Association of American Railroads
Research and Test Department

TRAIN ENERGY MODEL
VALIDATION USING REVENUE SERVICE
UNIT COAL TRAIN DATA

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APPENDIX A: TRAIN RESISTANCE

The total train resistance is the sum of all the resistances acting on all of the vehicles in the consist.

Let

- k = ordinal number of vehicle in consist
- N = total number of vehicles in consist
- R_k = total resistance acting on vehicle k in lbs
- R_{Bk} = bearing resistance acting on vehicle k in lbs
- R_{Rk} = rolling resistance acting on vehicle k in lbs
- R_{Ck} = curve resistance acting on vehicle k in lbs
- R_{Ak} = aerodynamic resistance acting on vehicle k in lbs
- R = total train resistance in lbs

Then

$$R = \Sigma_{k=1}^{k=N}(R_k) \qquad (1)$$

where

$$R_k = R_{Bk} + R_{Rk} + R_{Ck} + R_{Ak} \qquad (2)$$

Each of these resistances is considered in the following pages of this appendix.

A.1 Bearing Resistance

Let

k = ordinal number of vehicle in consist
R_{Bk} = bearing resistance in lbs
n_k = number of axles
C_{Bk} = bearing resistance coefficient in lbs/axle

Then

$$R_{Bk}=n_k C_{Bk} \tag{1}$$

Let

w_k = total vehicle weight in TONs
T = ambient temperature in degrees Fahrenheit
P_k = empirical power-law exponent
Q_k = empirical power-law multiplier
$b_1(i_{Bk}), b_2(i_{Bk}), b_3(i_{Bk})$
= empirical power-law exponent coefficients
$b_4(i_{Bk}), b_5(i_{Bk}), b_6(i_{Bk})$
= empirical power-law multiplier coefficients
i_{Bk} = bearing type index:

i_B	Bearing	b_1	b_2	b_3	b_4	b_5	b_6
1	worn T	.137	.00282	-.0000275	8.70	-.1120	.001000
2	new T	.280	-.00343	.0000169	4.47	.0208	.000893
3	worn B	.106	.00518	-.0000595	10.90	-.2290	.002420
4	new B	.291	-.00207	.0000267	4.55	.0271	-.000452

Then

$$C_{Bk}=Q_k w_k^{P_k} \tag{2}$$

where

$$P_k=b_1(i_{Bk})+b_2(i_{Bk})T+b_3(i_{Bk})T^2 \tag{3}$$

and

$$Q_k=b_4(i_{Bk})+b_5(i_{Bk})T+b_6(i_{Bk})T^2 \tag{4}$$

A.2 Rolling Resistance

Let

k = ordinal number of vehicle in consist
R_{Rk} = rolling resistance in lbs
w_k = total vehicle weight in lbs
C_{Rk} = rolling resistance coefficient in lbs/TON

Then

$$R_{Rk} = .0005 w_k C_{Rk} \quad (1)$$

Let

γ_k = gross rail load in lbs
τ_k = vehicle tare weight in lbs
$\epsilon(i_{Tk})$ = empty rolling resistance coefficient in lbs/TON
$\lambda(i_{Tk})$ = loaded rolling resistance coefficient in lbs/TON
where i_{Tk} = truck type index:

i_T	Truck	ϵ lbs/TON	λ lbs/TON
1	three-piece worn	2.25	2.13
2	three-piece new	2.25	1.57
3	radial	1.48	1.43
4	frame-braced	1.48	1.35
5	premium two-axle	1.47	1.02
6	single-axle	4.25	1.89

Then

$$C_{Rk} = \epsilon(i_{Tk}) - [\epsilon(i_{Tk}) - \lambda(i_{Tk})]\left[\frac{w_k - \tau_k}{\gamma_k - \tau_k}\right], \quad w_k < \gamma_k \quad (2)$$

and

$$C_{Rk} = \lambda(i_{Tk}), \quad w_k \geq \gamma_k \quad (3)$$

A.3 Curve Resistance

Let

k = ordinal number of vehicle in consist

R_{Ck} = curve resistance in lbs

w_k = total vehicle weight in TONs

C_{Ck} = curve resistance coefficient in lbs/TON

Then

$$R_{Ck} = w_k C_{Ck}(i_{Tk}, c_k) \tag{1}$$

where c_k = instantaneous track curve at vehicle C.G. in deg.

i_{Tk} = truck type index:

i_T	Truck Type
1	three-piece worn
2	three-piece new
3	radial
4	frame-braced
5	premium two-axle
6	single-axle

Truck Type	non-lubed curve table	lubed curve table
three-piece worn	1	2
three-piece new	1	2
radial	3	4
frame-braced	5	5
premium two-axle	6	6
single-axle	7	7

c (deg)	TABLE: 1	2	3	4	5	6	7
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.090	0.056	0.013	0.017	0.010	0.015	0.015
2	0.731	0.339	0.018	0.020	0.055	0.120	0.055
3	1.548	0.791	0.206	0.173	0.200	0.430	0.110
4	2.465	1.335	0.624	0.448	0.320	0.800	0.220
5	3.325	1.907	1.020	0.747	0.470	1.130	0.365
6	4.106	2.468	1.315	1.073	0.760	1.520	0.675
7	4.767	3.046	1.505	1.445	1.120	1.895	1.235
8	5.816	3.664	2.016	1.824	1.555	2.375	2.135
9	6.686	4.298	2.478	2.206	1.770	2.915	5.555
10	7.557	4.933	2.926	2.588	2.410	3.560	11.625
11	8.427	5.563	3.376	2.968	2.705	4.260	14.170
12	9.297	6.193	3.826	3.348	3.330	5.020	16.905
13	10.167	6.823	4.276	3.728	4.050	5.865	19.425
14	11.037	7.453	4.726	4.108	4.815	6.755	22.310
15	11.907	8.083	5.176	4.488	5.695	7.665	27.685

NOTE: Linear interpolation is used for non-integral values of track curve.

Exhibit A.1. Curve Resistance Coefficients.

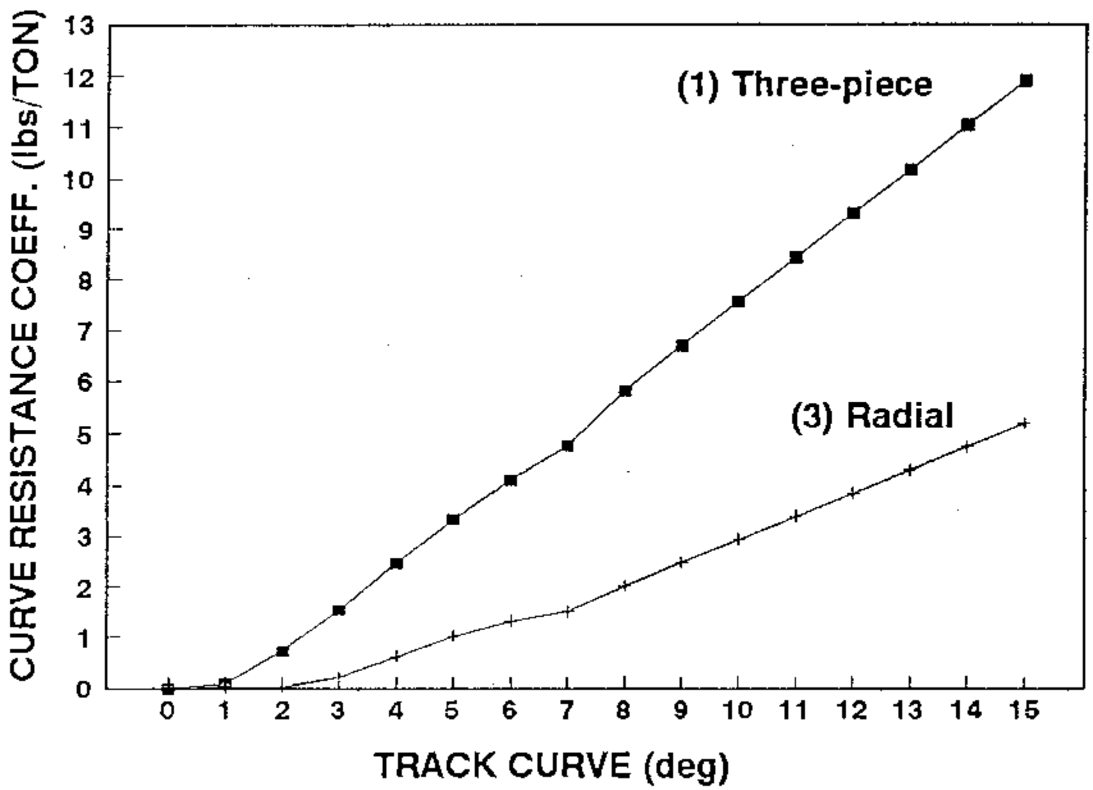

Exhibit A.2. Curve Resistance Coefficients for Unlubricated (1) Three-piece and (3) Radial Trucks.

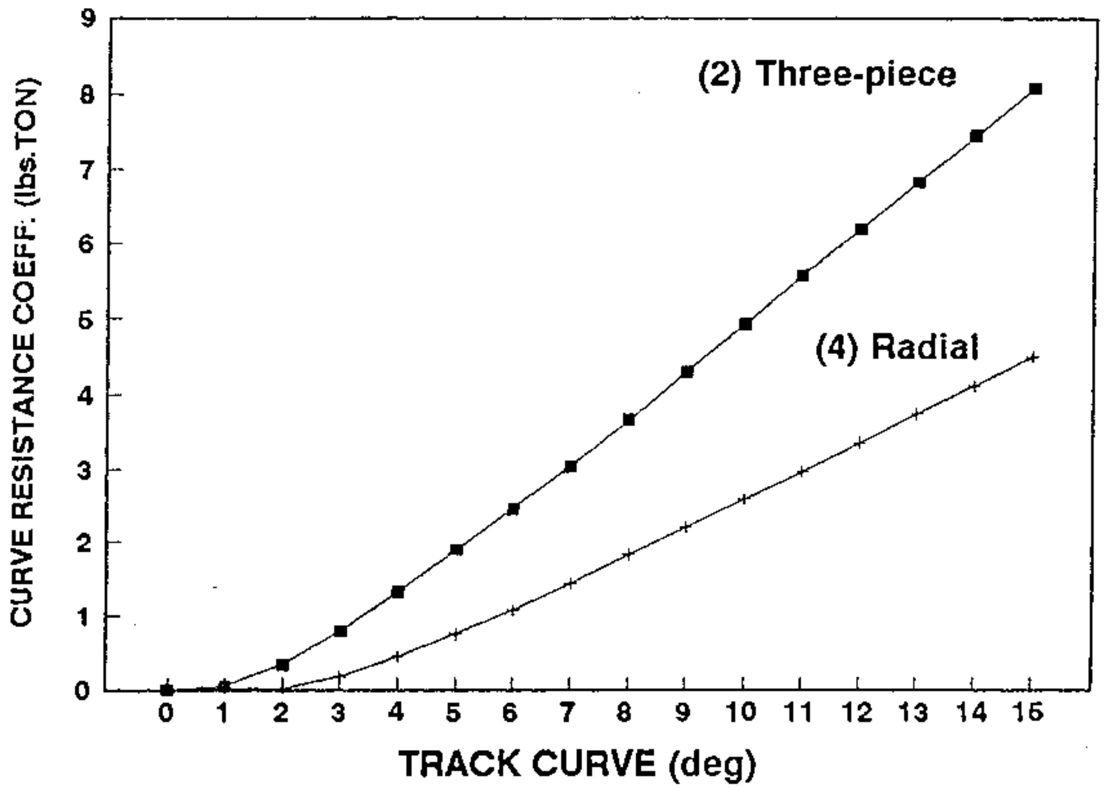

Exhibit A.3. Curve Resistance Coefficients for Lubricated (2) Three-piece and (4) Radial Trucks.

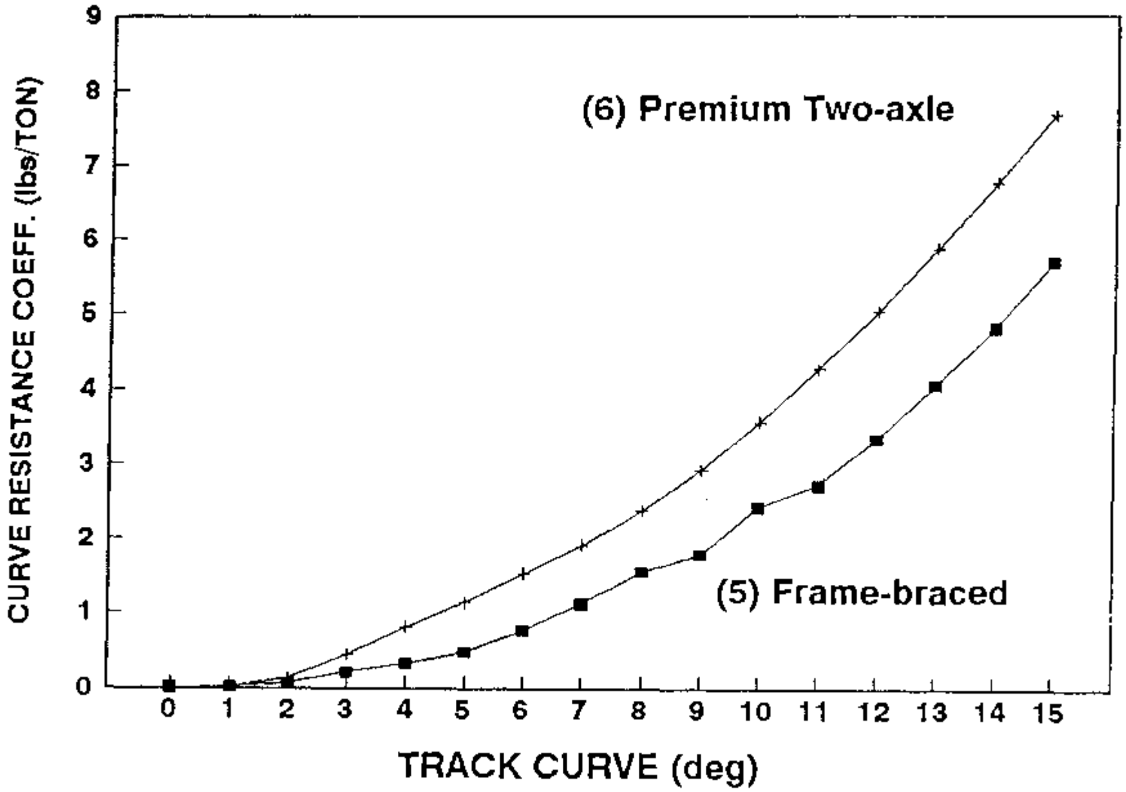

Exhibit A.4. Curve Resistance Coefficients for (5) Framed-braced and (6) Premium Two-axle Trucks.

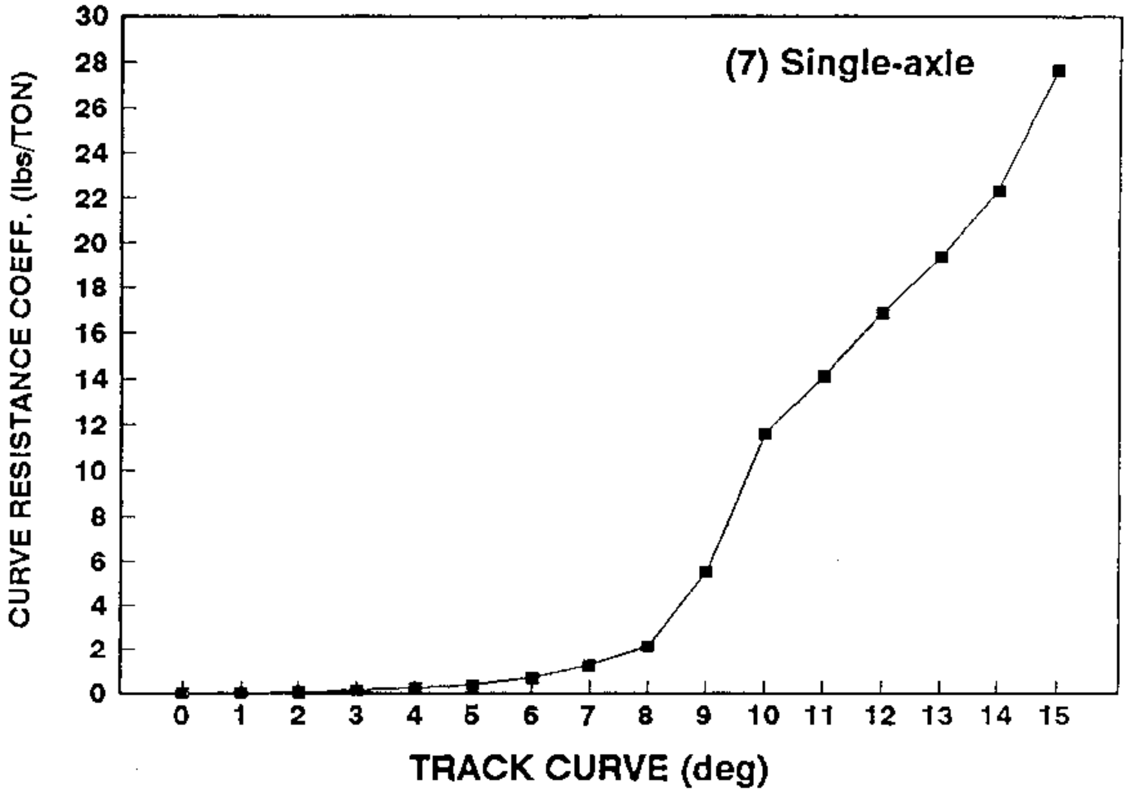

Exhibit A.5 Curve Resistance Coefficients for (7) Single-axle Truck.

A.4 Aerodynamic Resistance

Let k = ordinal number of vehicle in consist
R_{Ak} = aerodynamic resistance in lbs
v_k = vehicle velocity relative to the wind in mph
C_{Ak} = aerodynamic resistance coefficient in lbs/mph/mph

Then

$$R_{Ak} = v_k^2 C_{Ak} \tag{1}$$

Let r = air density factor
P = uncorrected barometric pressure in inches of Mercury
T = ambient temperature in degrees Fahrenheit
Y_k = yaw angle of vehicle
A_k = drag area of vehicle in square feet

Then

$$C_{Ak} = .5r(P,T)A_k(Y_k) \tag{2}$$

where

$$r(P,T) = .02057\frac{P}{T+460} \tag{3}$$

and $A_k(Y_k)$ is a seventh order polynomial in Y_k.

NOTE: The coefficients in the seventh order polynomial $A_k(Y_k)$ depend on the aerodynamic characteristics of the vehicle. However, these coefficients vary with k, so that the same type of vehicle may have different drag areas, depending on its position in the consist.

APPENDIX B: UNIT COAL TRAIN DATA

Vehicle	Zero Yaw Drag Area (sq.ft.)									
1- 10	204	68	63	71	67	64	62	61	60	59
11- 20	59	58	58	58	58	58	57	57	57	57
21- 30	57	57	57	57	57	57	57	57	57	57
31- 40	57	57	57	57	57	57	57	57	57	57
41- 50	57	57	57	57	57	57	57	57	57	71
51- 60	48	48	58	57	57	57	57	57	57	57
61- 70	57	57	57	57	57	57	57	57	57	57
71- 80	57	57	57	57	57	57	57	57	57	57
81- 90	57	57	57	57	57	57	57	57	57	57
91-100	57	57	57	57	57	57	57	57	57	57
101-103	57	57	80							

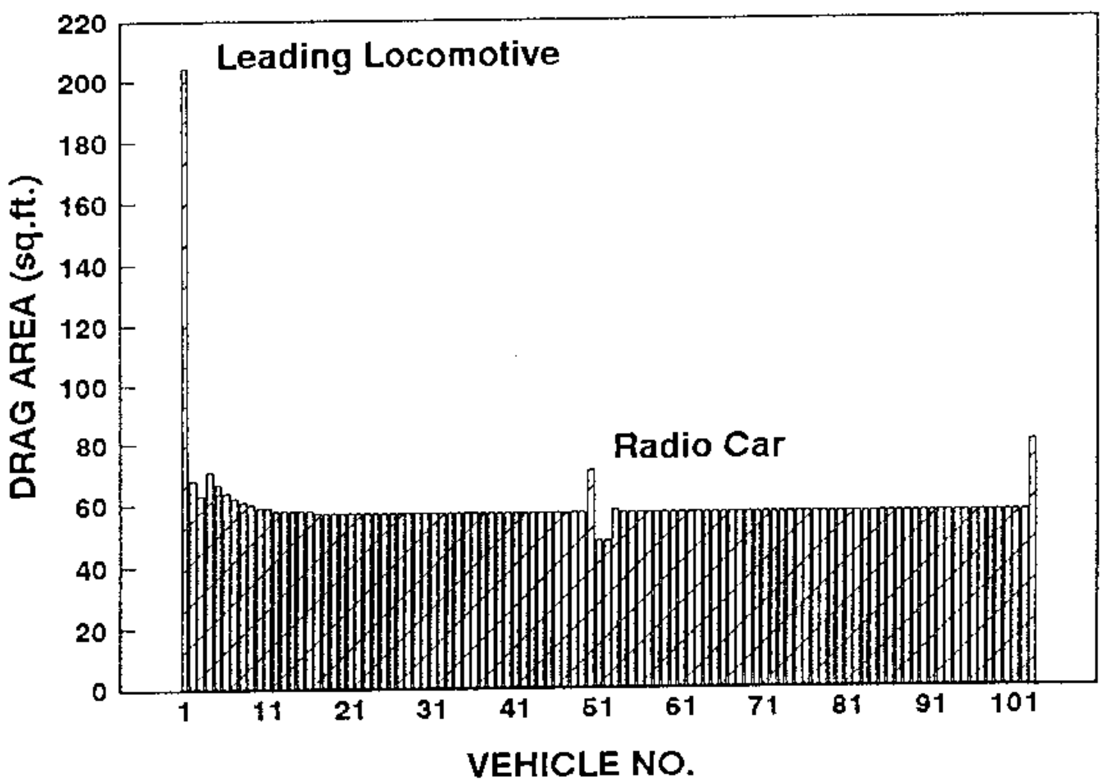

Exhibit B.1. Loaded Revenue Consist Zero Yaw Drag Areas.