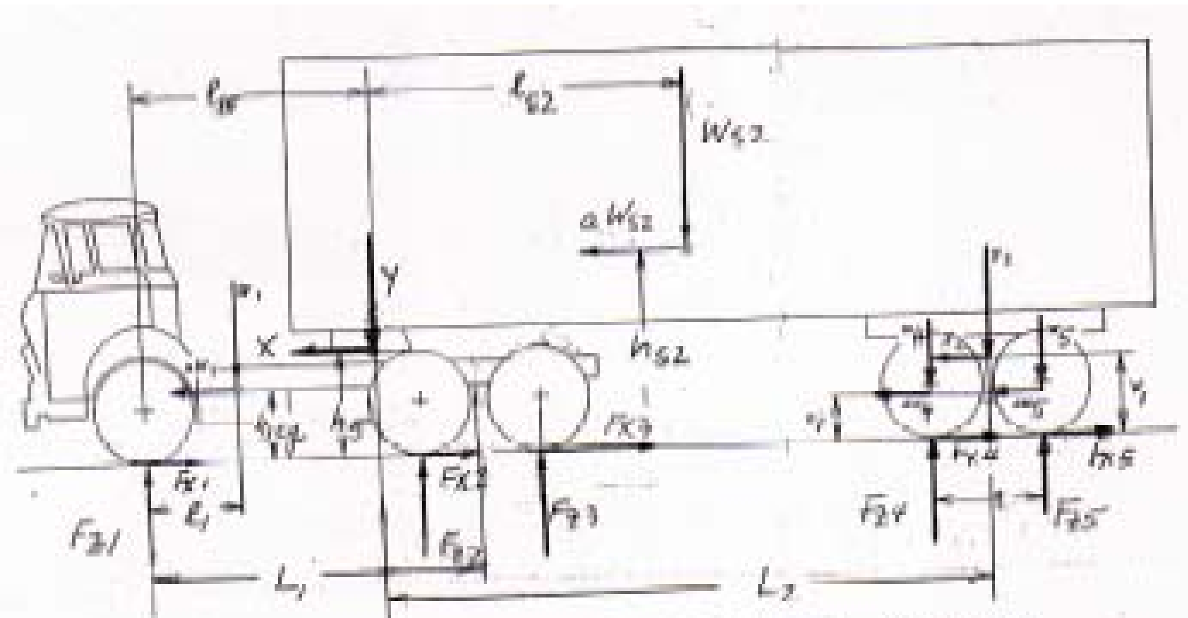

Figure 7: 3-S2 Air Springs/Walking Beam (3-S2 – AWB)

4.3. TRACTOR AIRSPRINGS – TRAILER LEAF SPRINGS (3-S2-ALS)

The forces and dimensions are illustrated in Figure 8. The normal forces of the 3-S2 tractor-trailer are (Re.6):

$$F_{z1} = W_1 (1 - \psi_1 + a\chi_1) + Y(1 - y + az_1);\ \text{lb} \qquad (24)$$

$$F_{z2} = (W_1(\psi_1 - a\chi_1) + Y(y - az_1))F_{z2sta}/(F_{z2sta} + F_{z3sta});\ \text{lb} \qquad (25)$$

$$F_{z3} = (W_1(\psi_1 - a\chi_1) + Y(y - az_1)F_{z3sta}/(F_{z2sta} + F_{z3sta});\ \text{lb} \qquad (26)$$

$$F_{z4} = (bdY_2/((c + d)(b/2 + av)) + w_4 - auw_4/(b/2 + av);\ \text{lb} \qquad (27)$$

$$F_{z5} = (bdY_2/((c + d)(b/2 - av)) + w_5 + auw_5/(b/2 - av);\ \text{lb} \qquad (28)$$

where:

$$Y = W_{S2} - Y_2((d(b/2 - av)/((c + d)(b/2 + av)) + c(b/2 + av)/((c + d)(b/2 - av)) + 1) \qquad (29)$$

$$+ (auw_4/(b/2 + av) - (auw_5/(b/2 - av);\ \text{lb}$$

$$Y_2 = (W_{S2}L_2(\psi_2 - a(\chi_2 - z_2)) + aG_1)/H_1;\ \text{lb} \qquad (30)$$

$$G_1 = uw_4/(b/2 + av)((z_1L_1 - v)a + L_2 - c - b) - uw_5/(b/2 - av)((z_1L_1 - v)a + L_2 + d + b);$$

$$\text{lbin.} \qquad (31)$$

$$H_1 = (d/(c + d)((z_1 L_1 - v)a + L_2 - c - b))((b/2 - av)/(b/2 + av)) +$$

$$(c/(d + c)((z_1L_1 - v)a + L_2 + d + b))((b/2 + av)/(b/2 - av)) +$$

$$(z_1L_1 - v)a + L_2;\ \text{in.} \qquad (32)$$

F_{zista} = statitc axle weight of i^{th} axle, lb
W_1 = tractor weight, lb
W_2 = trailer weight, lb
W_{S2} = sprung weight of trailer, lb
h_{1cg} = tractor center-of-gravity height, in.
h_{2cg} = trailer center-of-gravity height, in.
$y = l_{15}/L_1$
$z_1 = h_5/L_1$
$z_2 = h_5/L_2$
$\chi_1 = h_{1cg}/L_1$
$\chi_2 = h_{2cg}/L_2$
ψ_1 = static empty tractor (no trailer) rear axle loads divided by tractor weight

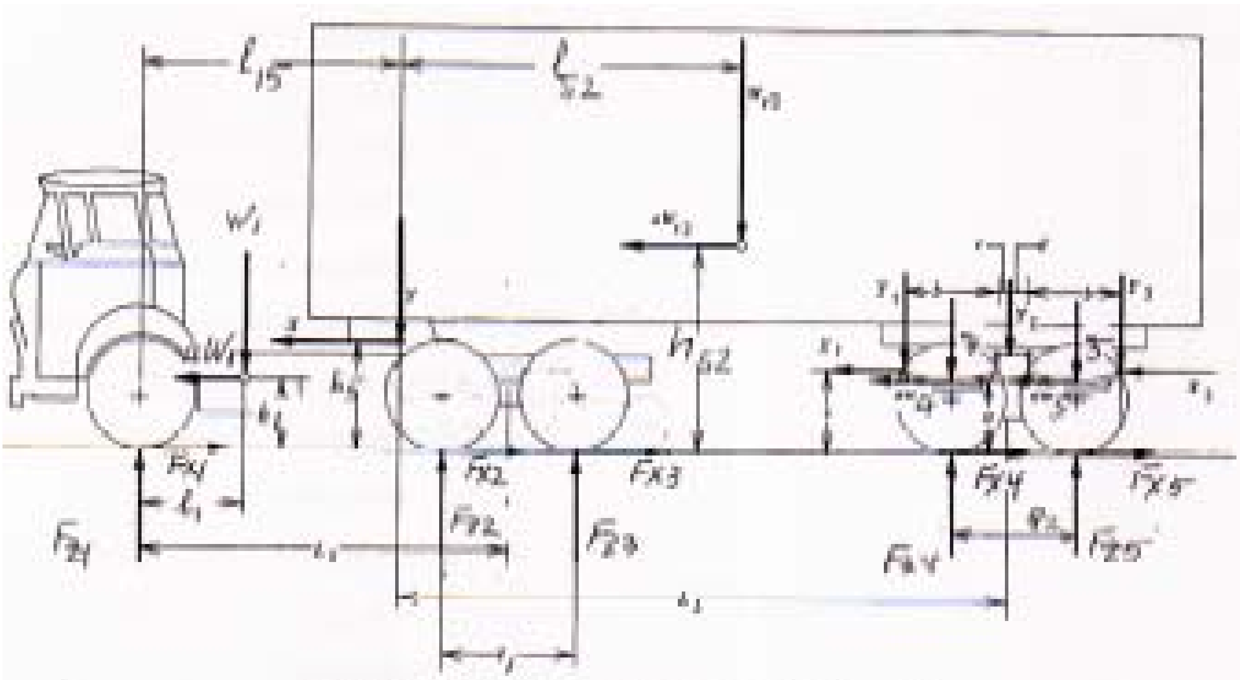

Figure 8: 3-S2 Air Springs/Leaf Springs (3-S2 – ALS)

ψ_2 = static semitrailer axle loads divided by semitrailer weight

The normal forces of a typical tractor-semitrailer equipped with leaf springs (3-S2-ALS) are illustrated in Figure 9. Inspection reveals axle load #4 approaching zero for decelerations greater than approximately 0.6g. Similar to the analysis for the straight truck equipped with rear leaf springs, axle #4 is expected to lock up first.

In one specific accident involving a 3-S2 – ALS combination, the plaintiff's expert claimed that the deceleration of the semi-tanker trailer was reduced due to the forward liquid load shift, and that this shift was the reason for the brakes of axle #4 to lock. However, the expert did not understand that the inter-axle load transfer was the cause of axle #4 to experience its decrease in normal force at decelerations of approximately 0.2 to 0.25g. Comparison testing between two different tractor-trailers, one a tanker with liquid load and the other a fixed load trailer, showed essentially equal braking effectiveness for both tests.

5.0. 2 S1–2 COMBINATION: TWO-AXLE TRACTOR, SINGLE-AXLE SEMITRAILER AND DOUBLE-AXLE TRAILER

The dimensions and forces are illustrated in Figure10. The tongue, connecting trailer 1 and 2, is assumed to be horizontal, that is, force X_2 is horizontal. Consequently, there is no vertical force component ($Y_2 = 0$) at the coupling point between semitrailer and pup-trailer.

The axle normal forces are:

$$F_{z1} = (W_1(L_1 - l_1) + aW_1h_1 + X_1h_5 + Y_1(L_1 - l_{15}))/L_1 \text{ ; lb} \qquad (32)$$

$$F_{z2} = W_1 + Y_1 - F_{z1} \text{ ; lb} \qquad (33)$$

$$F_{z3} = (W_2l_2 - X_2h_{23} - F_{x3}h_5 - aW_2(h_2 - h_5))/L_2 \text{ ; lb} \qquad (34)$$

$$F_{z4} = (W_3(L_3 - l_3) + aW_3h_3 - X_2h_{23})/L_3 \text{ ; lb} \qquad (35)$$

$$F_{z5} = W_3 - F_{z4} \text{ ; lb} \qquad (36)$$

where:

$$X_1 = F_{x1} + F_{x2} - aW_1\text{; lb} \qquad (36)$$

$$X_2 = X_1 - F_{x3} - aW_2 \text{ ; lb} \qquad (37)$$

$$Y_1 = W_2 - F_{z3} \text{ ; lb} \qquad (38)$$

h_1 = cg-height of tractor, in.
h_2 = cg-height of semitrailer, in.
h_3 = cg-height of pup-trailer, in.
h_{23} = tongue height between semitrailer and pup-trailer, in.

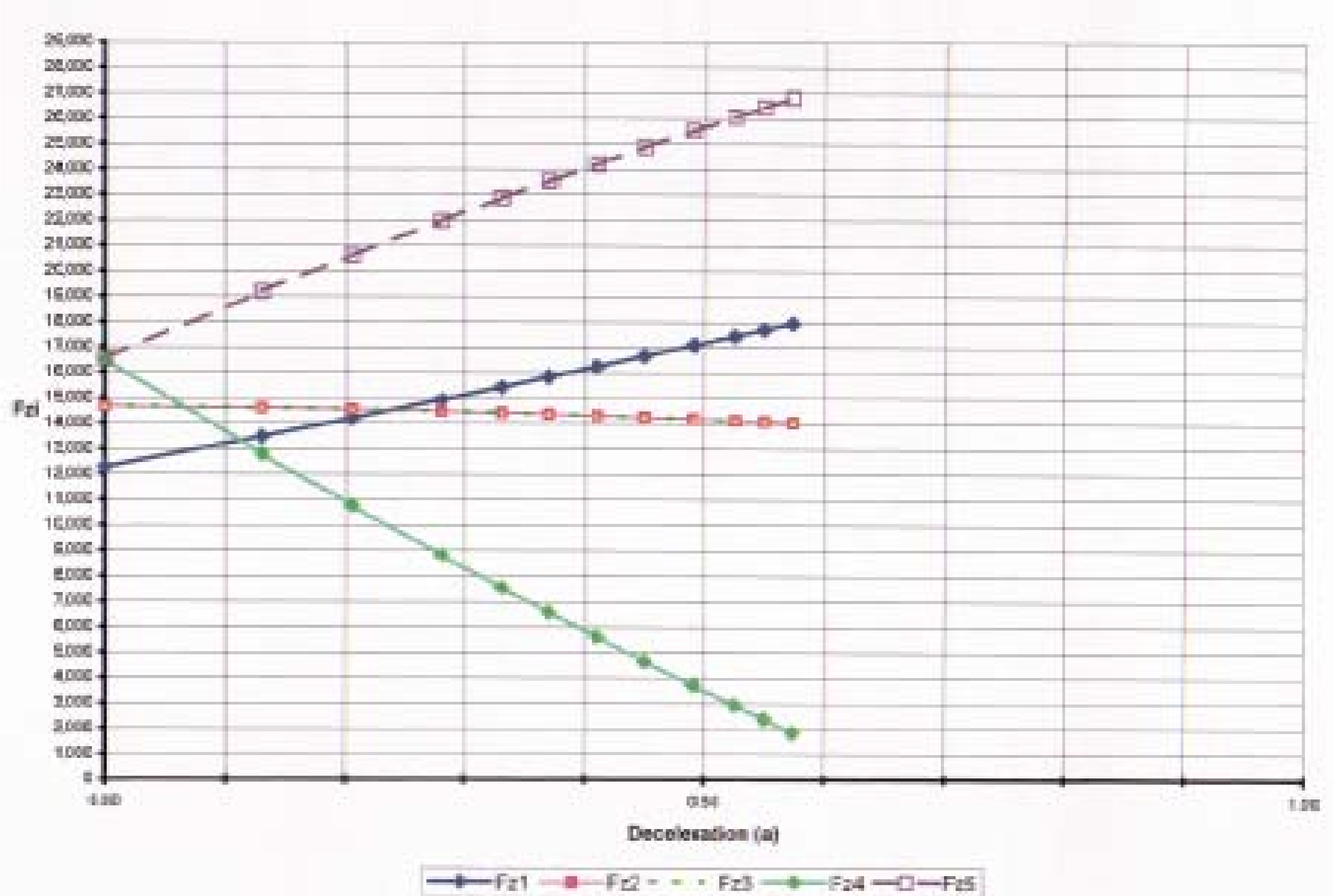

Figure 9: 3-S2 – ALS, Normal Forces

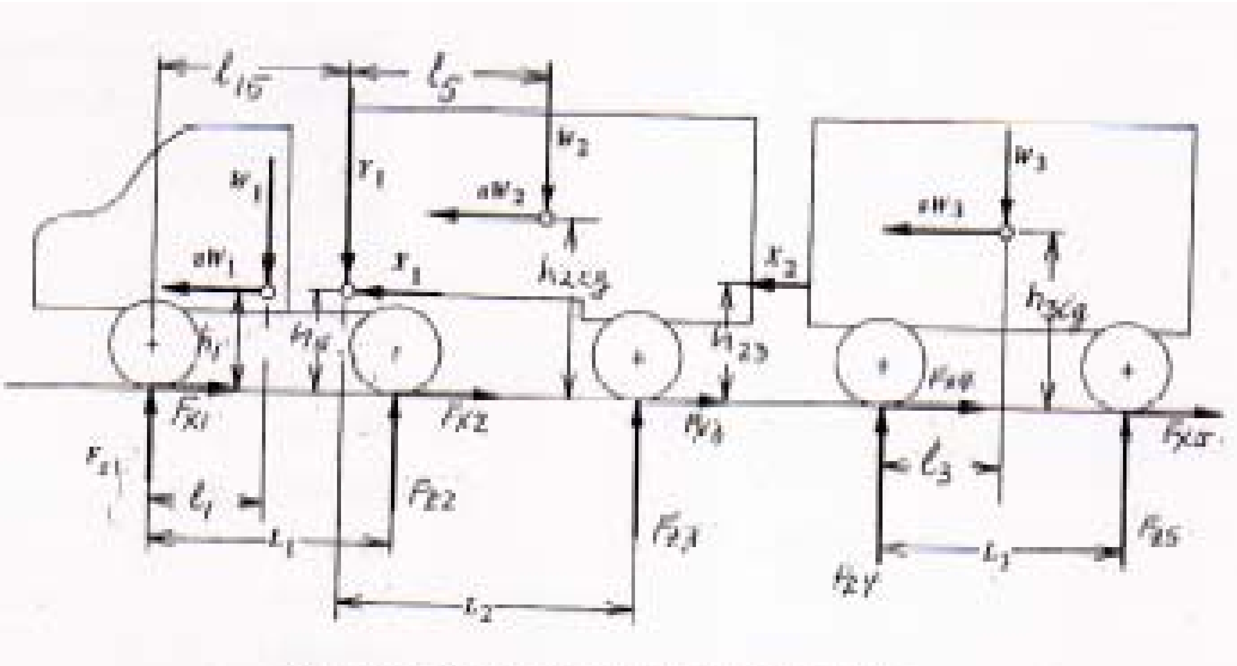

Figure 10: 2-S1-2 Tractor-Semitrailer-Double Trailer
Forces and Dimensions

L_1 = tractor wheelbase, in.
L_2 = semitrailer wheelbase, in.
L_3 = pup-trailer wheelbase, in.
l_1 = axle #1 to tractor cg., in.
l_5 = axle #1 to fifth wheel, in.
l_2 = fifth wheel to semitrailer cg., in.
l_3 = axle #4 to pup-trailer cg., in.
W_1 = weight of tractor, lb
W_2 = weight of semi-trailer, lb
W_3 = weight of two-axle trailer, lb

For a typical 2-S1-2 combination weighing 80,000 lb, the static axle loads have changed, for an 80 psi brake application resulting in a deceleration of 0.56g, as shown below:

a = 0 (static):	12,000 lb	17,000 lb	17,000 lb	17,000 lb	17,000 lb
a = 0.56g (dynamic):	14,506 lb	15,206 lb	16,234 lb	26,082 lb	7,918 lb

Inspection of the axle loads indicates a significant load decrease of axle #5, the rear axle of the pup-trailer. Consequently, the brakes of axle #5 are expected to lock first, possibly resulting in trailer swing.

6.0. CONCLUSIONS

The braking analysis presented is the basis for optimizing component selection for the design of air brake systems of straight trucks, as well as the investigative tool for the analysis of air brake failure including brake adjustment, skid mark interpretation accidents and brake lockup sequence involving straight trucks with two or three axles. The expert will be able to support speed calculations through proper engineering analysis. Guessing at dynamic axle loads as well as traction coefficients is eliminated.

Brake temperatures are calculated based upon the mechanical condition including slack adjuster travel of the particular truck under investigation. Defective brakes can be analyzed in terms of any geometrical and lining friction defects.

Truck manufacturers can use the analysis to design and/or optimize the brake system to meet certification requirements.

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