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16. Abstract

An extensive study of the dynamic performance of multitrailer vehicles, and the influence of double-drawbar dollies (C-dollies) on that performance is reported. Six vehicle configurations (five double-trailer combinations and one triple) are considered. The performance of the six vehicles is examined using a matrix of seven different converter dollies (an A-dolly and 6 C-dollies) and 15 different vehicle parametric variations (e.g., center-of-gravity height, tire-cornering stiffness, roll stiffness, etc.). The performance quality of the vehicles is judged using measures such as rearward amplification, yaw-damping ratio, static rollover stability, offtracking, and dynamic-load-transfer ratio.

The results from over 2800 computer simulation runs are used in a statistical regression analysis to produce simple methods for predicting performance numerics for A-trains based on vehicle parameters easily obtained in the field. Performance improvement factors for C-dollies are also developed. Recommendations for minimum performance standards and for C-dolly specifications are also reported.

An economic analysis comparing A-dollies and C-dollies is presented. This analysis is based on data from a field survey and the literature and includes purchase, start-up, operational, and accident cost considerations.

The report also includes the ancillary performance issue of backing ability.

Extensive appendices are included in Vol II. Vol III is a Technical Summary.

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APPENDIX A

VEHICLE PERFORMANCE MEASURES

In this study seven performance measures were used to evaluate the roll stability and control characteristics of more than 600 different vehicle variations. These measures were calculated by simulating the dynamic effects generated from five different simulation maneuvers. Table A-1 gives the maneuver name and shows which performance measure is derived from each of the five maneuvers.

Table A-1. The five maneuvers used to evaluate the performance measures of the various vehicle combinations

Maneuver Name	*Performance Measure*
RTAC-A	Static Rollover Stability
	High-speed Steady-state Offtracking
RTAC-B	Rearward Amplification
	High-speed Transient Offtracking
	Dynamic-Load-Transfer Ratio
	Yaw Damping
RTAC-C	Low-Speed Offtracking
Pulse Steer	Yaw Damping

Three of these maneuvers are defined as Roads and Transportation Association of Canada (RTAC) maneuvers. These maneuvers have been used extensively in Canada to evaluate vehicle performance. The specifics of the RTAC maneuvers and algorithms used to calculate their corresponding performance measures are defined in great detail in the work done by Ervin, R.D., et al. [5] and, therefore, will not be detailed here. However, some changes were made to improve these maneuvers and this appendix describes these changes and discusses the specifics of the pulse-steer maneuver to determine the yaw-damping performance measure.

STATIC ROLLOVER STABILITY

As shown in table A-1, the RTAC-A maneuver is used to estimate the static rollover stability limit and high-speed steady-state offtracking of a multitrailer vehicle. To estimate the high-speed steady-state offtracking, the maneuver begins with a constant-radius 10 second turn intended to maintain a constant lateral acceleration level of 0.2 g's. During this period, the transient lateral and roll motions of the vehicle die out and an estimate of the steady-state offtracking can be calculated. The maneuver then changes to a spiral path of slowly increasing curvature. This results in a slowly increasing lateral acceleration level that eventually leads to rollover of the vehicle. For this study both of these performance measures were simulated using a 62 mph (100 km/hr) forward velocity.

In this study the algorithms used to determine the steady-state condition and estimate the offtracking are identical to those defined in [5] and therefore, will not be discussed here. However, the method to estimate the static rollover stability limit of a vehicle was changed to improve its accuracy. These changes can be summarized in two ways:

First, changes were made to the path of the RTAC-A maneuver. Originally, the maneuver was simulated with a path input that used a combination of closed- and open-loop definitions. In [5], the maneuver begins in a closed-loop operation and the simulation's driver model steers the vehicle along a path generating the dynamic condition to estimate the steady-state offtracking. The path input would then change to an open-loop simulation, where control of the vehicle is produced by steer inputs at the front wheels of the tractor. This was necessary in the original RTAC-A maneuver because an additional performance measure, the steady-state yaw stability of the vehicle, was also measured. This additional performance measure had to be simulated in open-loop mode to prevent driver model intervention and yaw rectification of the vehicle. However, because control of the vehicle is not being corrected for yaw dynamics, the lateral acceleration experience of the vehicle may no longer be increasing in the linear fashion that is desired to estimate rollover threshold. This tends to violate the assumption of a steady-state increase in lateral acceleration and thus, reduces the accuracy of the steady-state rollover stability limit of the vehicle.

In this study the steady-state yaw stability performance measure was not considered. This allowed the maneuver to be changed to make a more accurate estimate of the rollover stability of a vehicle. By simulating the spiral-like portion of the maneuver using the closed-loop method, the driver model acts to maintain a linear increase in the lateral acceleration thus, generating a steady-state condition until rollover. This constant increase in lateral acceleration is demonstrated in figure A-1 for the lateral acceleration experience of the tractor of a 28x28-foot, A-train double. The new path was generated by specifying the lateral acceleration and time requirements for the maneuver and then integrating that information twice to generate the actual longitudinal and lateral path coordinates. The coordinates for the new maneuver are listed in table A-2. The maneuver is simulated using driver model parameters specified for optimum tracking precision.

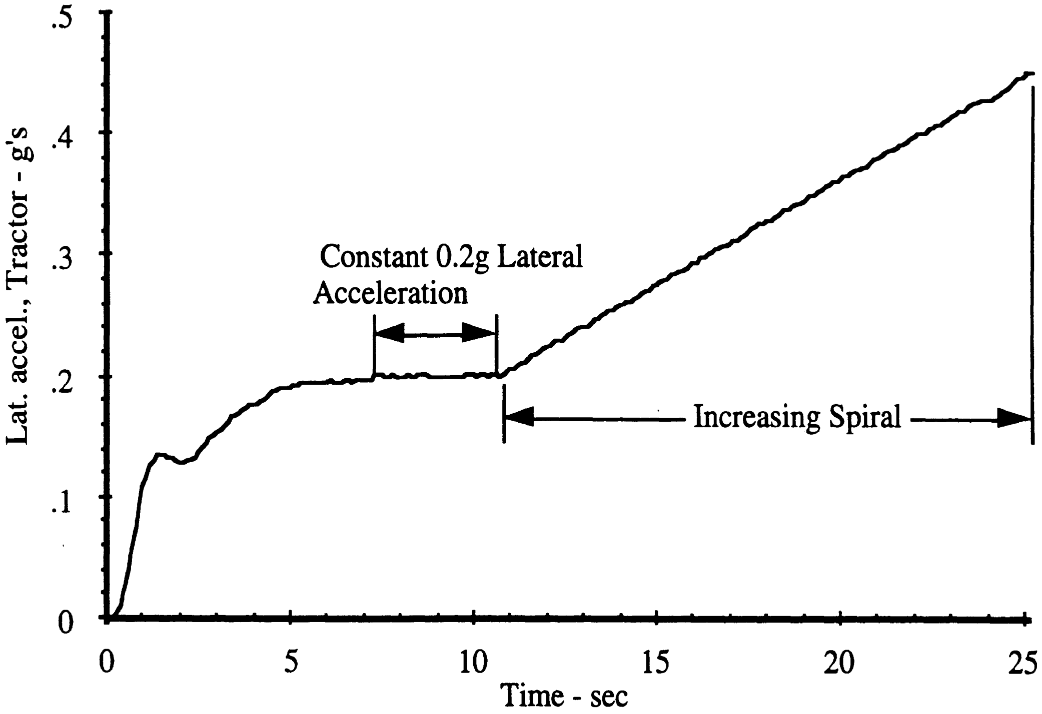

Figure A-1. Lateral acceleration time history of the tractor of an A-train, 28 x 28 foot double, during the new RTAC-A maneuver

The second change to improve the RTAC-A maneuver involves re-defining the method of estimating the time at which rollover instability occurs. As defined in [5], the original algorithms identified the first time at which a complete lift-off has occurred at all wheels on one side of any roll unit. (A roll unit is simply a portion of a vehicle combination that is roll-coupled and therefore can rollover independently of other parts of the vehicle. For example, an A-train double has two roll units; the first is the tractor and first semi-trailer combination; the second is the converter dolly and second semi-trailer combination. In a C-train all units are roll coupled thus, the entire vehicle combination is taken as one roll unit.) The corresponding lateral acceleration at this *captured* time is then used as a starting point for calculating an estimate of the static rollover stability of the vehicle. The actual reported lateral acceleration value is obtained from an arithmetic mean of that roll unit's lateral acceleration values over the period of ± 0.15 seconds about this captured time of lift-off. This was done to smooth out any high-frequency noise locally in the acceleration time history. See [5] for more details about this calculation.

A problem with estimating the static rollover stability limit as defined in [5], concerns the possible condition that the point of roll instability can occur without lift-off of all wheels on one side of the roll unit. For more information and a detailed explanation of this phenomenon see [20].

To improve upon the rollover estimate a new method of estimating the point-of-steady-state rollover threshold was developed. This method analyzes the primary roll stabilizing and destabilizing moments acting on the vehicle during a steady-state turn. Figure A-2 shows the roll plane forces and critical dimensions for a truck in a steady-state turn. As explained in [20], the moments, taken about point P, acting on the vehicle are:

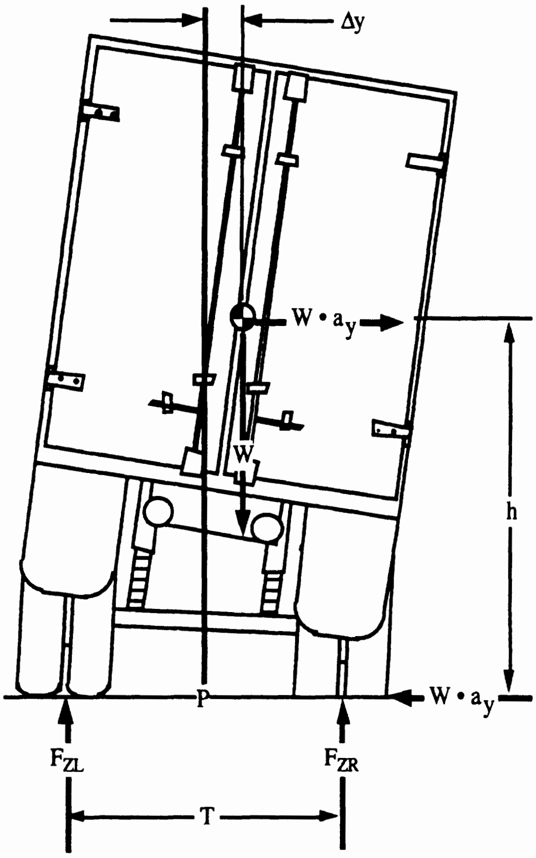

Figure A-2. A vehicle in a steady turn

i) $W \bullet a_y \bullet h$

—the primary destabilizing moment generated by the product of the vehicle weight and lateral acceleration acting at the vertical center of gravity.

ii) $W \bullet \Delta y$

— the secondary destabilizing moment resulting from the lateral compliance of the tires and suspensions.

iii) $(F_{ZR} - F_{ZL}) \bullet T/2$

— the stabilizing suspension moment arising due to a lateral transfer of vertical load between the inside and outside tires.

Table A-2. Longitudinal and lateral path coordinates for an improved, closed-loop, RTAC-A maneuver

x	y	x	y	x	y	x	y	x	y	x	y
0	0.0	497	52	907	245	1218	574	1330	1009	1154	1418
55	0.0	506	54	915	250	1222	582	1329	1018	1148	1425
64	0.0	514	57	922	255	1227	589	1329	1027	1141	1431
73	0.1	523	59	930	261	1231	597	1328	1036	1135	1437
82	0.2	532	62	937	266	1235	605	1327	1045	1128	1443
91	0.3	541	65	944	272	1240	614	1326	1054	1121	1449
100	0.4	549	67	951	277	1244	622	1325	1063	1114	1455
109	0.6	558	70	959	283	1248	630	1324	1072	1107	1461
118	0.8	567	73	966	288	1252	638	1322	1081	1100	1466
128	1.1	575	76	973	294	1256	646	1321	1090	1092	1472
137	1.4	584	79	980	300	1260	655	1319	1099	1085	1477
146	1.7	593	82	987	306	1263	663	1318	1108	1077	1482
155	2.1	601	85	994	311	1267	671	1316	1117	1070	1487
164	2.5	610	88	1001	317	1270	680	1314	1126	1062	1492
173	3.0	618	91	1008	323	1274	688	1312	1135	1055	1497
182	3.5	627	95	1014	329	1277	696	1309	1144	1047	1502
191	4.0	635	98	1021	335	1281	705	1307	1152	1039	1506
200	4.6	644	101	1028	342	1284	714	1304	1161	1031	1511
210	5.2	652	105	1035	348	1287	722	1302	1170	1023	1515
219	5.9	661	108	1041	354	1290	731	1299	1179	1015	1519
228	6.6	669	112	1048	360	1293	739	1296	1187	1007	1523
237	7.3	677	115	1054	367	1295	748	1293	1196	998	1527
246	8.1	686	119	1061	373	1298	757	1290	1204	990	1531
255	9.0	694	123	1067	380	1301	765	1287	1213	982	1535
264	9.9	702	126	1074	386	1303	774	1284	1221	973	1538
273	10.8	711	130	1080	393	1306	783	1280	1230	965	1541
282	11.8	719	134	1086	399	1308	792	1277	1238	956	1544
291	12.9	727	138	1093	406	1310	801	1273	1247	948	1547
300	14.0	735	142	1099	413	1312	810	1269	1255	939	1550
309	15.1	743	146	1105	419	1314	819	1265	1263	930	1553
318	16.3	752	150	1111	426	1316	827	1261	1271	921	1555
327	17.6	760	154	1117	433	1318	836	1257	1279	913	1558
336	18.9	768	159	1123	440	1319	845	1252	1287	904	1560
345	20.2	776	163	1129	447	1321	854	1248	1295	895	1562
354	21.6	784	167	1134	454	1322	863	1243	1303	886	1564
363	23.1	792	172	1140	461	1324	872	1239	1311	877	1565
372	24.6	800	176	1146	468	1325	881	1234	1319	868	1567
381	26.2	808	181	1151	476	1326	890	1229	1326	859	1568
390	27.8	815	185	1157	483	1327	899	1224	1334	850	1570
399	29.5	823	190	1162	490	1328	909	1219	1341	841	1571
408	31.3	831	195	1168	497	1329	918	1213	1349	832	1572
417	33.1	839	199	1173	505	1329	927	1208	1356	823	1572
426	35.0	847	204	1178	512	1330	936	1202	1363	814	1573
435	36.9	854	209	1183	520	1330	945	1197	1371	805	1573
444	38.9	862	214	1189	527	1331	954	1191	1378	795	1573
453	40.9	870	219	1194	535	1331	963	1185	1385	786	1573
462	43.1	877	224	1199	543	1331	972	1179	1392	777	1573
470	45.2	885	229	1203	550	1331	981	1173	1398	768	1573
479	47.4	892	234	1208	558	1331	990	1167	1405	759	1572
488	49.7	900	239	1213	566	1330	1000	1161	1412	750	1572

The summation of these moments yields the following expression:

$$W \bullet a_y \bullet h = (F_{ZR} - F_{ZL}) \bullet T/2 - W \bullet \Delta y \qquad (1)$$

To understand the relationship of these moments with the steady-state rollover stability limit of a vehicle it is helpful to represent them in a graphical form as shown in figure A-3. The right side of the graph corresponds to the right side of equation (1) and shows vehicle roll moment versus roll angle. Two moments are shown on this side of the graph. One is positive and represents the stabilizing moment generated by the vertical forces acting through the tires and suspension. The second moment diminishes the roll stability of the vehicle and is called the destabilizing moment. It results from the lateral displacement of the center of gravity due to lateral compliance in the tires and suspensions. The sum of these two moments is called the net restoring moment, and it is shown as the bold line in figure A-3. The left side of the graph (corresponding to the left side of the equation (1)) shows lateral acceleration versus roll moment. It represents the destabilizing moment due to lateral acceleration. In the context of estimating the rollover stability limit ,the way to interpret this graphical representation is: the vehicle will reach its roll stability limit when the lateral acceleration generated by the steady turn causes the vehicle to produce its maximum net restoring moment.

The algorithms used in this study are based upon this analysis of the rollover process. By finding the peak of the net restoring moment, corresponding to $\phi_{critical}$ in figure A-3, an estimate of the rollover stability limit of the vehicle can be made. The specific details of this calculation are discussed below, starting with definitions of the necessary

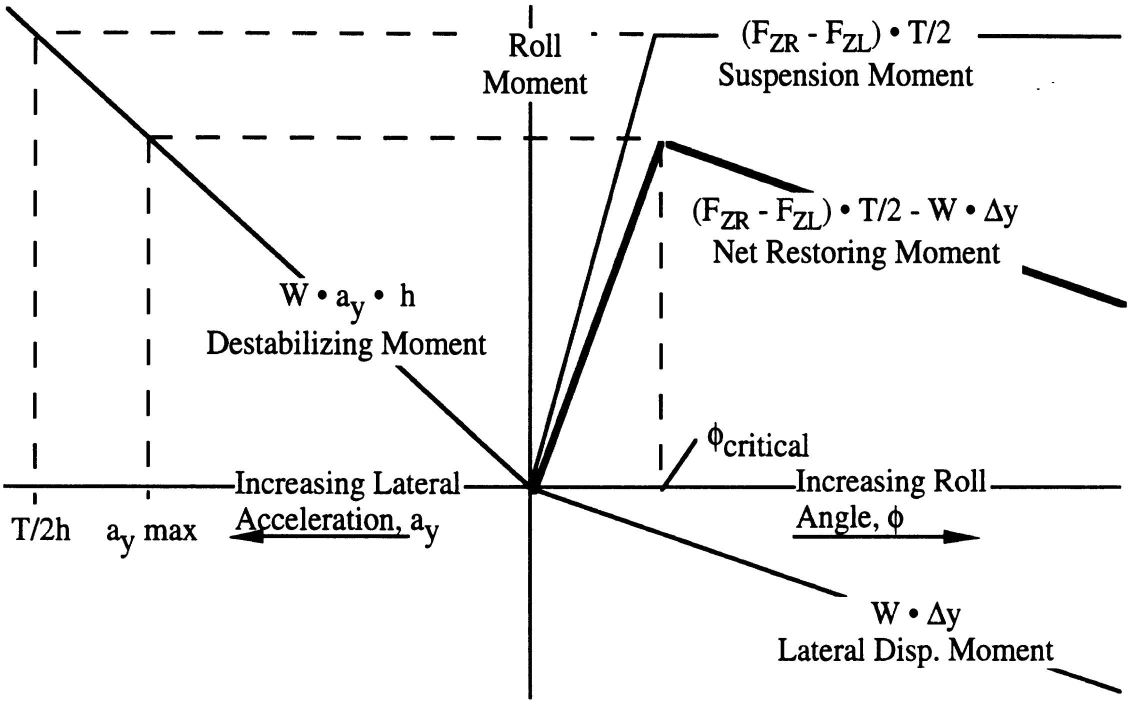

Figure A-3. Roll response of a suspended vehicle

variables. Figure A-4 is included to help identify some of these variables.

SPRWT(j) — weight the sprung mass of unit *j*

ϕSM(j,t) — roll angle of the sprung mass of unit *j* at simulation time *t*

AVϕUNS(j,t) — an average of the roll angles for each unsprung mass of unit *j* at simulation time *t*

AVHRC(i,j) — an average of the heights of the roll center of each axle of unit *j* comprising roll unit *i*

AVHCG(i,j) — an average of the heights of the center of gravity, as measured from the roll center of each axle of unit *j* comprising roll unit *i*

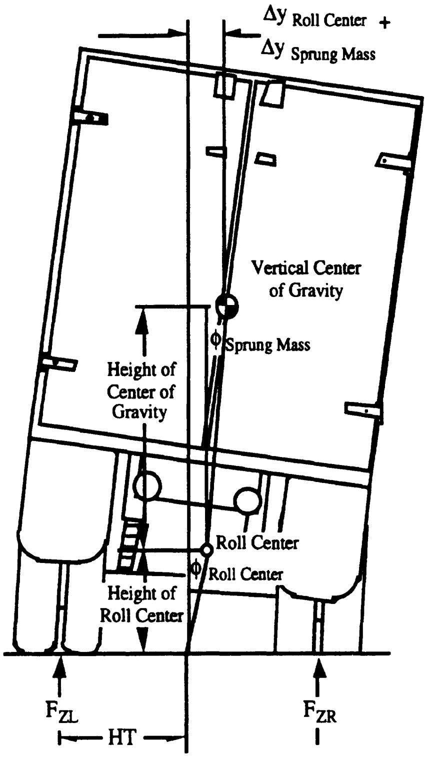

Figure A-4. Variable definitions

HT(i,k) — half-track of each axle *k* of roll unit *i*

F_{ZR}(i,j,k,t) — vertical force at time t acting on the right wheel of axle *k* of unit *j* of roll unit *i*

F_{ZL}(i,j,k,t) — vertical force at time *t* acting on the left wheel of axle *k* of unit *j* of roll unit *i*

Since there exists a rollover threshold for each roll unit of a vehicle, the calculations to determine the peak of the net restoring moment curve are done for each roll unit. The first step in this calculation is to determine the positive component of the net Using the definitions above, the suspension moment can be calculated for each roll unit *i*, and simulation time *t*, as follows:

$$\text{Suspension Moment for Roll Unit } i \text{ at time } t = \sum_{j=1}^{\text{no. of units}} \sum_{k=1}^{\text{no. of axles}} (F_{ZR}(i,j,k,t) - F_{ZL}(i,j,k,t)) \bullet HT(k)$$

The second component of the net restoring moment is derived from the lateral displacement moment. As with the suspension moment, the lateral displacement moment is calculated for each roll unit *i*, and simulation time *t*, as follows:

$$\text{Lateral Displacement moment for Roll Unit } i \text{ at time } t = \sum_{j=1}^{\text{no. of units}} \mathrm{SPRWT(j)} \bullet \mathrm{AVHRC(i,j)} \bullet \phi\mathrm{SM(j,t)} + \mathrm{AVHCG(i,j)} \bullet \mathrm{AV}\phi\mathrm{UNS(j,t)}$$

Since the last event in an RTAC-A maneuver is rollover, for computational efficiency the algorithm starts at the end of the time history file and works backward in time, calculating these two moments for each roll unit of a vehicle. To find the peak of the net restoring moment, the algorithm simply subtracts the lateral displacement moment from the suspension moment at one time step and compares that number to the same calculation at the previous time step. The comparison of net restoring moment values at two corresponding time steps yields a slope for net restoring moment. By recalculating the slope of net restoring moment as the algorithm moves through the simulation time history, the algorithm can find the time when the slope changes sign and thus the peak of the net restoring moment. As stated above, this peak corresponds to the point-of-rollover instability of the roll unit, and the corresponding lateral acceleration reached at this point in time is taken as an estimate of the static rollover threshold for the roll unit. If a vehicle has multiple roll units, the lateral acceleration for the roll unit that reaches its instability first is taken as the estimated rollover threshold for the entire vehicle.

REARWARD AMPLIFICATION

The rearward amplification phenomenon, and the specific manner in which it is measured, are illustrated in figure A-5. The upper portion of the figure shows the paths of the tractor and of the second trailer of a double as they may develop during evasive maneuvering. The lower section illustrates the resulting time history of the lateral acceleration of the tractor and trailer. The amplified nature of the trailer response is evident. The level of rearward amplification experienced by a vehicle is frequency dependent and tends to be more severe in quick, evasive maneuvers than during normal lane-change maneuvers. The amount of rearward amplification is measured by the ratio of peak values of trailer and tractor lateral acceleration.

The level of rearward amplification experienced by a given multi-unit vehicle is measured by simulating a quick evasive RTAC-B maneuver. The maneuver is specified to generate a 0.15g lateral acceleration at the tractor while maintaining a constant forward velocity of 62 mph (100 kph). There is evidence that the level of rearward amplification experienced by a vehicle is a frequency-dependent phenomena. To capture this effect, the rearward amplification for each vehicle configuration is measured using three lane-change maneuvers, each with a different frequency content (i.e., periods of 2.0, 2.5, and 3.0 seconds). The results of each maneuver are compared, and the largest (worst) rearward amplification ratio is reported for each vehicle combination.

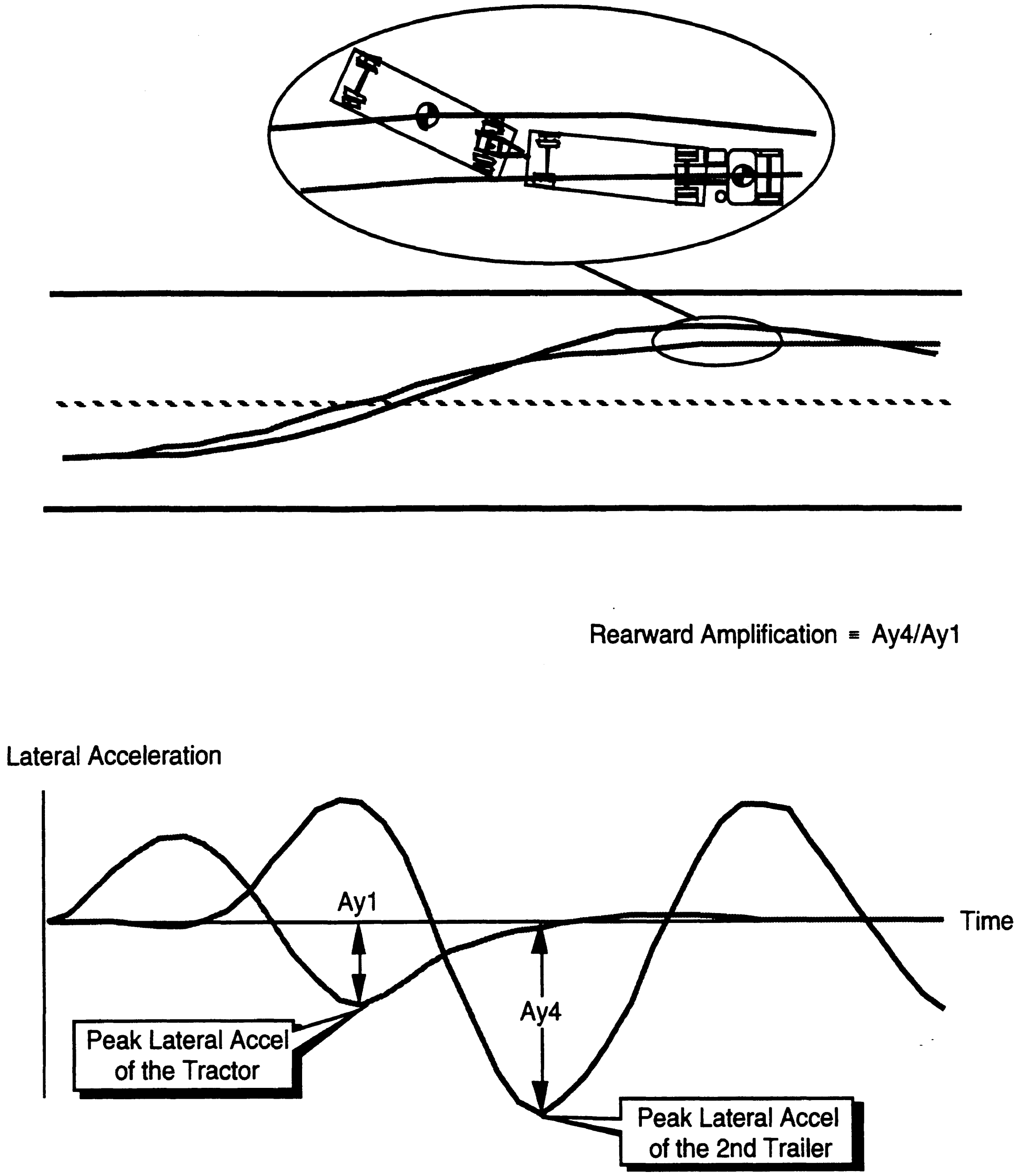

Figure A-5. Illustration of the Rearward Amplification Phenomenon

YAW DAMPING (AS MEASURED WITH THE RTAC-B AND PULSE-STEER MANEUVERS)

Low or negative yaw damping is undesirable in a multitrailer vehicle system because such a vehicle may exhibit large, sustained, or unstable oscillatory motions of the rear trailer even with little or no excitation at the tractor. These motions can result in lane intrusion and/or in vehicle rollover. In this study yaw damping was measured by observing the rate at which trailer lateral motions die out (or grow) after a brief, minor disturbance. In this study two maneuvers were used to measure yaw damping. By extending the simulation time of the three RTAC-B maneuvers[1], there were sufficient data to evaluate damping qualities of the various vehicle combinations. A second pulse-steer maneuver was also run to evaluate this behavior. This maneuver, conducted at 62 mph (100 kph) constant forward velocity, consisted of a 2-degree (road-wheel) steering pulse maintained for 0.2 second duration followed by 8 seconds of zero steer [1].

The measure used to evaluate the yaw damping resulting from these maneuvers is technically called the fraction of critical damping, denoted as ξ. The definition of ξ is the ratio of the damping coefficient to the critical damping coefficient (c/c_c). It can be calculated by measuring how fast the lateral motion or acceleration dies out after a forced disturbance of the vehicle. The procedure used in this study to measure the fraction of critical damping begins by measuring the rate of decay of the free oscillation in the vehicle combination. This is done by calculating the logarithmic decrement, denoted as Δ. By definition, Δ is the natural logarithm of the ratio of any two successive amplitudes in an oscillating system. Figure A-6 is a lateral acceleration time history, of the rear-most trailer in an A-train double. The figure shows the successive amplitudes used to calculate the logarithmic decrement.

The equation defining logarithmic decrement is:

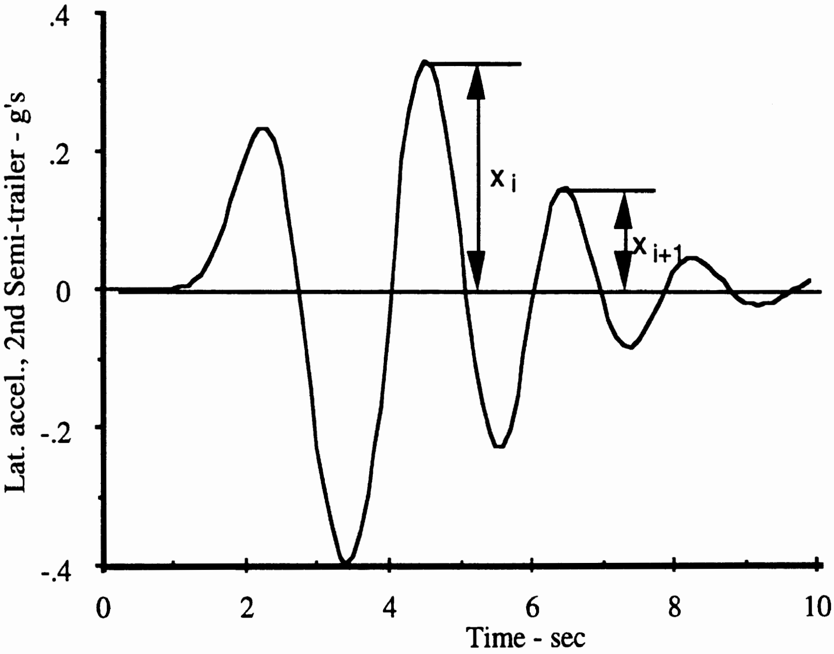

Figure A-6. Lateral acceleration time history of rearmost trailer of a 28x28 A-train double

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[1] For a detailed description of the RTAC "b" maneuver see [5].

$$\Delta = \ln\left(\frac{x_i}{x_{i+1}}\right) \tag{1}$$

Where x_i and x_{i+1} are the successive peak values, as shown in figure A-6.

The logarithmic decrement can also be defined in terms of the fraction of critical damping. This is shown in the equation below.

$$\Delta = \frac{2\pi\xi}{(1-\xi^2)^{0.5}} \tag{2}$$

By rewriting equation (2) and solving for ξ, it is found that the fraction of critical damping can be calculated for the logarithmic decrement.

The computer program used to find the logarithmic decrement was written to search the lateral acceleration time history of the rearmost trailer backward in time to find the last six peak acceleration values (both positive and negative). On the basis of these values, two successive positive and negative ratios were calculated. From these four ratios an average ratio was calculated. This average ratio and the last ratio were then used separately to calculate the fraction of critical damping. Analysis of the results showed that the last ratio value provided the most consistent results across all the vehicle combinations and, therefore, was used to report the damping findings. Even though the pulse-steer maneuver was designed specifically for measuring the damping of the various vehicle configurations, it was found to be too benign for the C-train combinations and, when analyzing the lateral acceleration of the rearmost trailers, not enough oscillation occurred to make the results from this maneuver reliable. Therefore, the damping results shown in this report are from the RTAC-B maneuver.

APPENDIX B

DOLLY PARAMETERS AND CHARACTERISTIC

In this appendix, we articulate the rationale behind the identification of certain dolly parameters deserving special scrutiny in this study. Since it is our ultimate goal to determine the necessary and sufficient statement of dolly properties ensuring acceptable dynamic performance in the multitrailer combination, we must formulate hypotheses linking certain dolly characteristics with performance, per se. We recognize that different vehicles will have different inherent performance qualities, so that the dolly required to obtain the minimum performance qualities will be different for different vehicles. We also note that dolly properties warranting attention here fall into two categories, viz., those that might be seen as "mandatory" from a dynamic performance point of view and those that are appraised as "desirable" for the sake of economic (cost and productivity) value rather than vehicle performance reasons.

In the presentation that follows, each of the properties of interest will be discussed and the form of a constraining specification will be proposed. Each specification is examined by means of numerical variation in the course of the simulation study conducted in this project. The following discussion, then, is by way of introduction to each dolly property as a generic characterization whose numerical significance is illustrated via the parametric sensitivity results presented in appendix C.

Because of the generic difference between A-dollies and C-dollies (both in their physical layout and in their influences on performance measures), some specifications do not apply to both styles of dolly. In any case, however, the specifications are functions of the variables GTWR and GAWR. GTWR is "gross *trailing* weight rating." It is a rating to be supplied by the manufacturer that indicates the maximum total weight that the dolly can tow. It includes the weight of *all* units aft of the dolly in question, i.e., the semitrailer that the dolly supports plus all following dollies and semitrailers. GAWR is the "gross axle weight rating" of the dolly. It is a rating to be supplied by the manufacturer that indicates the maximum allowable static axle load of the dolly. (These specifications apply to single axle dollies only.)

In the each subsection which follows, individual parameters describing the dolly geometry, construction, and mechanical properties are discussed in turn. As listed in table

Table B-1. Preliminary dolly specifications

Specification	*Class 1 Dolly* *Improved A-Dolly*	*Class 2 Dolly* *Light C-Dolly*	*Class 3 Dolly* *Heavy C-Dolly*
Mandatory Properties:			
Tongue length (hitch-to-axle distance):	≤ 102" (all)		
With single-axle towing trailer:		≤ 80"	≤ 80"
With multi-axle towing trailer:		≤ 136"	≤ 136"
Overall track width:	102"	102"	102"
Hitch position:			
Height above ground:	12–13"	35–36"	35–36"
Lateral spacing:	NA	29.75–30"	29.75–30"
Effective suspension roll compliance:	≤ 3.2° @ 0.38g	≤ 4.9° @ .38g	≤ 4.9°/0.38g
Hitch and frame strength (hitch loads):			
Longitudinal:	± 1.15 GTWR	±(.58 GTWR + 3.6 GARW)	±(.58 GTWR + 3.6 GARW)
Vertical:	NA	±0.4 GARW	±0.8 GARW
Lateral:	NA	±0.8 GARW	±0.8 GARW
Trailer-to-Trailer roll stiffness:	NA	±300,000 in-lb @ ≤ |15| deg	±600,000 in-lb @ ≤ |15| deg
Tire-cornering compliance:	≤ 10 deg/g	≤ 10 deg/g	≤ 10 deg/g
Axle roll steer coefficient:	0.15-.25 deg/deg understeer	NA	NA
Steering System:	NA	Option 1 or 2	Option 1 or 2
Desirable Properties:			
Weight:	≤ 2500 lbs	≤ 3200 lbs	≤ 3900 lbs
Coupling time:	≤ 1.1 TR	≤ 1.2 TR	≤ 1.2 TR
Backing Ability:	Straight line	Straight and Cornering	Straight and Cornering

B-1, a preliminary form of each specification is stated as it guided the setting of parameter values for variation in the simulation study.

TONGUE LENGTH

The tongue length of the dolly is defined as the longitudinal distance from the pintle hitch to the axle. It is also often referred to as the dolly wheelbase. In the case of the A-dolly, this specification is related to low-speed offtracking performance. Theoretical work at UMTRI has shown that, surprisingly to some, dolly tongue length does not have a major influence on rearward amplification.

As a performance specification the dolly shall not increase offtracking, relative to offtracking with a baseline A-dolly, by more than 0.3 meters. An 80-inch tongue-length A-dolly was chosen as the baseline condition. This length is on the long side of "typical" conventional A-dollies. Given this choice, the performance limit (in the test procedure adopted in Canada via recommendations by the Roads and Transportation Association of Canada (RTAC)) would be reached by an A-dolly of approximately 102-inch tongue length.

For C-dollies, excessive tongue length, combined with dolly-steering properties, can degrade high-speed offtracking and damping ratio. The definition of "excessive" is related to the relative size of the loads carried by the fixed axles of the lead trailer and the dolly axles.

OVERALL TRACK WIDTH

Overall track width is the basic parameter in determining the roll stability potential of any vehicle. More track width is better, and the specified 102 inch is the widest track allowed under current U.S. law.

HITCH POSITION—HEIGHT

As regards the A-dolly, unpublished work has shown that rearward amplification can be reduced by lowering the pintle hitch. Presumably the mechanism involved is that roll motions of the lead trailer add to the lateral motion of the pintle in proportion to the height above the ground (or the height dimension that offsets the hitch from a suspension roll center). A minimum value of 12 inches (.305 m) is seen as the lowest level reasonable in relation to ground clearance.

For the C-dollies, hitch heights are not seen as particularly important to performance, but consistent hitch height is obviously necessary for logistical reasons. A height value of

36 inches (.914 m) is consistent with current U.S. practice (SAE recommended practice) and with Canadian C-dolly practice and rules.

HITCH POSITION—LATERAL SPACING

Again, consistent lateral spacing for C-dollies is important as a logistical matter. For strength and stiffness, it is also advantageous to space the hitches in a manner such that they fall close to the (typical) lateral positions of the frame rail. A lateral spacing of 30 inches (.762 m) between hitch centers provides the alignment with frame rails and is consistent with current Canadian rules.

EFFECTIVE ROLL COMPLIANCE

This specification is meant to control the combined influence on roll stability of the dolly suspension roll compliance and roll center height, and any compliance of the dolly structure between the fifth wheel and suspension. The *effective compliance* measure is illustrated in figure B-1. The measure is meant to simulate the compliant response of the dolly suspension in a turn of 0.38 g lateral acceleration (the static roll stability limit in the preliminary vehicle performance specifications) when loaded by a nominal, worst-case trailer.

"Worst case" is defined as a trailer which (i) loads the dolly suspension to its full GAWR and has the rather high center of gravity of 90 inches (2.29 m). This C.G. height is the approximate figure B-1 value that will be seen with a van trailer loaded to both full-weight and full-volume capacity with uniform density freight. That is, the trailer is at its maximum weight and the cargo C.G. is mid-way between the floor and ceiling of the van. The loading pattern shown in the figure B-1 simulates the roll related loading which this worst-case trailer would apply during a turn of the 0.38 g condition (given the assumption that the trailer suspension is doing its "fair share" of the job). Thus, the roll angle between the dolly axle and the fifth wheel surface is used as a measure of total compliance under the referenced turn condition.

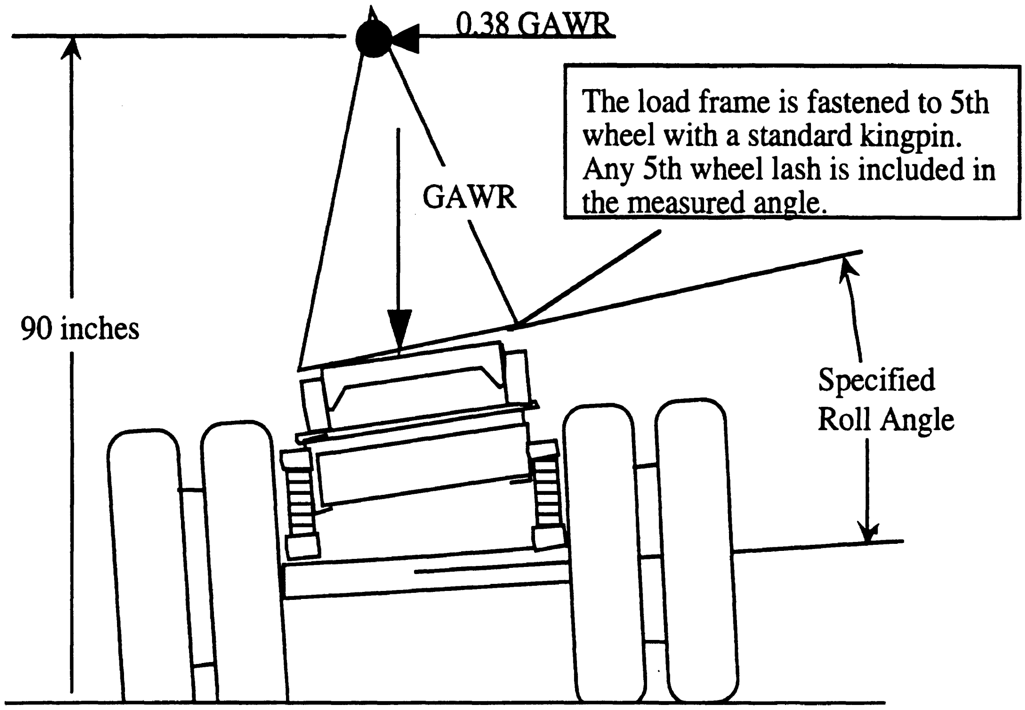


Figure B-1. Measurement of the Effective Dolly Roll Compliance

A value of relative roll angle equal to 4.9 degrees for C-dolly equipment was primarily selected to ensure the dolly suspension does its *fair share* in roll-restraining this worst case trailer in a steady turn that takes the vehicle to its desired level of rollover limit. If the worst case trailer were constrained to this roll angle in the reference turn, it would just be on the edge of rollover.

A corresponding value of 3.2 degrees chosen for the A-dolly was meant to do the same, and more. That is, the observation has been made that reducing roll motion can directly reduce rearward amplification. Thus, by more severely reducing the allowed compliance of an A-dolly, one seeks to reduce the roll motion of the full trailer attending rearward amplification.

HITCH AND FRAME STRENGTH

Strength parameters that serve to specify hitch and frame structural design goals involve minimum values of longitudinal, vertical, and lateral loading that must be sustained at the hitch positions without yielding. There is only one loading requirement for the A-dolly class, viz., a longitudinal load of ± 1.15 GTWR. This is current (SAE) recommended practice in the U.S. and is also contained in the Canadian rules. Vertical and lateral loads are not specified. In practice, these loads are very much smaller than longitudinal loads. It is assumed that structures provided to withstand the longitudinal loads will have no problem with these other, smaller loads.

The C-dolly, however, experiences significant hitch loads in all three directions. Longitudinal loads derive from both towing loads and from yaw moment at the hitch produced by side loads at the tires. The specified longitudinal load for *each* of the two C-dolly hitch points derives from (i) 50% percent of the conventional towing load specification, plus (ii) the longitudinal load developed by the application of peak tire side force on a good road surface (m = 0.8), that is, $\left[0.8\ \text{GAWR}\left(\text{tongue length}/\text{hitch spacing}\right)\right]$. The longer tongue length of 136" is used to derive the value of 3.6 GAWR. This value can be applied to both classes of C-dolly. When applied with a GAWR of 20,000 lb (probably the most common for single axle dollies) and a GTWR of 40,000 lb, the result is ±95,200 lbs, very similar to the Canadian specification of ±90,000 lb.

The C-dolly and the towing trailer pintle hitch must tolerate sustained, simultaneous application of the specified longitudinal loads in opposing directions, repeated once in each direction, that is, for example, tensile load on the right side combined with compression load on the left side, and then the reverse. The lateral load specification for the C-dollies also derives from the peak tire side force loading pattern. It represents the shear load that the hitches see in the same loading scenario given above. The entire load is assumed to be applied separately, and in both directions, to each hitch. This is seen as realistic since the lateral spacing of the hitch eyes and the pintle hitches is likely to be sufficiently different to cause this loading in practice.

The large, vertical force loads experienced by C-dolly hitches derive from the roll moment developed between the two trailers when they experience relative roll motions. Simulation study has yielded predictions of as high as 670,000 in-lb of roll-coupling moment in severe maneuvers. Severe maneuver and curb-climbing tests with fully loaded 27' doubles have produced maximum measured loads of only 260,000 in-lb. The effective stiffness of the roll coupling is very important in this mechanism, and differences in this parameter in simulated and real vehicles probably accounts for the difference. For a preliminary specification, a rather conservative value was chosen, equivalent to 600,000 in-lb for a 20,000 lb GAWR. The vertical strength specification for the Class 2 C-dolly is rather arbitrarily set at 50 percent of the heavy dolly specification.

The loading pattern required is similar to that for longitudinal strength, that is, simultaneous application of loads of opposite polarity repeated once in each direction.

TRAILER-TO-TRAILER ROLL STIFFNESS

Any specification for dolly frame roll stiffness will be related to the vertical hitch load specification. That is, it will require that the combined frame/suspension/fifth wheel/pintle hitch structure of the dolly be sufficiently stiff to allow development of the roll moment implied by the specified vertical hitch loads within the confines of ±15 degrees of relative roll angle between the two trailers. This implies an effective roll-coupling stiffness of 40,000 lb/deg for the heavier Class 3 dolly and half of that value for the Class 2 dolly.

Such a specification implies that the "test" would be conducted with the dolly connected to a pair of mating pintles mounted on a loading frame simulating the towing trailer. Similarly, the dolly would be coupled to a frame at the fifth wheel. The relative angular deflection is then specified as the angle between the two (simulated) trailers. The specification would be applied in this manner to ensure that all meaningful lash elements are included in the measurement. Of course, the specified stiffness must be delivered for both polarities of deflection. All of the loading and stiffness specifications, including their synergistic relationships, will be examined in the simulation study.

TIRE-CORNERING COMPLIANCE

Tire-cornering compliance (F_z/C_a) is important in every dimension of vehicle handling performance. Generally, lower compliance (i.e., a higher value of cornering stiffness, C_α) is better. In practice, the specification indicated in table B-1 simply implies that modern steel belted radial tires would be required, but through the application of this basic performance-related quality.

SUSPENSION ROLL STEER COEFFICIENT

Suspension roll steer is a dolly parameter that may have potential for reducing rearward amplification in A-trains. It is known that roll steer of the proper polarity can have an effect that is similar to that of a decrease in tire compliance.

STEERING SYSTEM SPECIFICATIONS

The axle of a C-Dolly may be either self-steering or controlled-steering according to the following specifications.

Option 1—Self-steering

The tires of the C-dolly axle may be self-steering by virtue of a caster mechanism. The steering system must be equipped with a centering mechanism such that:

- The application of total tire side forces (sum of left and right side forces) at a magnitude equal to 0.3 GAWR in either direction will not result in a steer angle of magnitude in excess of one degree.
- The centering force mechanism must sustain a minimum total tire side force of magnitude 0.3 GAWR over the full range of steering deflection provided by the self-steering mechanism.

- When starting from either polarity of full steering limit, a reduction of total tire side force to a level of no less than 0.1 GAWR will result in a reduction of steer angle to a level of less than one degree in magnitude.
- The application of tire brake force, *separately* at either the right or left side tire (or dual tire pair) and at a magnitude equal to 0.1 GAWR in either direction will not result in a steer angle of magnitude in excess of one degree.

These items shall be accomplished with the dolly loaded to a vertical axle load equal to the GAWR. Application of tire side forces shall be parallel to the wheel spindle axis and at a position 2 inches (.05 m) aft of this axis in the plan view. Application of tire brake forces shall be in the wheel plan for single tires or in the centroidal plan of the dual tire pair for dual tires.

In addition:

- The steering system must be equipped with an on-center locking mechanism capable of remote actuation by the driver in the cab and manual actuation at the dolly in the case of failure of the remote system.
- The steering system must include a "stop" to prevent interference between the tires and frame at large steer angles.
- The steering system, limit stops, and center-locking mechanism must be strong enough to sustain the separate application of a total axle side force and/or a single-side brake force equal in magnitude to the GAWR and similar in the manner of application as described above.

The centering mechanism specifications are intended to insure sufficient tire side force capability to preclude poor high-speed offtracking or insufficient yaw damping. The requirement for a center lock is to (i) allow for backing, and (ii) allow for an "emergency" and/or "poor road conditions" operating mode in which the self-steering axle is essentially converted to a non-steering axle.

Option 2 — Controlled-steering

The Class-2 or Class-3 C-Dollies can also be considered as equipped with a controlled steering mechanism. The mechanism must provide positive control of the steer angle of the dolly tires as a function of the yaw articulation of the dolly and its *towed* trailer. Properties of the steering system must be such that:

- Within the range of ±5 degrees of articulation angle, the steering system ratio must be as follows:

$$N \equiv \frac{-\delta}{\Gamma} \leq 1.1 \bullet \frac{OH + TL}{WB} \qquad (4)$$

- At articulation angles ranging from 5 degrees to 30 degrees in magnitude, the steering ratio must be as follows:

$$N \equiv \frac{-\delta}{\Gamma} \leq 1.25 \bullet \frac{OH + TL}{WB} \quad (5)$$

In equations 4 and 5:

N: is the steering ratio,

d: is the steer angle of the dolly tires, positive when the tires steer clockwise relative to the dolly in the overhead view,

G: is the yaw articulation angle of the dolly and its *towed* trailer, positive when the dolly is turned clockwise relative to the towed trailer in the overhead view,

OH: is the "overhang" dimension of the pintle hitch, i.e., the longitudinal distance from the *towing* trailer rear suspension center line to the pintle hitch connection to the dolly,

TL: is the tongue length of the dolly,

WB: is the wheelbase of the *towed* trailer.

- At articulation angles of magnitude greater than 30 degrees, the steering system may "disengage" and allow free castering of the dolly tires but must have re-engaged when the magnitude of the articulation angle drops below 30 degrees.
- The steering system must include a "stop" to prevent interference between the tires and frame at high steer angles.
- The steering system must allow articulation angles over the range of ±100 degrees without damage.
- The steering system must be equipped with an on-center locking mechanism, manually actuated at the dolly, so designed that, when locked, the dolly can be used with standard semitrailers as a non-steering C-dolly.
- The steering system may require special modification of the towed trailer, but such modifications must leave the trailer compatible with conventional dollies.
- The steering system must be equipped with an on-center locking mechanism, manually actuated at the dolly, and the steering system so designed that, when the steering system is locked, the dolly may be used as a non-steering C-dolly with unmodified semitrailers.
- The steering system, limit stops, and center-locking mechanism must be strong enough to sustain the separate application of a total axle side force and/or a single-side brake force equal in magnitude to the GAWR and similar in the manner of application as described above.

Note that these specifications allow C-dollies with non-steering axles, since a steering system with a "ratio of zero" can meet all of the requirements.

WEIGHT

Dolly weight is obviously a property that falls outside of the realm that influences dynamic performance of the vehicle—minimization of dolly weight is simply an important "desirable goal." Clearly weight and the properties of stiffness and strength are basically in opposition. Just as clearly, dolly purchasers and manufacturers are motivated to keep dolly weight at a minimum by economic factors. The numbers given here are estimates of realistic target weights for the classes specified. Example of dollies are known to exist which (i) approximately fit the three performance classifications and (ii) are at or near the specified weights.

COUPLING TIME

Coupling time is an objective measure of "ease of coupling." Here, the issue is the excess time required to hitch a C-dolly, relative to a conventional A-dolly, and to a far lesser extent, whether the A-dolly with a low hitch height can be hitched as conveniently as a conventional A-dolly. Thus the specifications are given as a multiple of a "Reference time," T_R. That is, a reasonably skilled and practiced driver shall be capable of hitching the specified dolly in the time indicated, relative to the reference time that the same driver requires to hitch a conventional A-dolly and without significantly greater physical effort. Field experience indicates that hitching hardware exists that will rather easily meet this specification.

BACKING ABILITY

The ability to back the assembled vehicle, as well as the ability to hitch the dolly conveniently, constitute the most significant elements of "ease of operation." The "desirable specifications" include the ability to back the A-dolly in a straight line and the C-dollies in straight line or in cornering, i.e. "with strategy."

A-trains are often made capable of backing in a straight line by providing a mechanism by which the fifth wheel articulation is locked on-center. This is most common in construction vehicles where dump trains must be backed into position. Otherwise, such features are rather uncommon.

The inclusion of this specification for C-dollies is redundant with the requirements of the steering system. Vehicles using the controlled-steering C-dolly may be backed by virtue of its inherent design. It requires no special driver actions. Vehicles using the self-steering C-dolly may be backed once the steering mechanism is locked on center.

In either case, the backing vehicle is inherently unstable and requires substantial driver skill to stabilize the system.

APPENDIX C

PARAMETRIC SENSITIVITY PLOTS

This appendix contains the computer simulation results showing the parametric sensitivities of the vehicle combinations. The appendix is broken down into seven major sections by dolly type, viz., (1) A-dolly, (2) 2C1-type C-dolly, (3) 2C2-type C-dolly, (4) 2C3-type C-dolly, (5) 3C1-type C-dolly, (6) 3C2-type C-dolly, (7) 3C3-type C-dolly. Within each of these major sections there is (1) and table presenting the actual values of the performance measures obtained in the simulation runs and (2) sensitivity plots based on those measures. The measures are presented as relative values in the plots, that is, showing the change in the measure relative to that obtained in the baseline condition. In each section, plots are given for the matrix of various performance measures and vehicle configurations. Each group of sensitivity plots is headed by a *key* that shows the plotting symbols along with the vehicle parameter variations they represent.

Table C-1 is an index to the summary data tables and the sensitivity plots. Page number is given as a function of performance measure and dolly type.

Table C-1. Page number index for the sensitivity plots

	Dolly Types						
Performance Measure	*A*	*2C1*	*2C2*	*2C3*	*3C1*	*3C2*	*3C3*
Summary of Results	26	56	75	94	113	132	151
Static Rollover Threshold	28	57	76	95	114	133	152
High-Speed Steady-State Offtrack.	32	60	79	98	117	136	155
Rearward Amplification	36	63	82	101	120	139	158
Dynamic-Load-Transfer Coefficient	40	66	85	104	123	142	161
Transient High-Speed Offtracking	44	69	88	107	126	145	164
Damping Ratio (RTAC-B)	48	72	94	110	129	148	167
Damping Ratio (pulse maneuver)	52	--	--	--	--	--	--

SENSITIVITY STUDY RESULTS FOR THE A-DOLLY

Table C-2. Performance measures obtained with the A-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio (B)	Damping Ratio (P)
28x28basa	0.438	-1.143	2.381	0.850	2.323	0.208	0.278
28x28do1a	0.441	-1.180	2.367	0.851	2.385	0.205	0.275
28x28do2a	0.440	-1.205	2.345	0.848	2.439	0.205	0.277
28x28pl1a	0.370	-1.195	2.490	1.000	2.497	0.138	0.213
28x28pl2a	0.526	-1.119	2.221	0.702	1.989	0.272	0.343
28x28pl3a	0.438	-1.141	2.312	0.851	2.418	0.202	0.300
28x28pl4a	0.439	-1.145	2.425	0.851	2.273	0.208	0.260
28x28se1a	0.438	-1.174	2.430	0.871	2.403	0.208	0.280
28x28se2a	0.438	-1.114	2.324	0.835	2.243	0.209	0.277
28x28sp2a	0.431	-1.148	2.406	0.901	2.405	0.191	0.255
28x28sp3a	0.444	-1.140	2.297	0.836	2.247	0.230	0.304
28x28ss4a	0.447	-1.239	2.471	0.922	2.668	0.217	0.285
28x28su1a	0.396	-1.167	2.350	0.982	2.433	0.171	0.229
28x28tl1a	0.443	-0.733	2.166	0.797	1.406	0.194	0.251
28x28tl2a	0.440	-1.980	2.954	0.995	4.180	0.214	0.284
32x32basa	0.447	-1.184	2.116	0.756	1.974	0.269	0.321
32x32do1a	0.448	-1.216	2.124	0.759	2.041	0.266	0.314
32x32do2a	0.449	-1.248	2.126	0.757	2.080	0.260	0.313
32x32pl1a	0.370	-1.220	2.161	0.925	2.138	0.203	0.248
32x32pl2a	0.558	-1.167	1.993	0.596	1.766	0.324	0.390
32x32pl3a	0.447	-1.184	2.116	0.756	1.974	0.269	0.321
32x32pl4a	0.447	-1.184	2.172	0.749	1.862	0.274	0.304
32x32se1a	0.447	-1.208	2.154	0.773	2.036	0.268	0.322
32x32se2a	0.448	-1.152	2.078	0.739	1.912	0.269	0.320
32x32sp2a	0.443	-1.191	2.165	0.788	2.039	0.259	0.311
32x32sp3a	0.455	-1.182	2.042	0.719	1.889	0.308	0.365
32x32ss4a	0.466	-1.267	2.202	0.758	2.115	0.322	0.365
32x32su1a	0.397	-1.199	2.138	0.879	2.083	0.232	0.270
32x32ti1a	0.451	-0.675	1.942	0.687	1.032	0.259	0.287
32x32ti2a	0.449	-1.912	2.461	0.896	3.487	0.255	0.315
38x20basa	0.440	-1.089	2.342	0.805	1.866	0.202	0.210
38x20do1a	0.440	-1.121	2.319	0.804	1.922	0.209	0.216
38x20do2a	0.441	-1.153	2.304	0.800	1.982	0.224	0.223
38x20pl1a	0.364	-1.116	2.430	1.000	2.062	0.155	0.166
38x20pl2a	0.534	-1.083	2.170	0.651	1.605	0.244	0.268
38x20pl3a	0.440	-1.088	2.366	0.800	1.938	0.203	0.210
38x20pl4a	0.440	-1.089	2.442	0.804	1.798	0.195	0.206
38x20se1a	0.440	-1.117	2.391	0.821	1.920	0.203	0.210
38x20se2a	0.440	-1.062	2.289	0.787	1.812	0.201	0.210
38x20sp2a	0.427	-1.094	2.352	0.841	1.923	0.186	0.188
38x20sp3a	0.443	-1.087	2.228	0.768	1.758	0.210	0.230
38x20ss4a	0.457	-1.185	2.450	0.837	2.072	0.210	0.216
38x20su1a	0.406	-1.093	2.396	0.927	1.970	0.167	0.174
38x20ti1a	0.441	-0.620	2.104	0.747	1.030	0.189	0.189
38x20ti2a	0.441	-1.871	2.740	0.941	3.367	0.229	0.213
45x28basa	0.448	-1.148	1.903	0.698	1.643	0.270	0.277
45x28do1a	0.448	-1.180	1.920	0.704	1.705	0.269	0.277
45x28do2a	0.448	-1.207	1.927	0.703	1.742	0.274	0.276
45x28pl1a	0.374	-1.184	2.002	0.852	1.875	0.207	0.213
45x28pl2a	0.555	-1.132	1.734	0.541	1.399	0.327	0.343
45x28pl3a	0.448	-1.150	1.762	0.669	1.677	0.295	0.278
45x28pl4a	0.448	-1.147	2.001	0.708	1.600	0.260	0.261
45x28se1a	0.448	-1.177	1.936	0.711	1.691	0.271	0.278
45x28se2a	0.448	-1.118	1.870	0.686	1.595	0.271	0.277
45x28sp2a	0.435	-1.153	1.957	0.729	1.718	0.250	0.256
45x28sp3a	0.451	-1.145	1.830	0.653	1.531	0.294	0.303
45x28ss4a	0.465	-1.265	1.964	0.703	1.822	0.279	0.286
45x28su1a	0.399	-1.161	1.969	0.809	1.791	0.220	0.227
45x28tl1a	0.449	-0.591	1.724	0.630	0.829	0.244	0.251
45x28tl2a	0.450	-2.082	2.277	0.811	3.152	0.298	0.267
45x45basa	0.425	-1.331	1.648	0.608	1.656	0.375	0.399
45x45do1a	0.425	-1.367	1.668	0.617	1.723	0.371	0.392
45x45do2a	0.425	-1.403	1.687	0.621	1.785	0.368	0.385
45x45pl1a	0.345	-1.426	1.807	0.781	2.067	0.274	0.321
45x45pl2a	0.521	-1.284	1.539	0.465	1.379	0.445	0.445
45x45pl3a	0.424	-1.332	1.564	0.600	1.727	0.386	0.440
45x45pl4a	0.425	-1.330	1.712	0.627	1.581	0.351	0.383
45x45se1a	0.425	-1.359	1.670	0.619	1.696	0.375	0.399
45x45se2a	0.425	-1.305	1.625	0.598	1.615	0.373	0.399
45x45sp2a	0.409	-1.347	1.708	0.641	1.758	0.336	0.375
45x45sp3a	0.430	-1.322	1.614	0.580	1.562	0.407	0.421
45x45ss4a	0.443	-1.475	1.710	0.617	1.854	0.403	0.413
45x45su1a	0.384	-1.360	1.727	0.717	1.849	0.321	0.349
45x45ti1a	0.425	-0.699	1.462	0.544	0.828	0.321	0.399
45x45tl2a	0.424	-2.533	1.996	0.729	3.445	0.329	0.386
3X28BASA	0.436	-1.776	4.050	1.000	3.748	0.207	0.330
3X28DO1A	0.439	-1.841	3.742	1.000	3.772	0.193	0.320
3X28DO2A	0.441	-1.900	3.620	1.000	4.150	0.196	0.310
3X28PL1A	0.364	-1.850	3.263	1.000	3.751	NA	0.305

Table C-2 (continued). Performance measures obtained with the A-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio (B)	Damping Ratio (P)
3X28PL2A	0.520	-1.733	3.053	0.947	3.065	0.269	0.345
3X28PL3A	0.436	-1.774	3.157	1.000	4.513	0.152	0.309
3X28PL4A	0.435	-1.778	4.324	1.000	3.806	NA	0.325
3X28SE1A	0.436	-1.832	5.000	1.000	4.502	0.190	0.336
3X28SE2A	0.436	-1.725	3.093	1.000	3.692	0.213	0.323
3X28SP2A	0.409	-1.806	4.990	1.000	1.815	0.240	0.259
3X28SP3A	0.423	-1.774	3.325	1.000	2.612	0.243	0.312
3X28SS4A	0.441	-1.605	3.659	1.000	3.225	0.228	0.296
3X28SU1A	0.413	-1.807	2.813	1.000	2.679	0.196	0.315
3X28TI1A	0.438	-1.145	2.768	0.970	1.788	0.206	0.378
3X28TI2A	0.432	-2.995	3.841	1.000	6.477	NA	0.243

Sensitivity Plots of Static Rollover Threshold

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

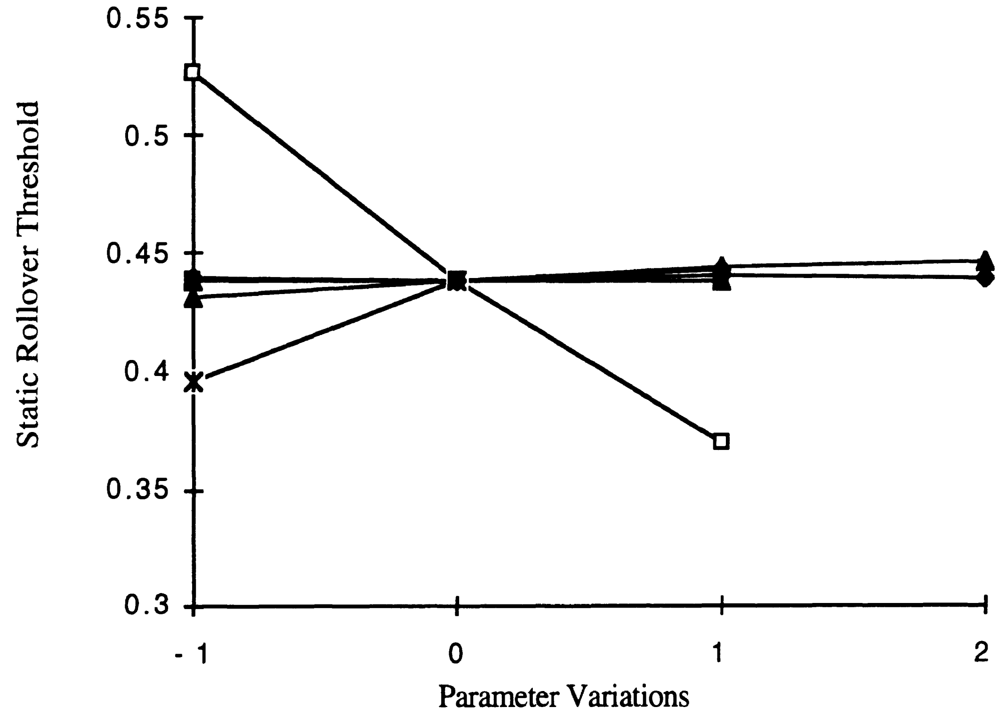


Figure C-1. Sensitivity of static rollover threshold: 28'x28' five-axle A-train double

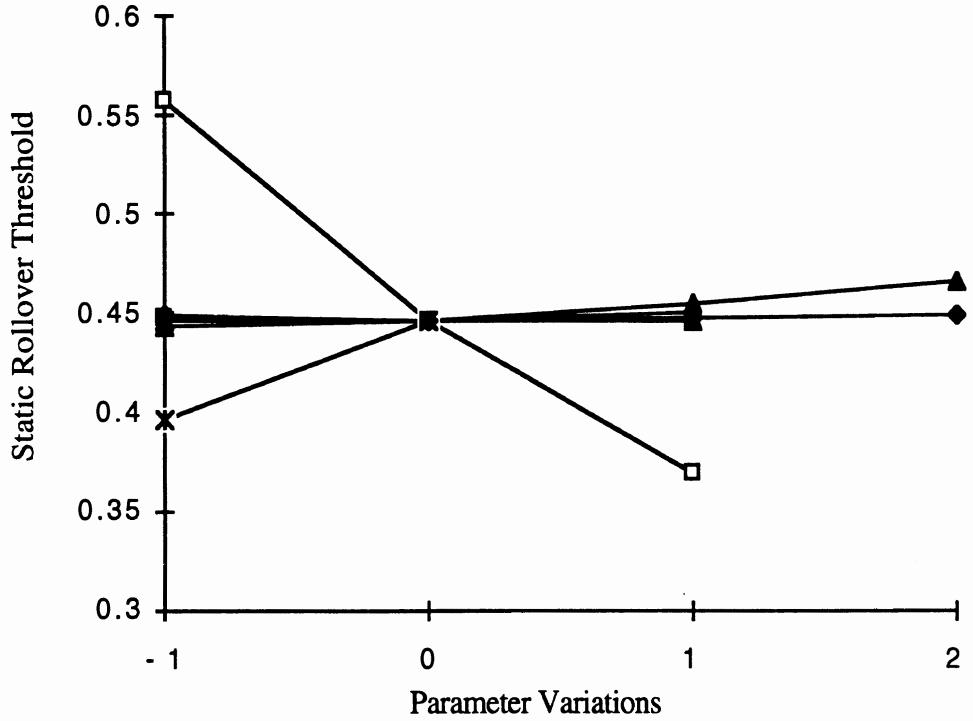


Figure C-2. Sensitivity of static rollover threshold: 32'x32' eight-axle A-train double

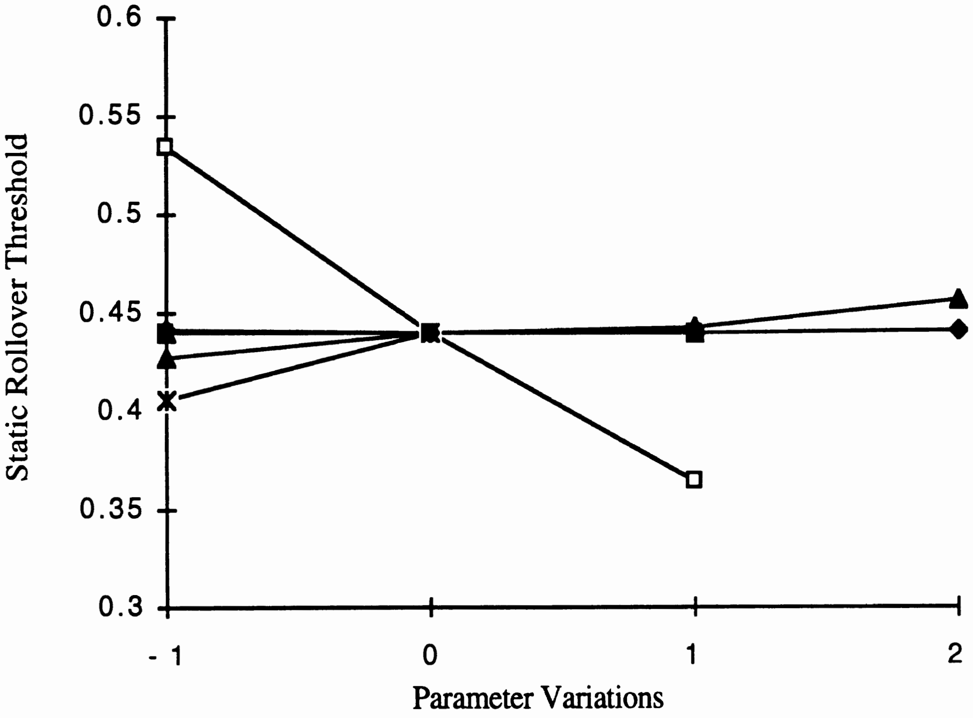


Figure C-3. Sensitivity of static rollover threshold: 38'x20' seven-axle A-train double

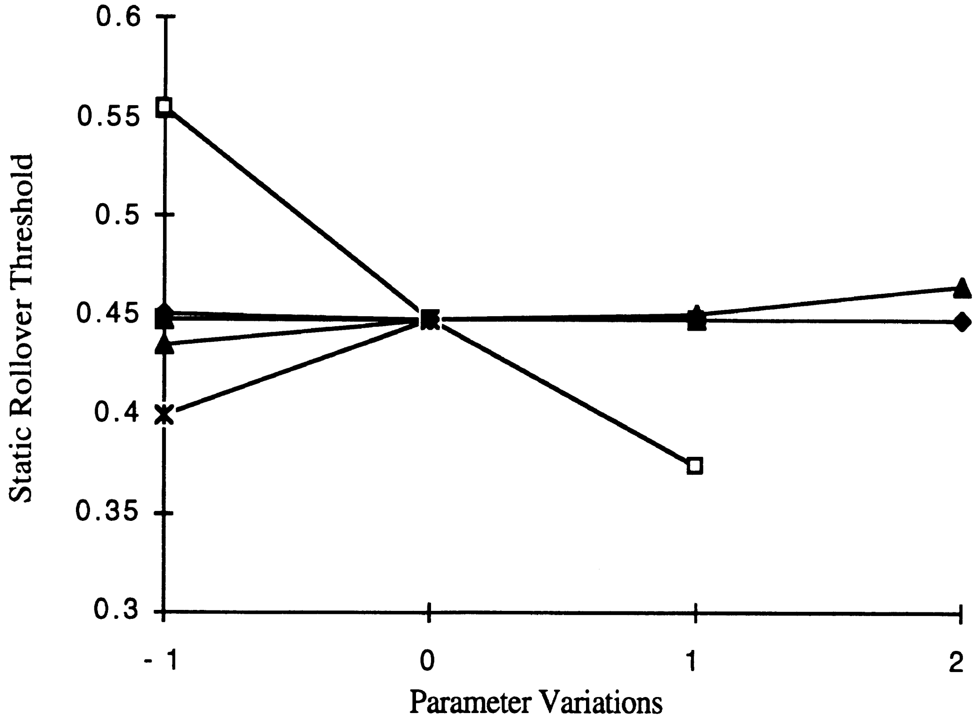


Figure C-4. Sensitivity of static rollover threshold: 45'x28' seven-axle A-train double

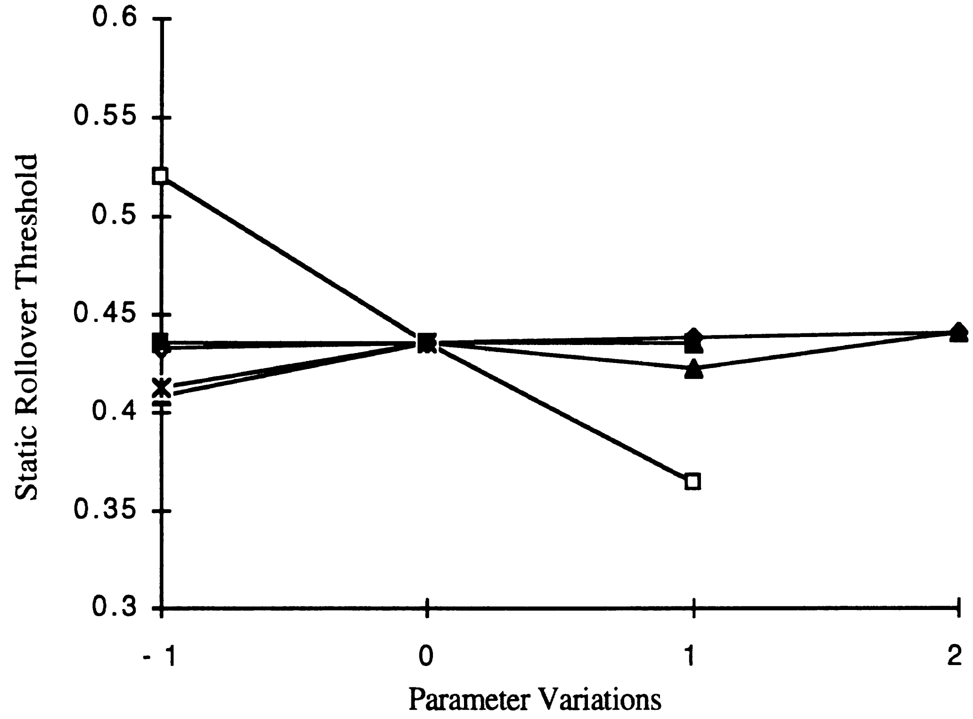


Figure C-5. Sensitivity of static rollover threshold: 28'x28'x28' seven-axle A-train triple

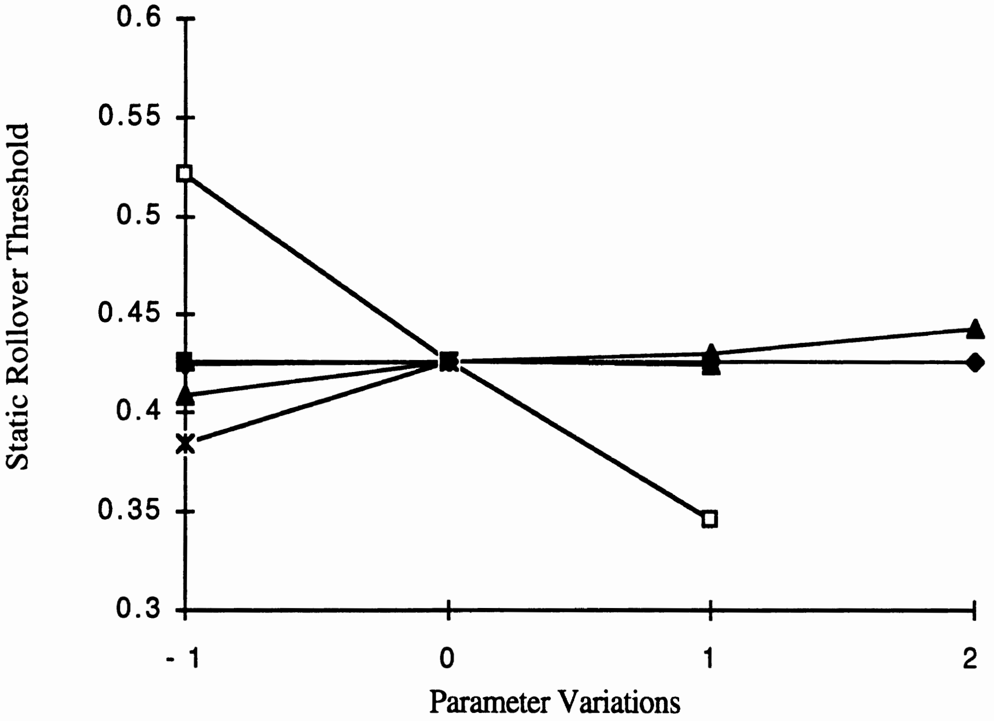


Figure C-6. Sensitivity of static rollover threshold: 45'x45' eight-axle A-train double

Sensitivity Plots of High-Speed Steady-State Offtracking

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

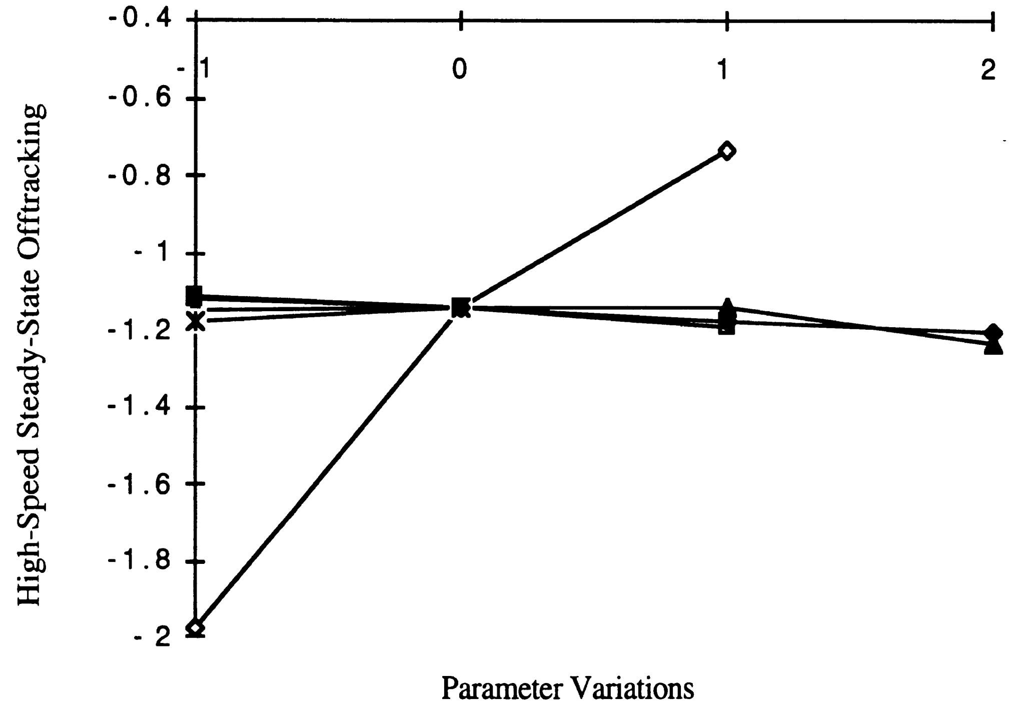


Figure C-7. Sensitivity of high-speed steady-state offtracking: 28'x28' five-axle A-train double

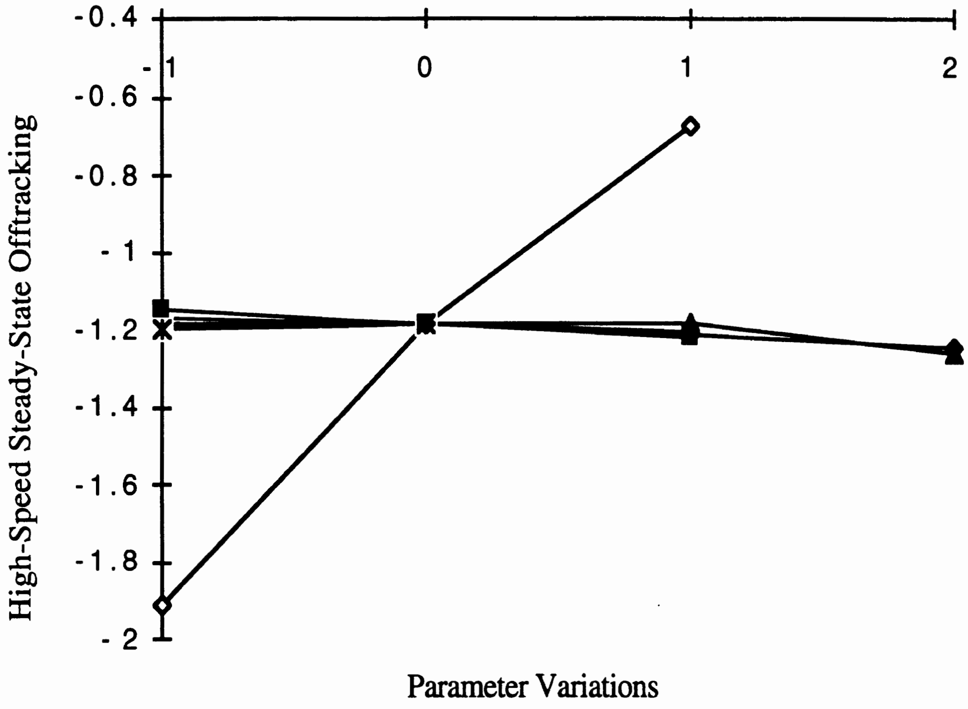


Figure C-8. Sensitivity of high-speed steady-state offtracking: 32'x32' eight-axle A-train double

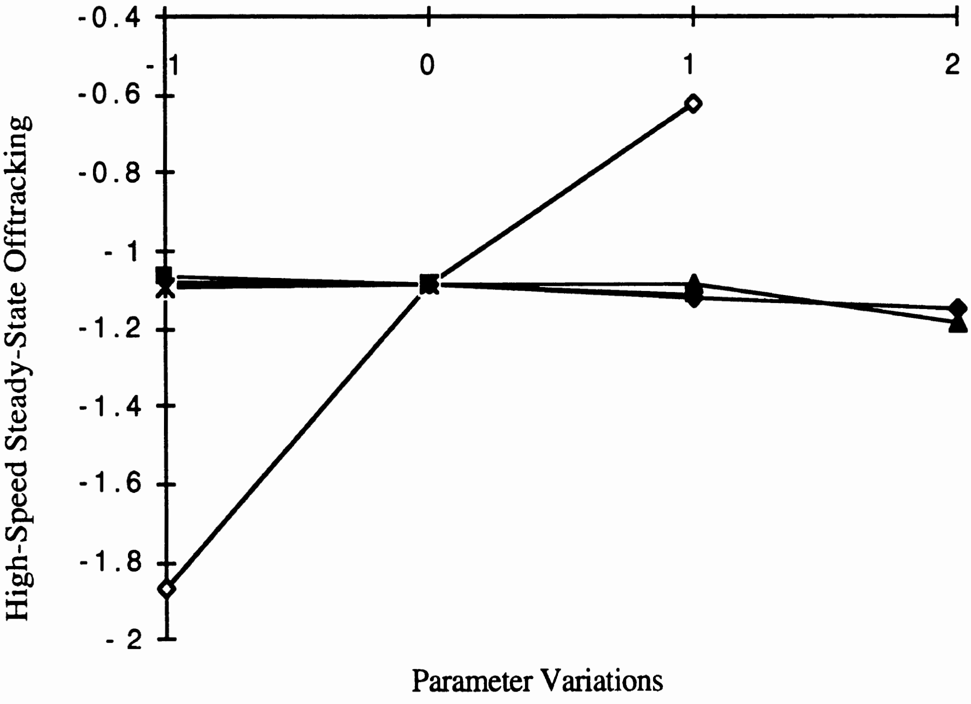


Figure C-9. Sensitivity of high-speed steady-state offtracking: 38'x20' seven-axle A-train double

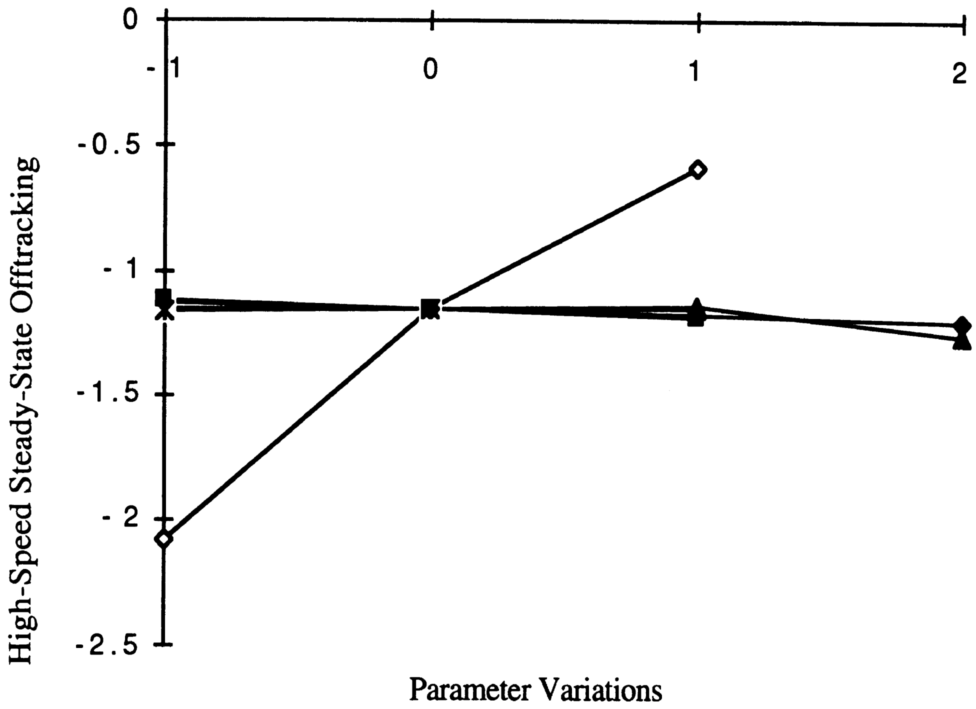


Figure C-10. **Sensitivity of high-speed steady-state offtracking: 45'x28' seven-axle A-train double**

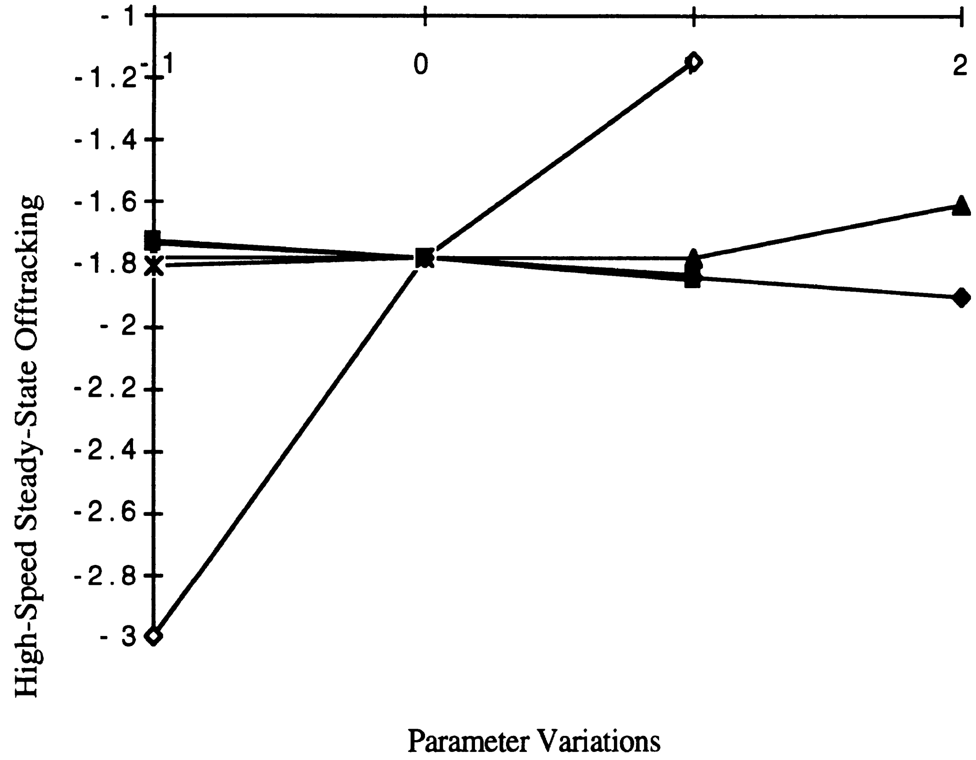


Figure C-11. **Sensitivity of high-speed steady-state offtracking: 28'x28'x28' seven-axle A-train triple**

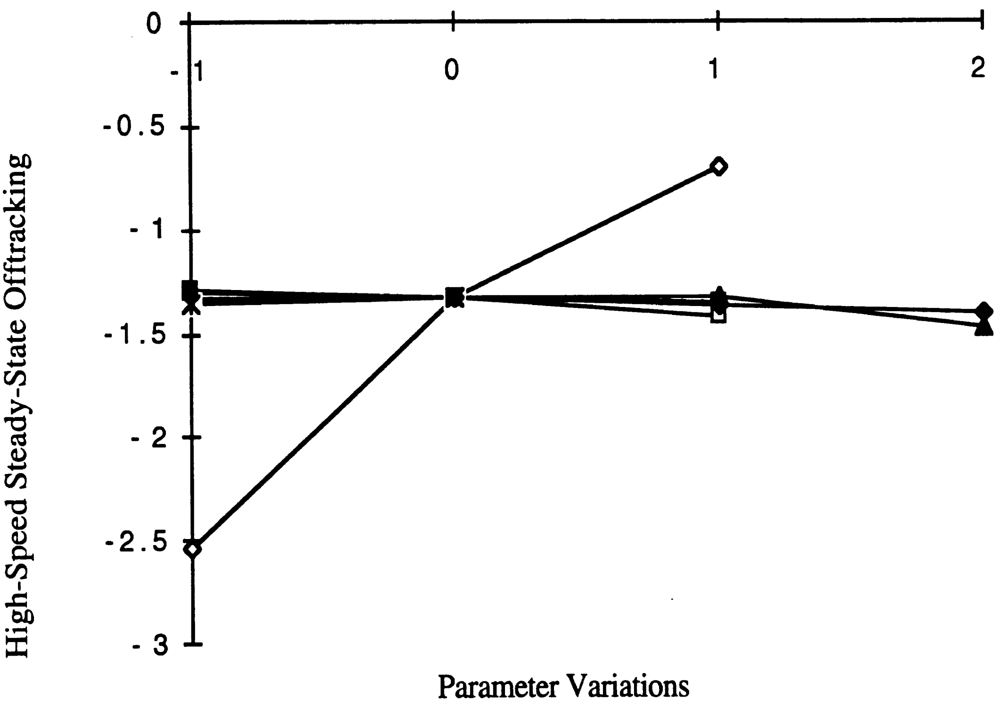


Figure C-12. **Sensitivity of high-speed steady-state offtracking: 45'x45' eight-axle A-train double**

Sensitivity Plots of Rearward Amplification

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

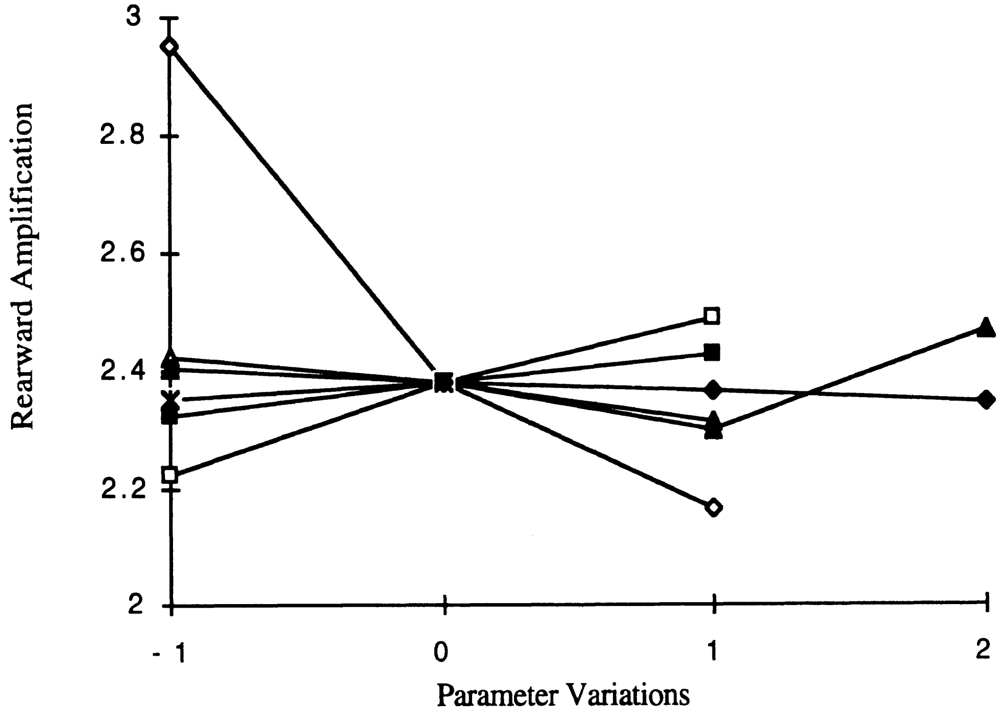


Figure C-13. Sensitivity of rearward amplification: 28'x28' five-axle A-train double

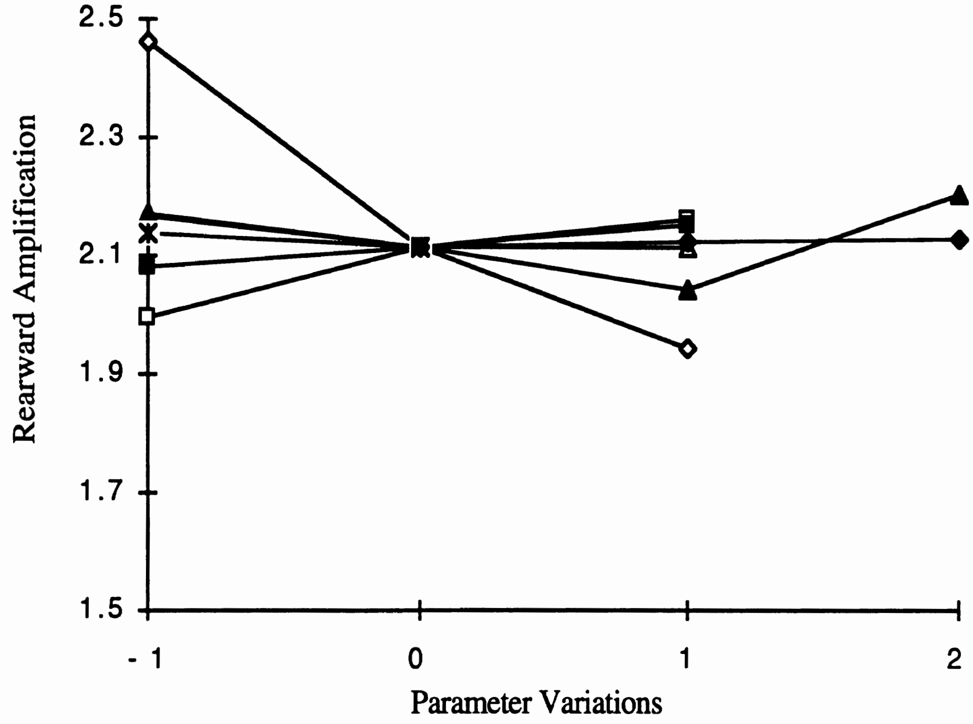


Figure C-14. Sensitivity of rearward amplification: 32'x32' eight-axle A-train double

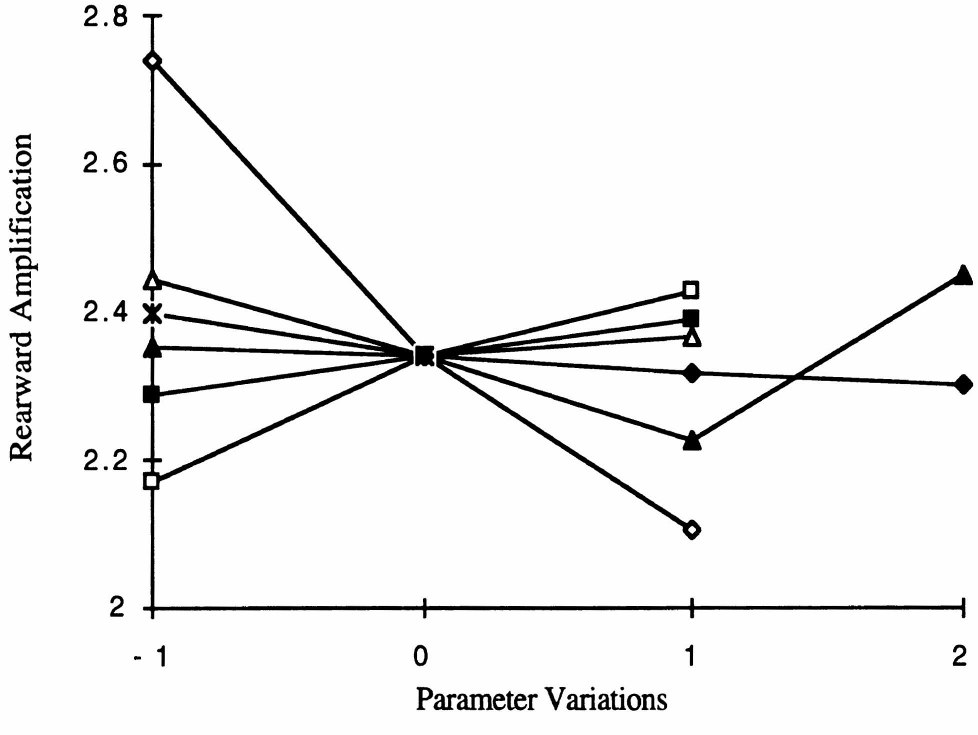


Figure C-15. Sensitivity of rearward amplification: 38'x20' seven-axle A-train double

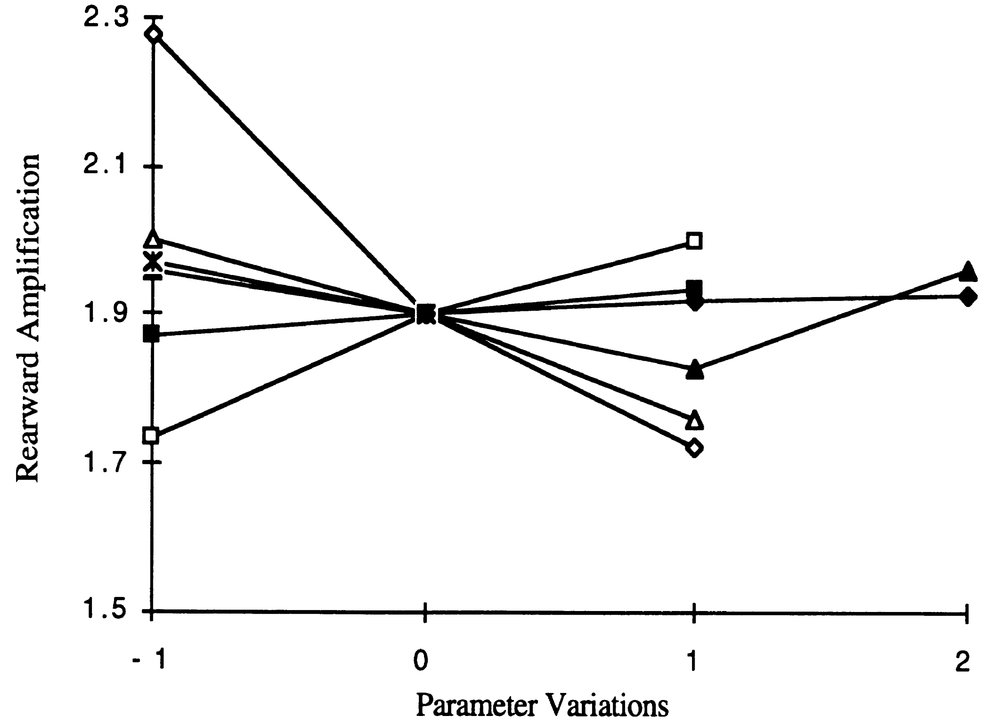


Figure C-16. Sensitivity of rearward amplification: 45'x28' seven-axle A-train double

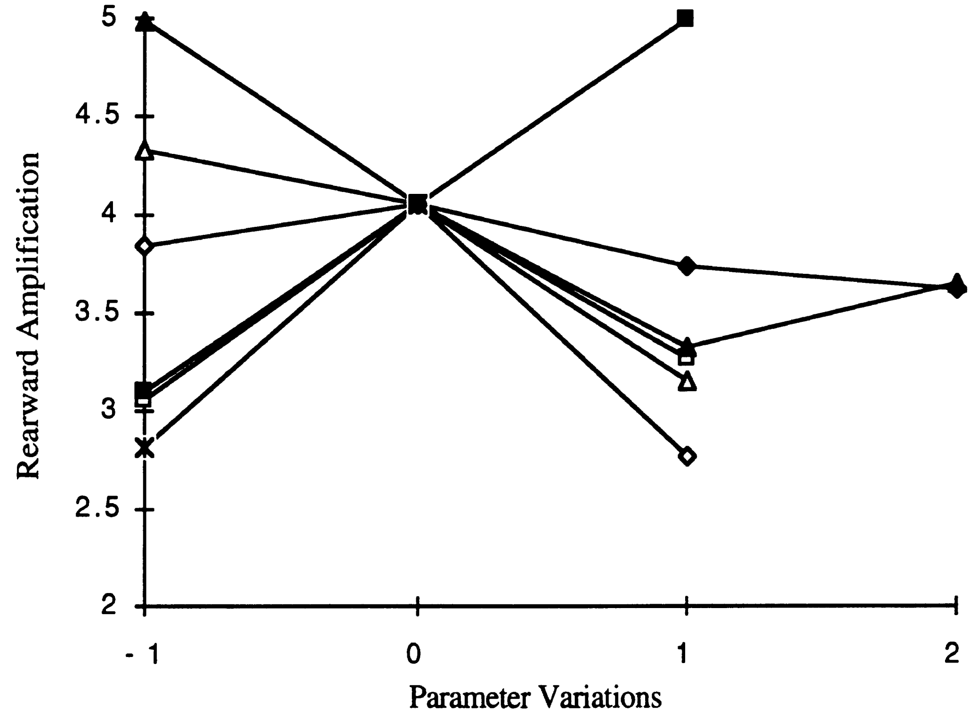


Figure C-17. Sensitivity of rearward amplification: 28'x28'x28' seven-axle A-train triple

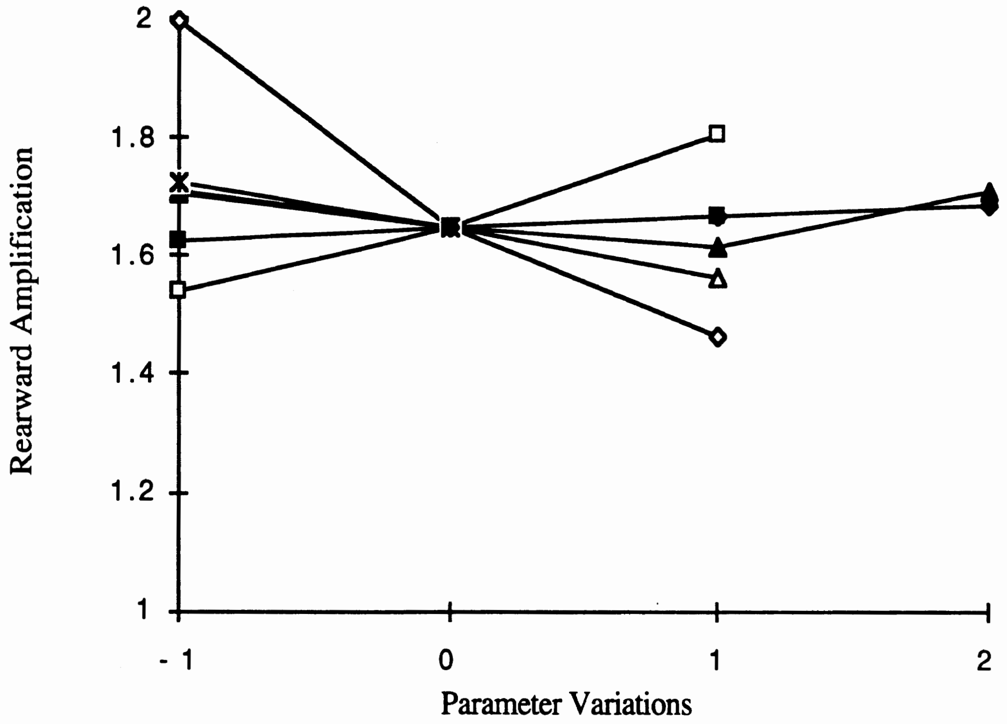


Figure C-18. Sensitivity of rearward amplification: 45'x45' eight-axle A-train double

Sensitivity Plots of Dynamic-Load-Transfer Ratio

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✱	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

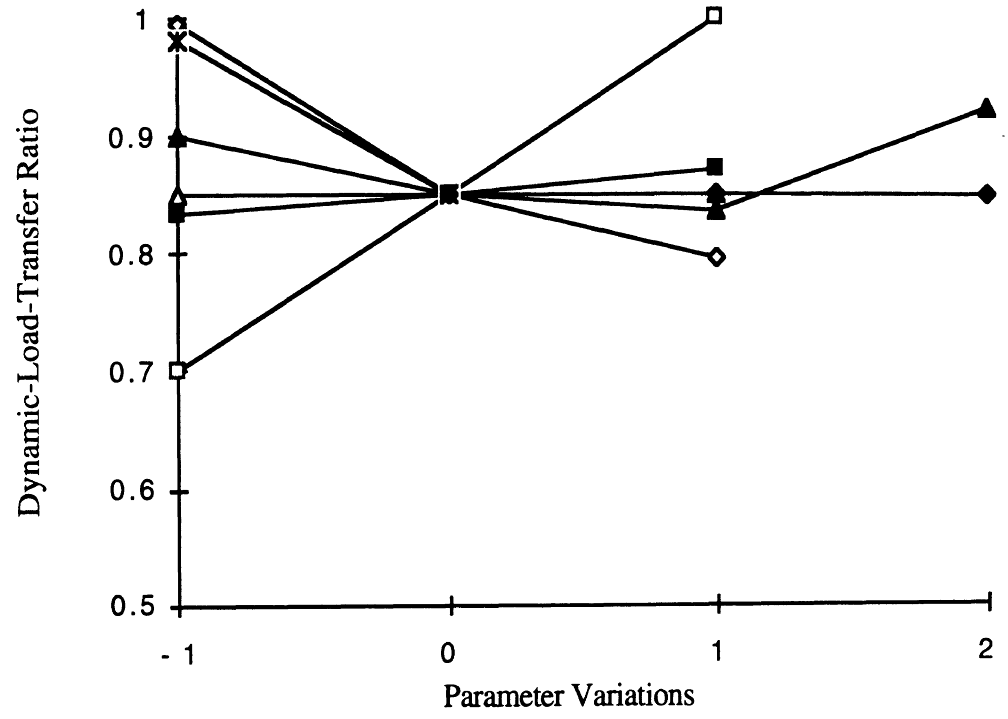


Figure C-19. Sensitivity of dynamic-load-transfer ratio: 28'x28' five-axle A-train double

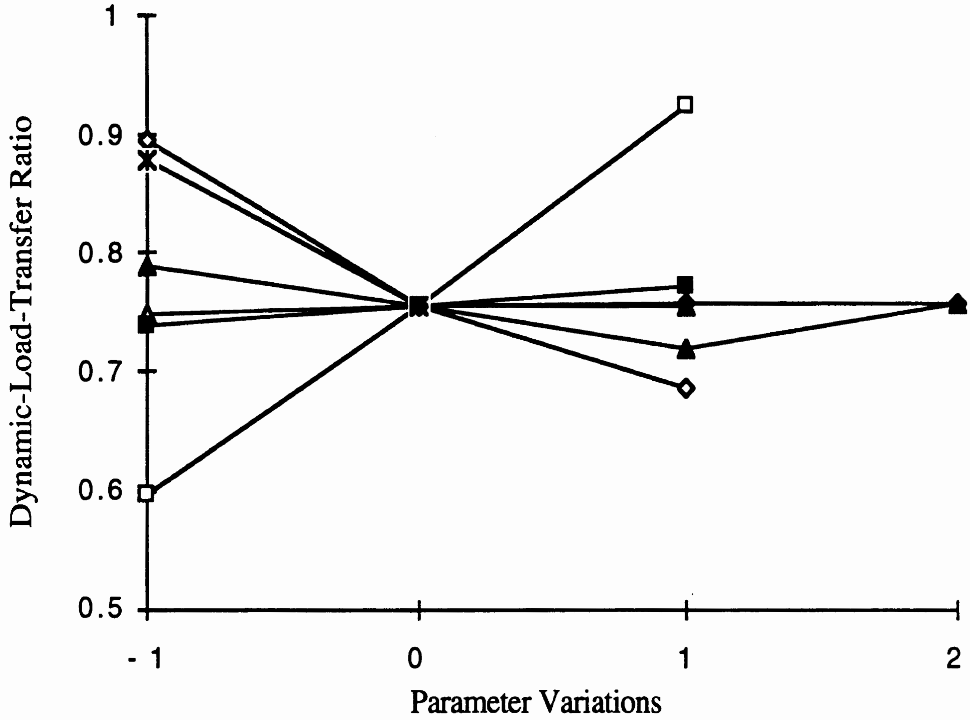


Figure C-20. Sensitivity of dynamic-load-transfer ratio: 32'x32' eight-axle A-train double

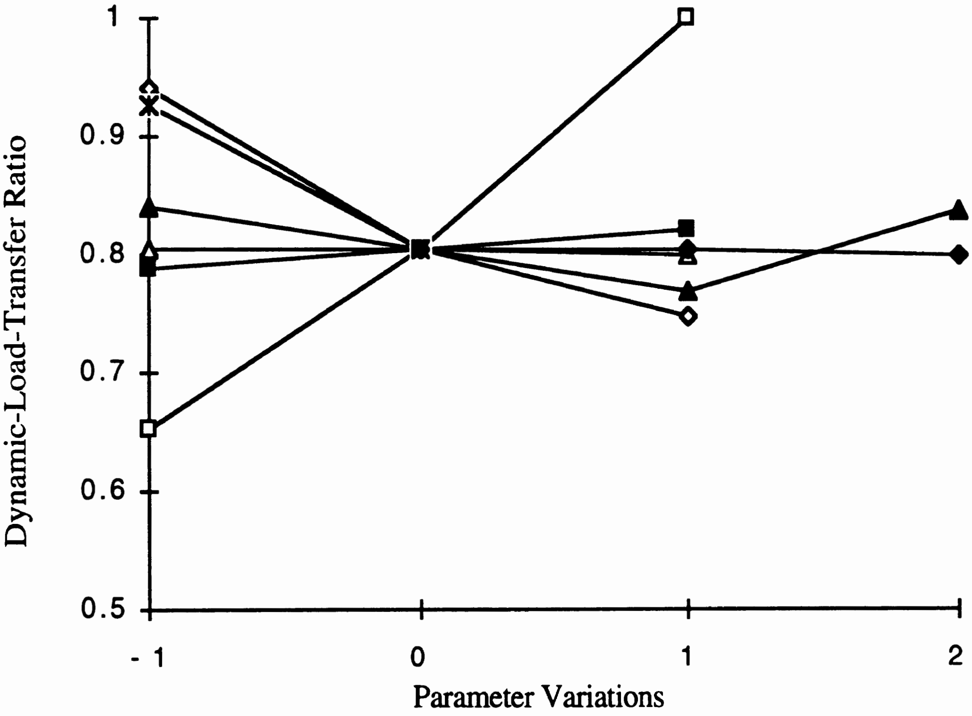


Figure C-21. Sensitivity of dynamic-load-transfer ratio: 38'x20' seven-axle A-train double

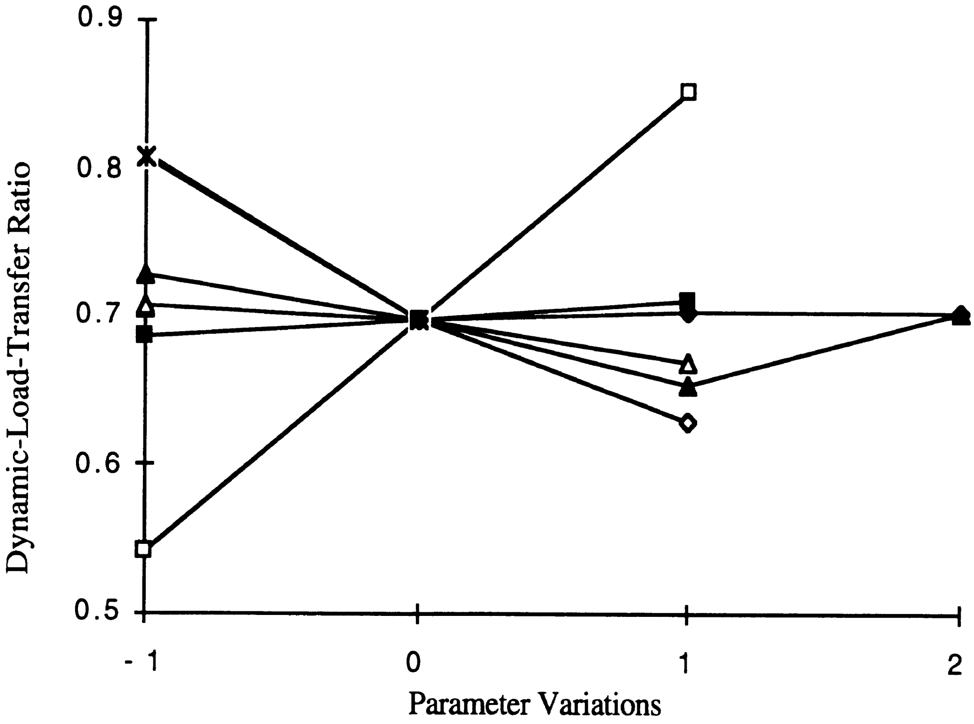


Figure C-22. Sensitivity of dynamic-load-transfer ratio: 45'x28' seven-axle A-train double

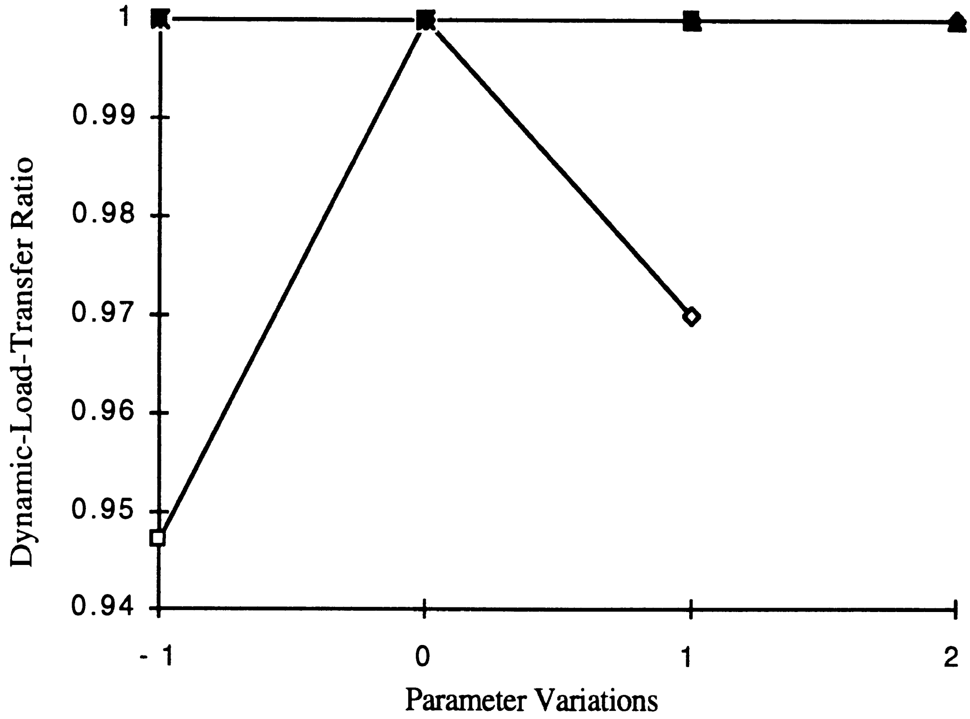


Figure C-23. Sensitivity of dynamic-load-transfer ratio: 28'x28'x28' seven-axle A-train triple

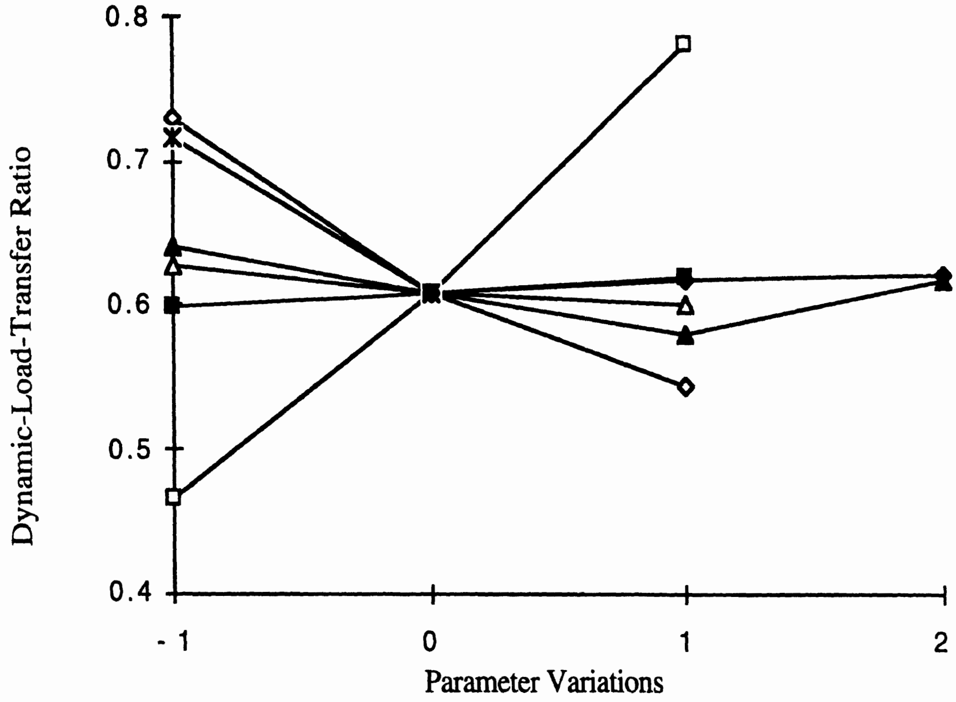


Figure C-24. Sensitivity of dynamic-load-transfer ratio: 45'x45' eight-axle A-train double

Sensitivity Plots of Transient High-Speed Offtracking

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

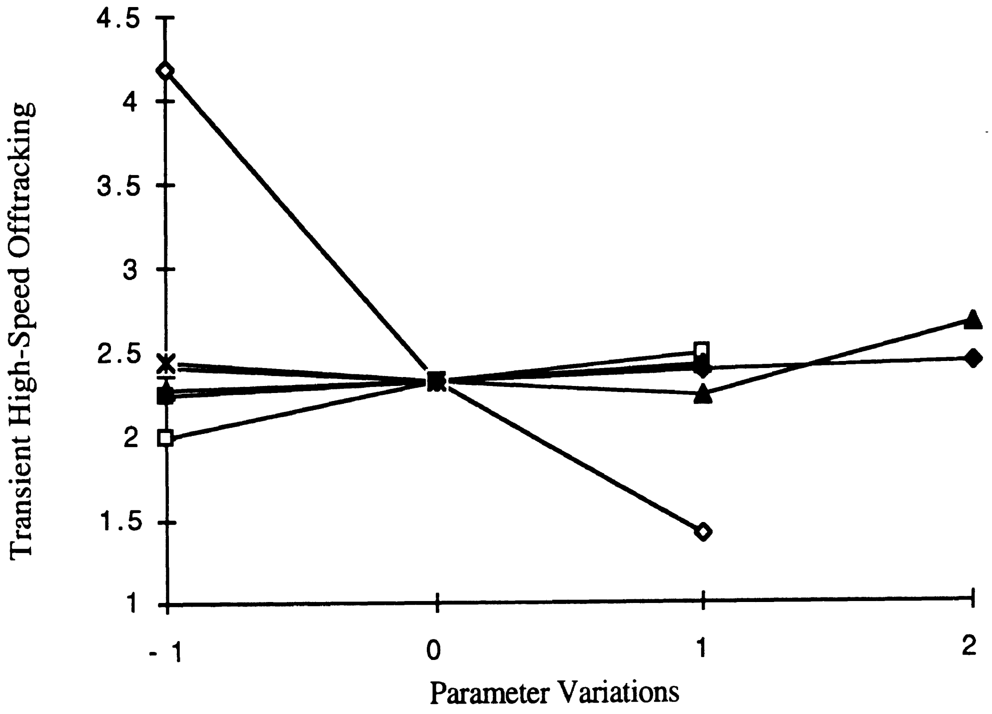


Figure C-25. Sensitivity of transient high-speed offtracking: 28'x28' five-axle A-train double

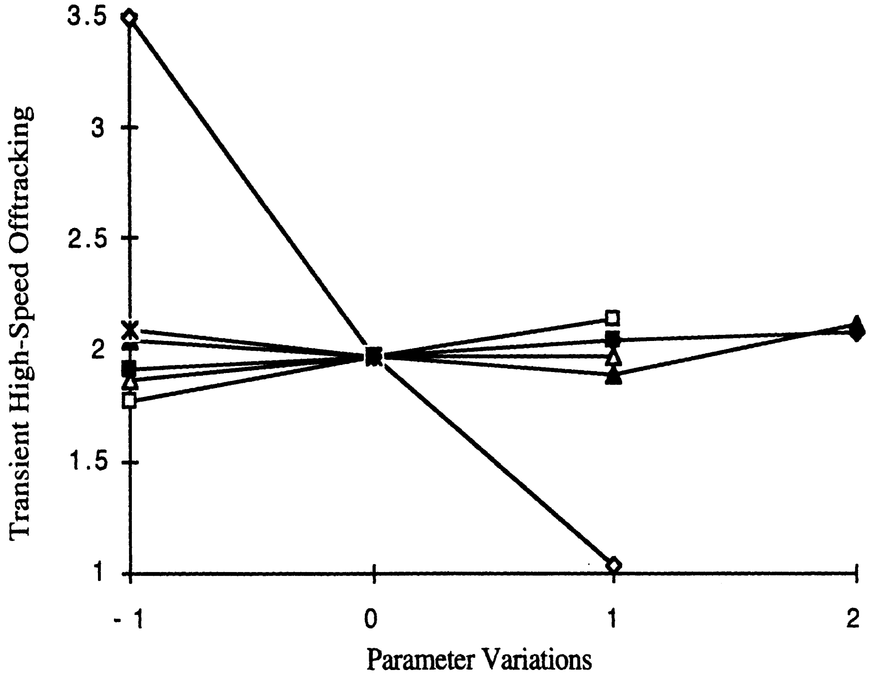


Figure C-26. Sensitivity of transient high-speed offtracking: 32'x32' eight-axle A-train double

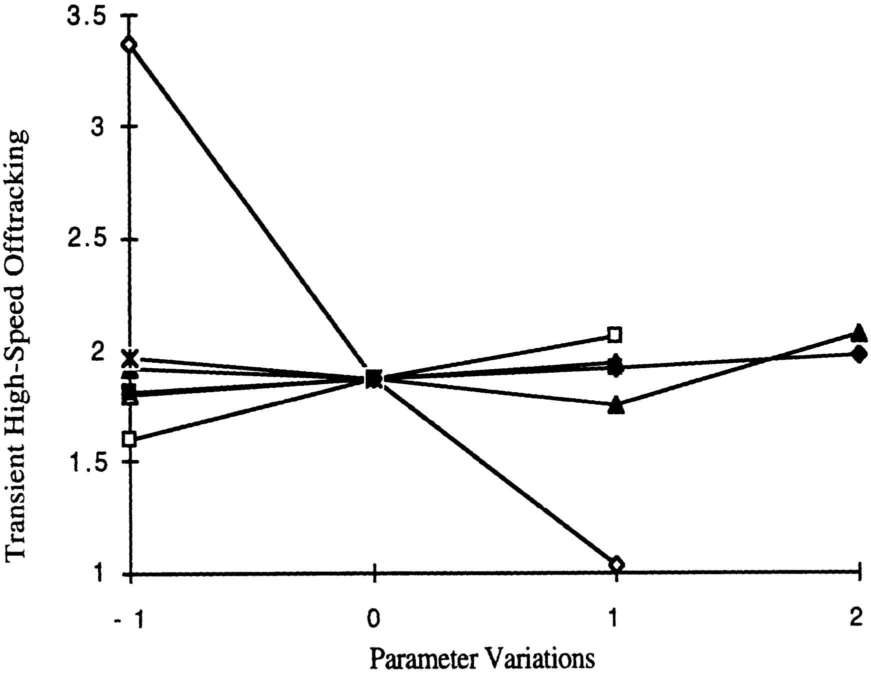


Figure C-27. Sensitivity of transient high-speed offtracking: 38'x20' seven-axle A-train double

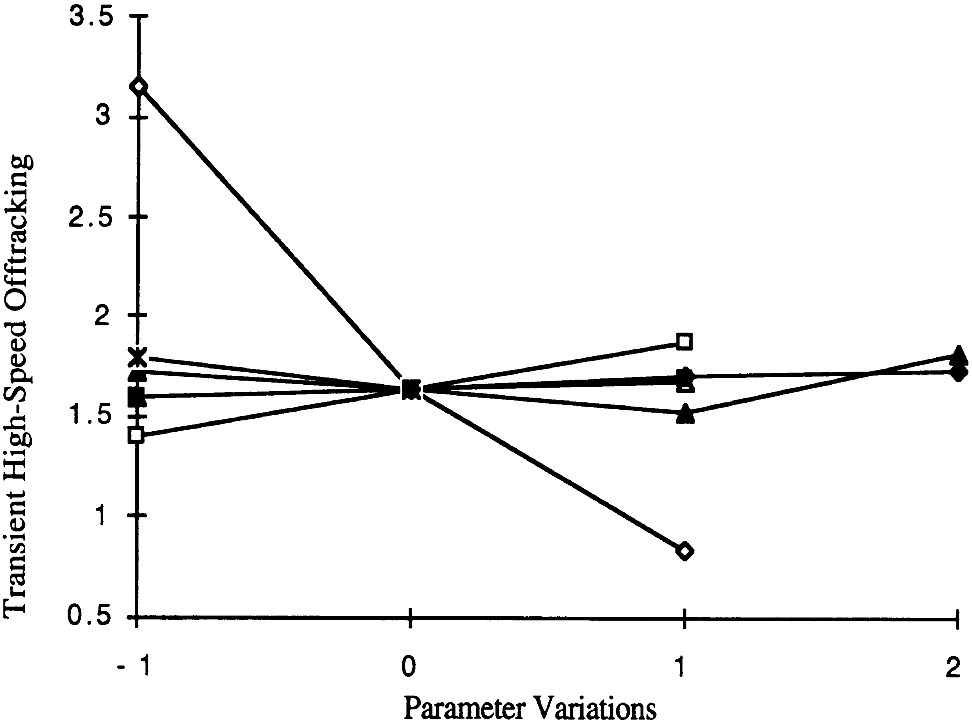


Figure C-28. Sensitivity of transient high-speed offtracking: 45'x28' seven-axle A-train double

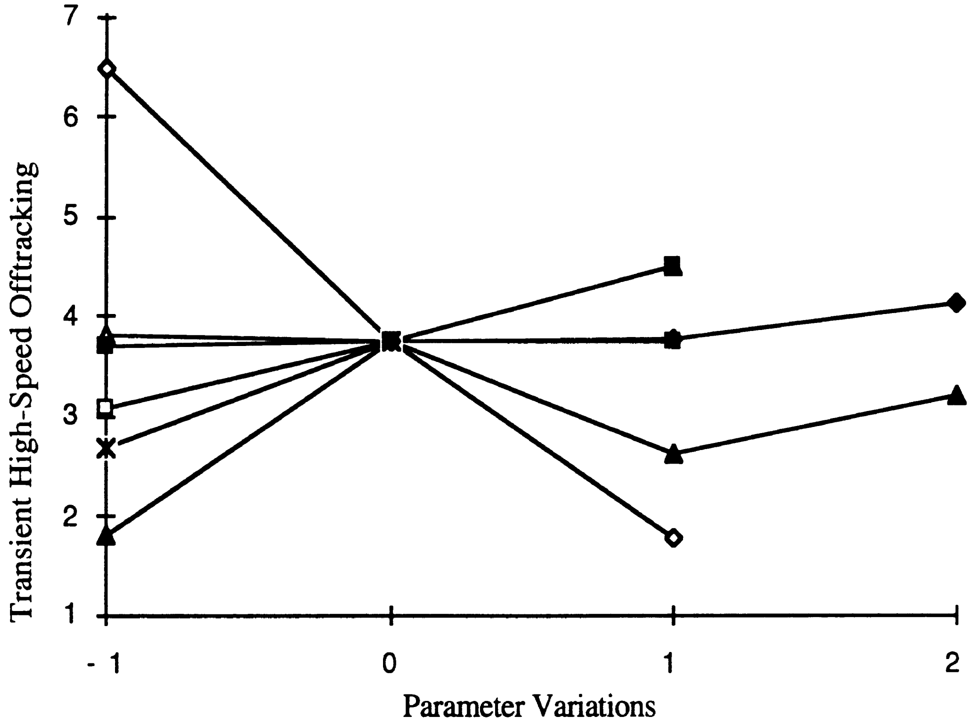


Figure C-29. Sensitivity of transient high-speed offtracking: 28'x28'x28' seven-axle A-train triple

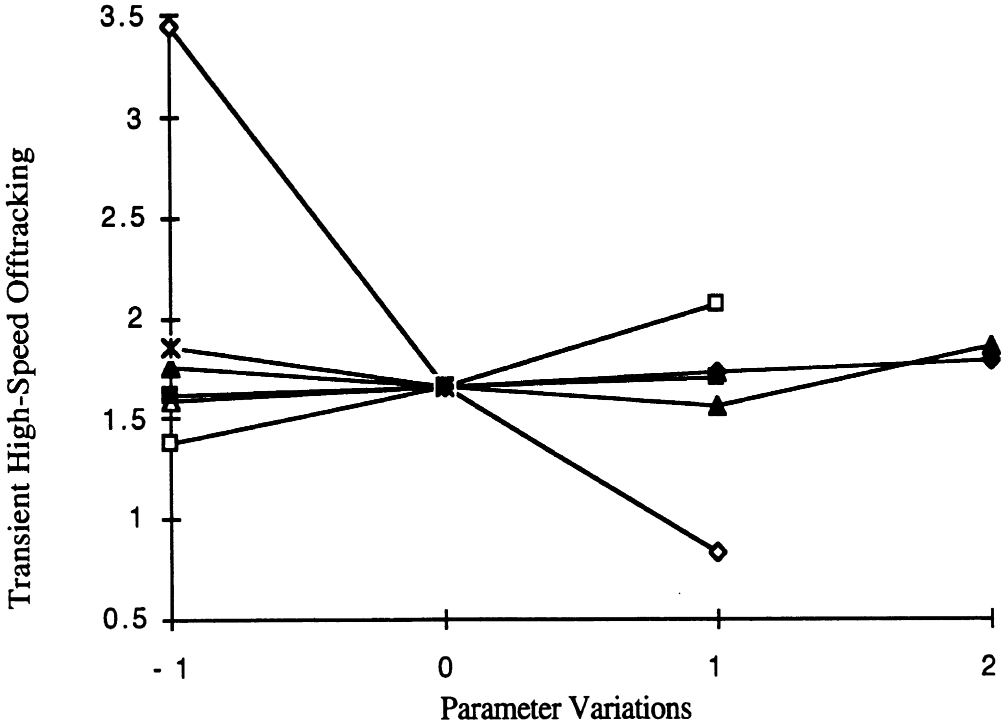


Figure C-30. Sensitivity of transient high-speed offtracking: 45'x45' eight-axle A-train double

Sensitivity Plots of Damping Ratio in the RTAC-B Maneuver

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
─□─	Payload cg height, inches	70	85	100	None
─△─	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
─◇─	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
─▲─	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
─✱─	Overall axle width, inches	96	102	None	None
─■─	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
─◆─	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

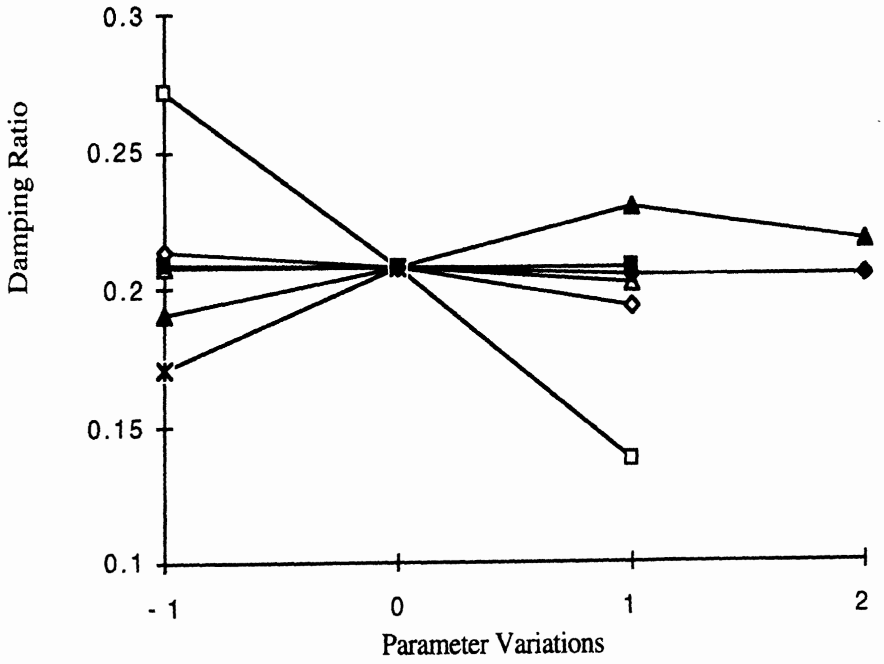


Figure C-31. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28' five-axle A-train double

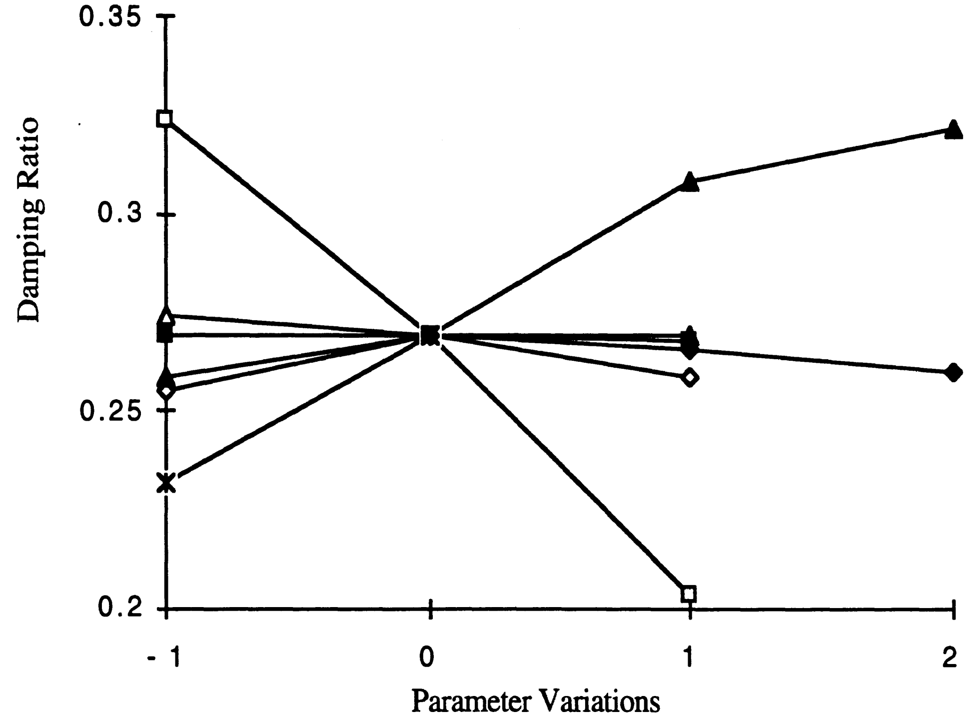


Figure C-32. Sensitivity of damping ratio in the RTAC-B maneuver: 32'x32' eight-axle A-train double

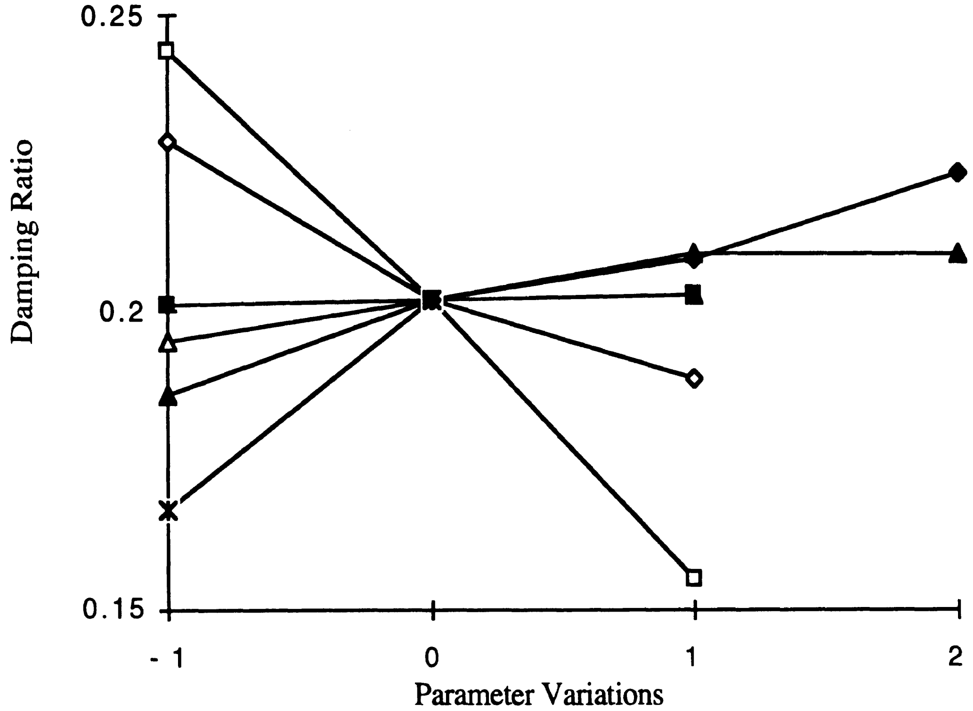


Figure C-33. Sensitivity of damping ratio in the RTAC-B maneuver: 38'x20' seven-axle A-train double

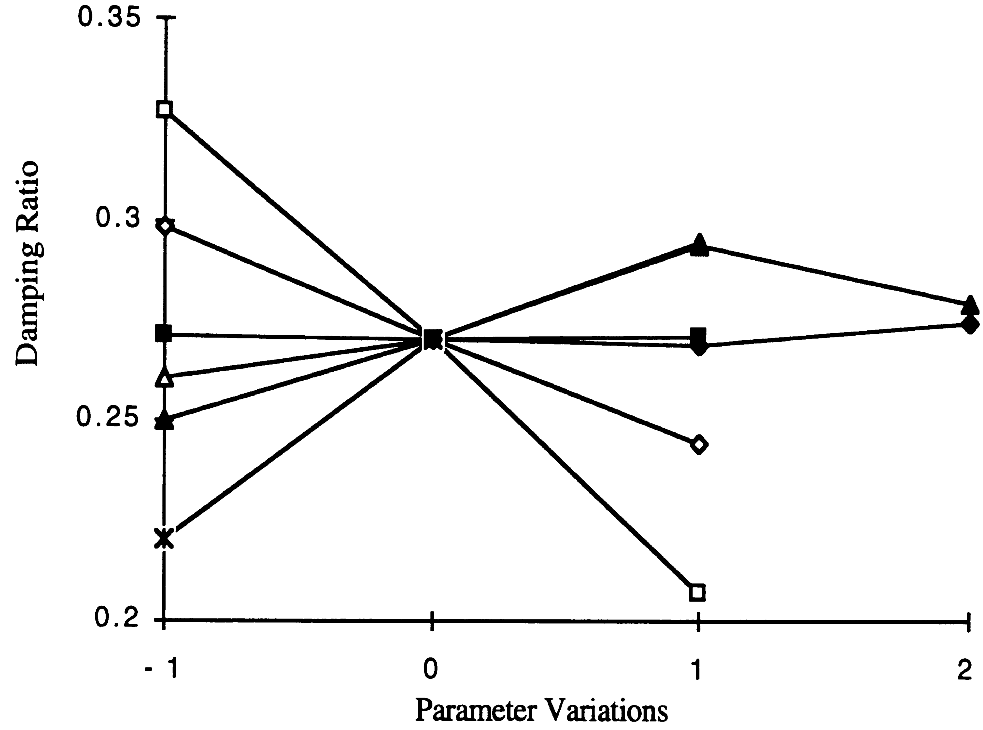


Figure C-34. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x28' seven-axle A-train double

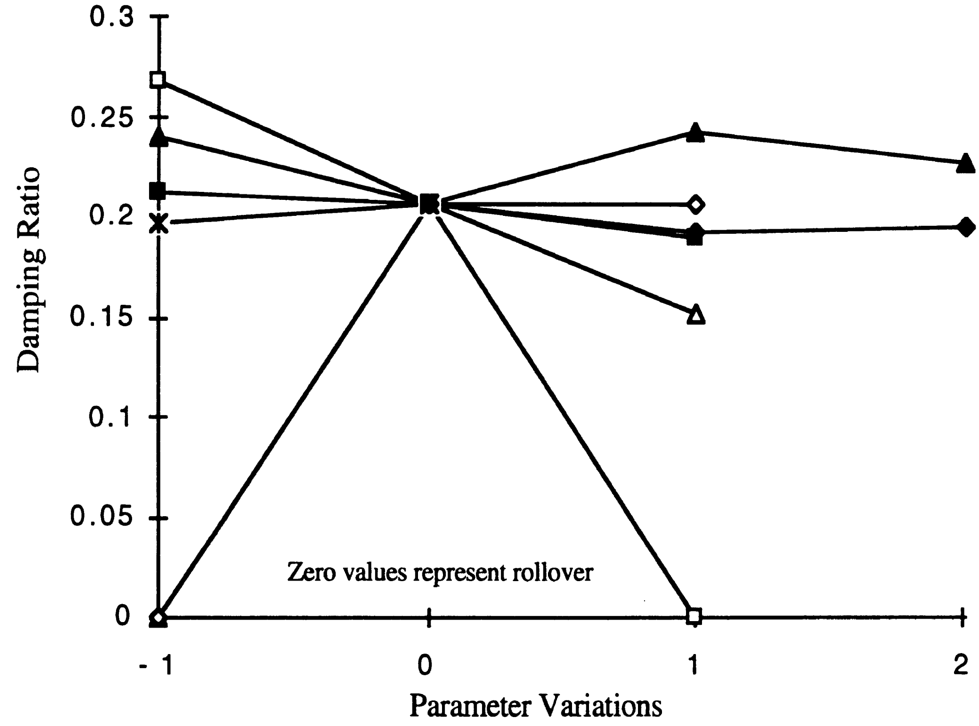


Figure C-35. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28'x28' seven-axle A-train triple

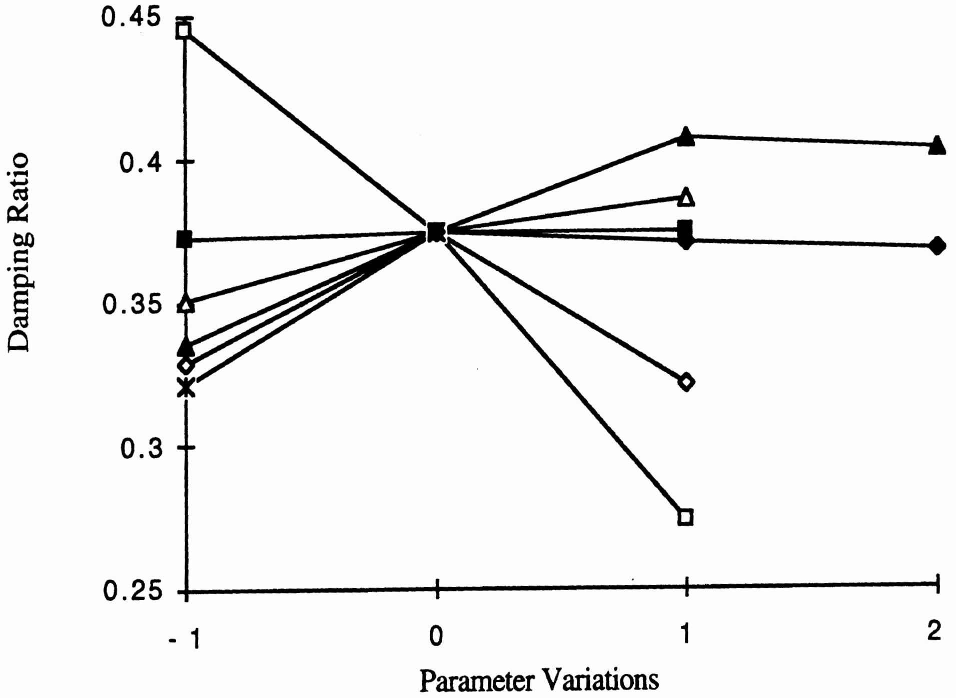


Figure C-36. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x45' eight-axle A-train double

Sensitivity Plots of Damping Ratio in the Pulse-Steer Maneuver

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

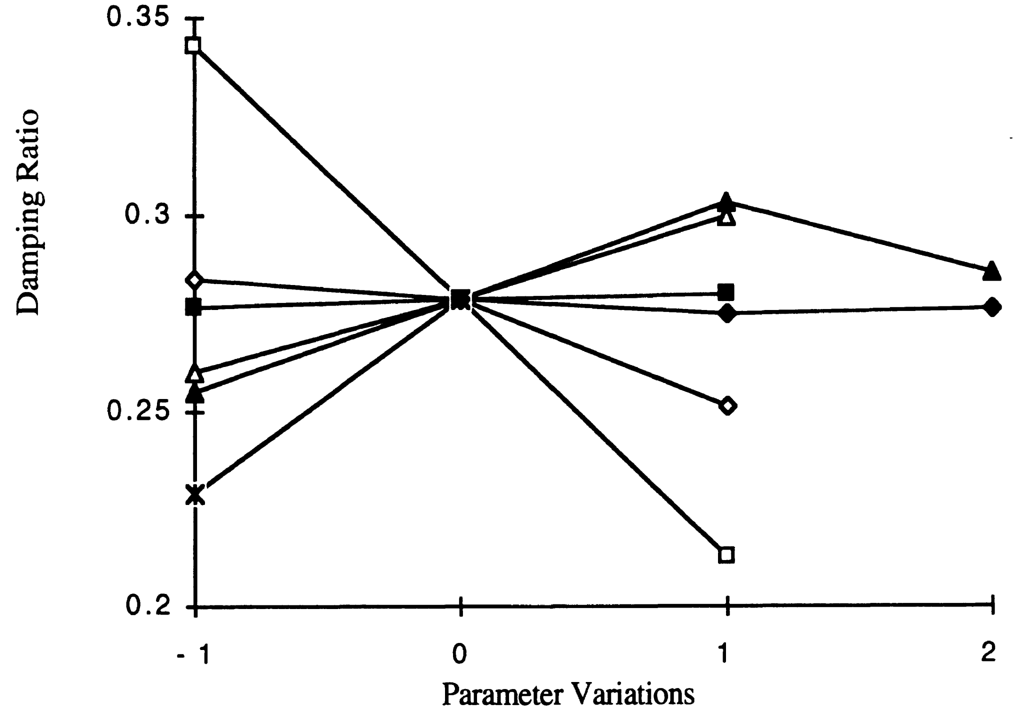


Figure C-37. Sensitivity of damping ratio in the pulse-steer maneuver: 28'x28' five-axle A-train double

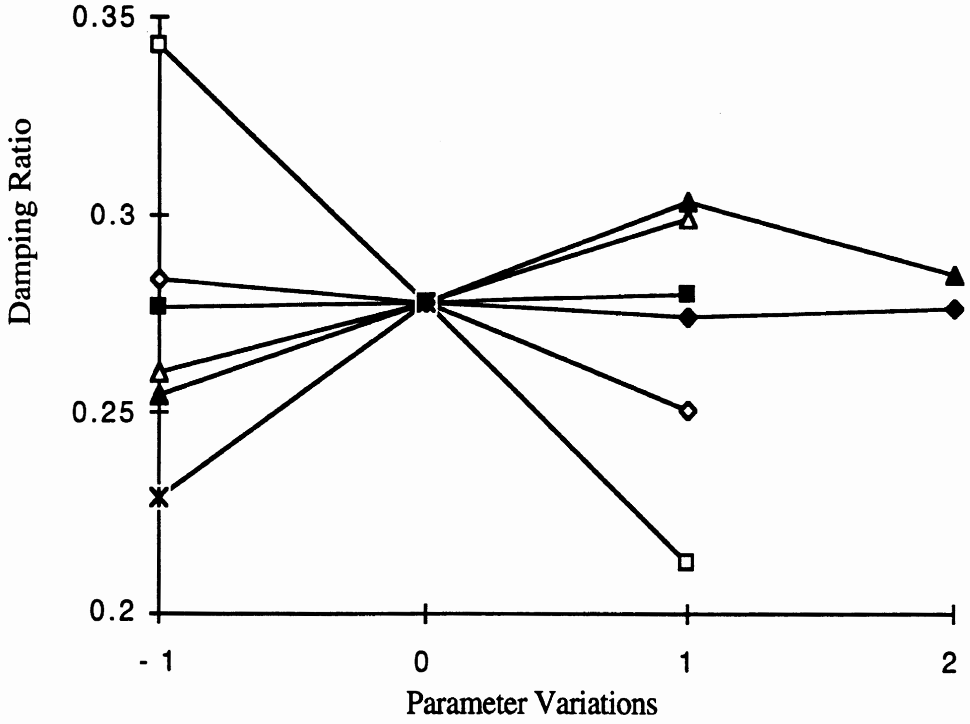


Figure C-38. Sensitivity of damping ratio in the pulse-steer maneuver: 32'x32' eight-axle A-train double

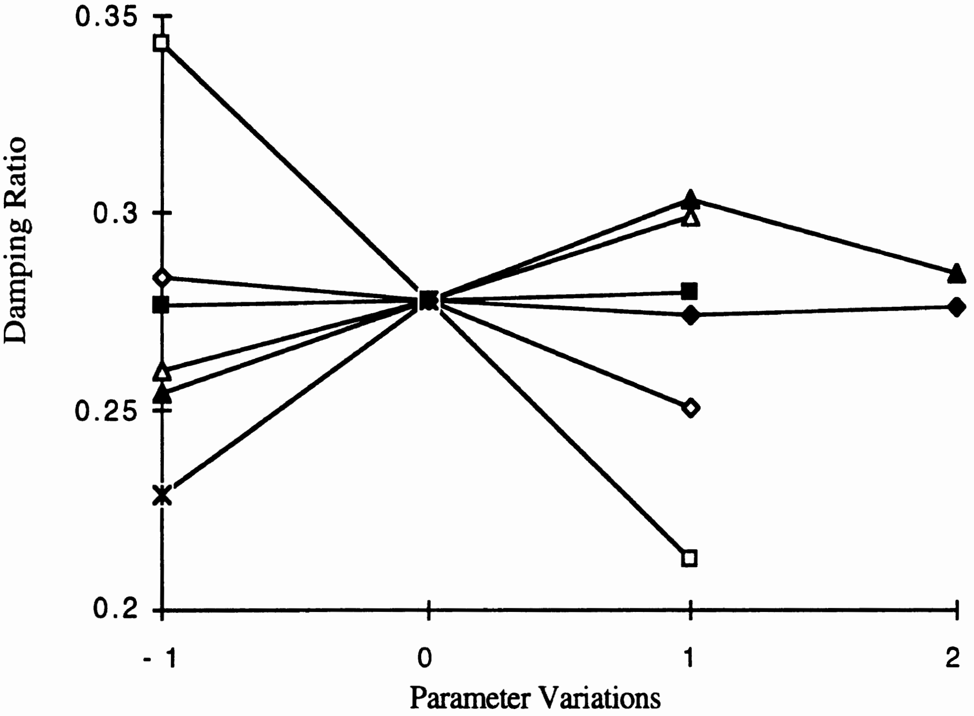


Figure C-39. Sensitivity of damping ratio in the pulse-steer maneuver: 38'x20' seven-axle A-train double

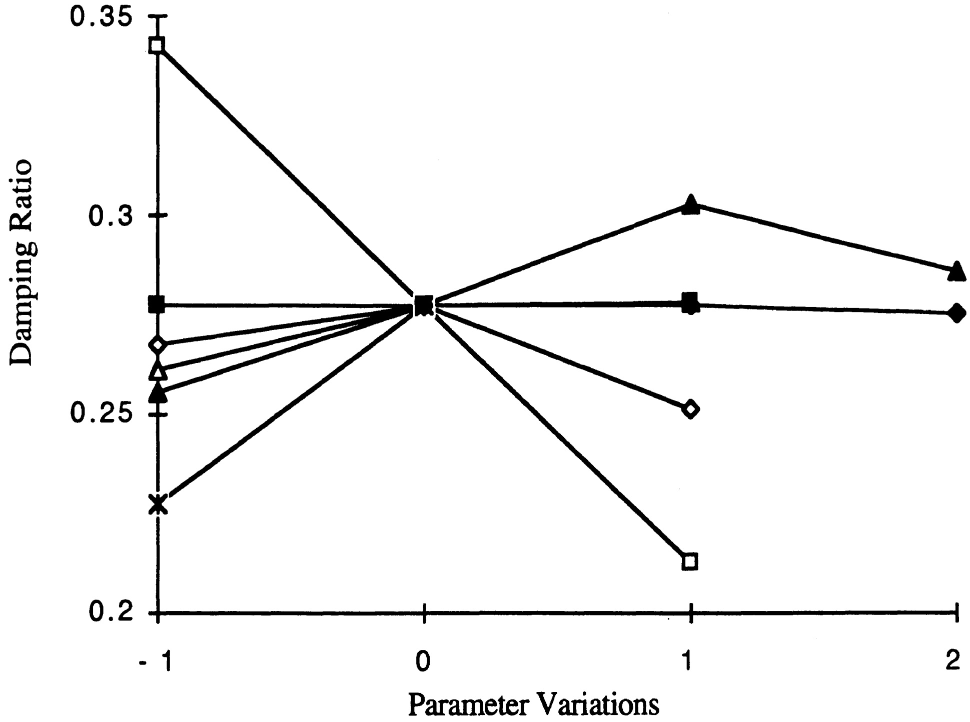


Figure C-40. Sensitivity of damping ratio in the pulse-steer maneuver: 45'x28' seven-axle A-train double

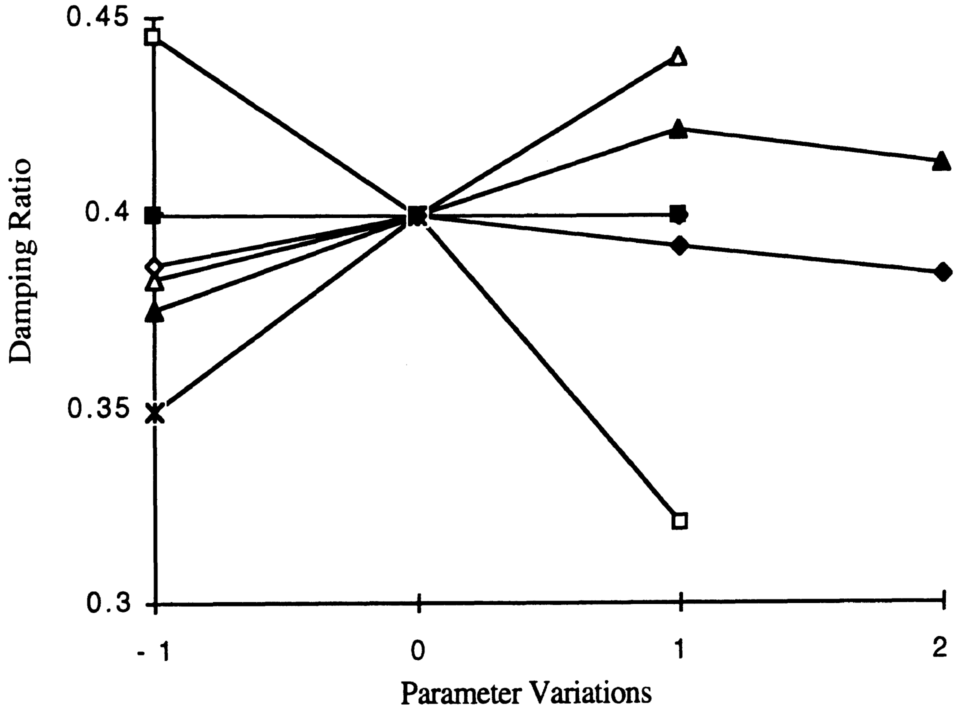


Figure C-41. Sensitivity of damping ratio in the pulse-steer maneuver: 28'x28'x28' seven-axle A-train triple

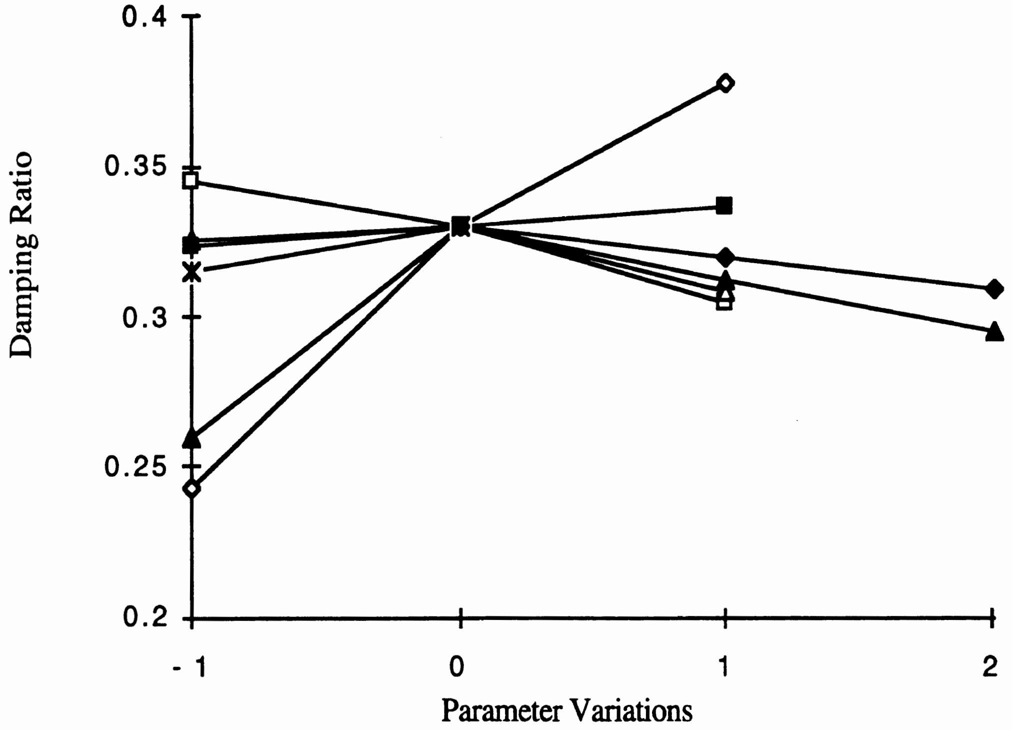


Figure C-42. Sensitivity of damping ratio in the pulse-steer maneuver: 45'x45' eight-axle A-train double

SENSITIVITY STUDY RESULTS FOR THE 2C1-DOLLY

Table C-3. Performance measures obtained with the 2C1-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio
28x28bas2C1	0.427	-1.074	1.716	0.464	1.551	0.231
28x28do12C1	0.425	-1.101	1.716	0.456	1.572	0.226
28x28do22C1	0.424	-1.121	1.710	0.450	1.584	0.218
28x28pl12C1	0.370	-1.119	1.848	0.573	1.772	0.046
28x28pl22C1	0.527	-1.048	1.627	0.368	1.366	0.299
28x28pl32C1	0.429	-1.074	1.754	0.464	1.718	0.243
28x28pl42C1	0.425	-1.074	1.712	0.458	1.431	0.252
28x28se12C1	0.425	-1.092	1.716	0.458	1.563	0.227
28x28se22C1	0.428	-1.056	1.718	0.468	1.535	0.234
28x28sp22C1	0.419	-1.077	1.762	0.478	1.602	0.211
28x28sp32C1	0.432	-1.071	1.667	0.443	1.488	0.247
28x28ss42C1	0.458	-1.172	1.739	0.458	1.693	0.284
28x28su12C1	0.407	-1.096	1.799	0.522	1.676	0.215
28x28tl12C1	0.428	-0.766	1.650	0.434	0.995	0.206
28x28tl22C1	0.435	-1.637	1.872	0.460	2.574	0.386
32x32bas2C1	0.442	-1.142	1.607	0.405	1.421	0.293
32x32do12C1	0.440	-1.166	1.611	0.401	1.442	0.284
32x32do22C1	0.440	-1.191	1.610	0.395	1.457	0.273
32x32pl12C1	0.376	-1.172	1.697	0.498	1.553	0.190
32x32pl22C1	0.532	-1.121	1.527	0.325	1.303	0.355
32x32pl32C1	0.442	-1.142	1.607	0.405	1.421	0.293
32x32pl42C1	0.443	-1.143	1.572	0.399	1.275	0.285
32x32se12C1	0.441	-1.157	1.610	0.402	1.435	0.284
32x32se22C1	0.442	-1.121	1.608	0.409	1.404	0.302
32x32sp22C1	0.435	-1.145	1.633	0.416	1.450	0.270
32x32sp32C1	0.443	-1.136	1.562	0.388	1.370	0.334
32x32ss42C1	0.458	-1.225	1.597	0.393	1.494	0.284
32x32su12C1	0.413	-1.158	1.667	0.454	1.494	0.243
32x32tl12C1	0.445	-0.736	1.476	0.377	0.817	0.355
32x32tl22C1	0.449	-1.668	1.753	0.406	2.257	0.443
38x20bas2C1	0.434	-1.028	1.729	0.415	1.269	0.264
38x20do12C1	0.434	-1.058	1.745	0.410	1.290	0.257
38x20do22C1	0.434	-1.089	1.756	0.406	1.306	0.248
38x20pl12C1	0.364	-1.056	1.907	0.524	1.467	0.192
38x20pl22C1	0.549	-1.023	1.591	0.326	1.124	0.313
38x20pl32C1	0.434	-1.027	1.690	0.413	1.340	0.232
38x20pl42C1	0.433	-1.028	1.757	0.412	1.157	0.225
38x20se12C1	0.434	-1.045	1.737	0.412	1.281	0.258
38x20se22C1	0.434	-1.011	1.720	0.418	1.256	0.271
38x20sp22C1	0.423	-1.031	1.775	0.428	1.311	0.242
38x20sp32C1	0.439	-1.026	1.648	0.394	1.201	0.320
38x20ss42C1	0.451	-1.124	1.727	0.406	1.365	0.250
38x20su12C1	0.409	-1.036	1.827	0.465	1.366	0.237
38x20tl12C1	0.431	-0.664	1.628	0.387	0.733	0.195
38x20tl22C1	0.441	-1.581	1.857	0.419	2.072	0.201
45x28bas2C1	0.438	-1.066	1.444	0.343	1.029	0.273
45x28do12C1	0.438	-1.085	1.446	0.337	1.040	0.262
45x28do22C1	0.439	-1.105	1.445	0.332	1.049	0.319
45x28pl12C1	0.370	-1.103	1.555	0.424	1.221	0.223
45x28pl22C1	0.581	-1.044	1.361	0.272	0.926	0.227
45x28pl32C1	0.439	-1.066	1.438	0.334	1.192	0.234
45x28pl42C1	0.438	-1.065	1.422	0.344	0.932	0.185
45x28se12C1	0.438	-1.078	1.445	0.339	1.036	0.264
45x28se22C1	0.438	-1.049	1.442	0.346	1.025	0.286
45x28sp22C1	0.430	-1.071	1.469	0.352	1.070	0.309
45x28sp32C1	0.444	-1.062	1.403	0.327	0.979	0.269
45x28ss42C1	0.454	-1.184	1.458	0.335	1.115	0.206
45x28su12C1	0.412	-1.084	1.504	0.382	1.117	0.262
45x28tl12C1	0.437	-0.635	1.297	0.326	0.557	0.217
45x28tl22C1	0.446	-1.729	1.595	0.336	1.880	0.323
3X28BAS2C1	0.426	-1.625	2.086	0.365	2.759	0.311
3X28DO12C1	0.430	-1.681	2.088	0.357	3.093	0.376
3X28DO22C1	0.432	-1.742	2.057	0.347	3.119	0.368
3X28PL12C1	0.363	-1.692	2.134	0.435	3.266	0.349
3X28PL22C1	0.495	-1.585	1.985	0.301	2.195	0.403
3X28PL32C1	0.427	-1.624	2.123	0.361	3.256	0.320
3X28PL42C1	0.427	-1.626	2.101	0.367	2.554	0.373
3X28SE12C1	0.427	-1.657	2.063	0.359	2.978	0.379
3X28SE22C1	0.426	-1.597	2.102	0.376	2.538	0.310
3X28SP22C1	0.414	-1.645	2.257	0.383	3.024	0.367
3X28SP32C1	0.427	-1.620	2.056	0.351	2.406	0.393
3X28SS42C1	0.438	-1.456	2.019	0.381	2.662	0.334
3X28SU12C1	0.403	-1.659	2.134	0.407	3.164	0.268
3X28TI12C1	0.431	-1.210	2.063	0.360	1.387	0.309
3X28TI22C1	0.430	-2.376	2.210	0.377	3.464	0.275

Sensitivity Plots of Static Rollover Threshold

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

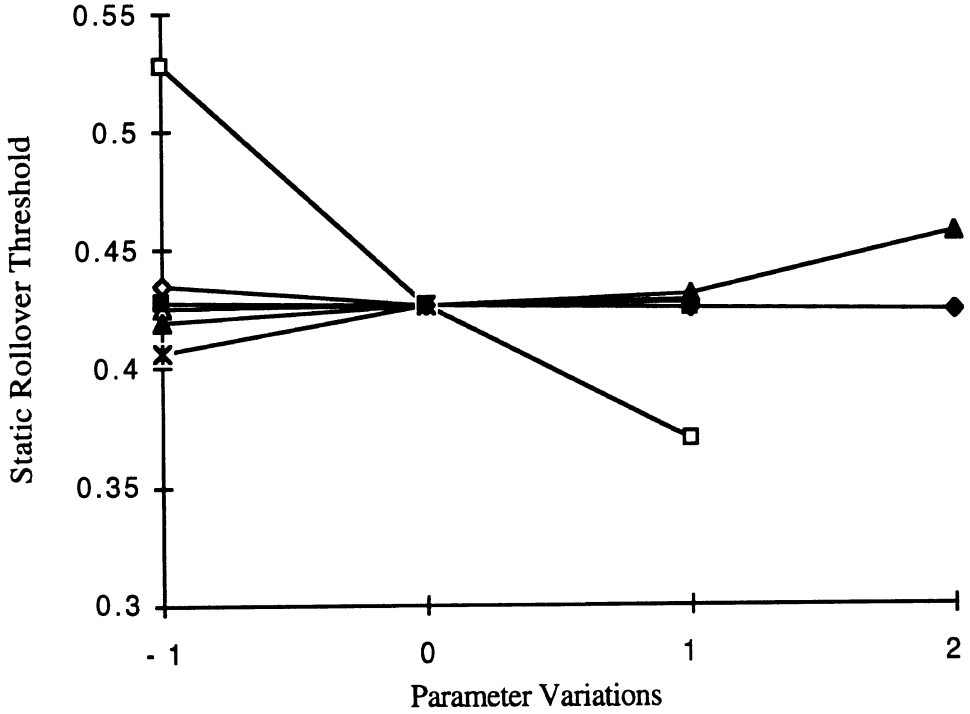


Figure C-43. Sensitivity of static rollover threshold: 28'x28' five-axle 2C1-train double

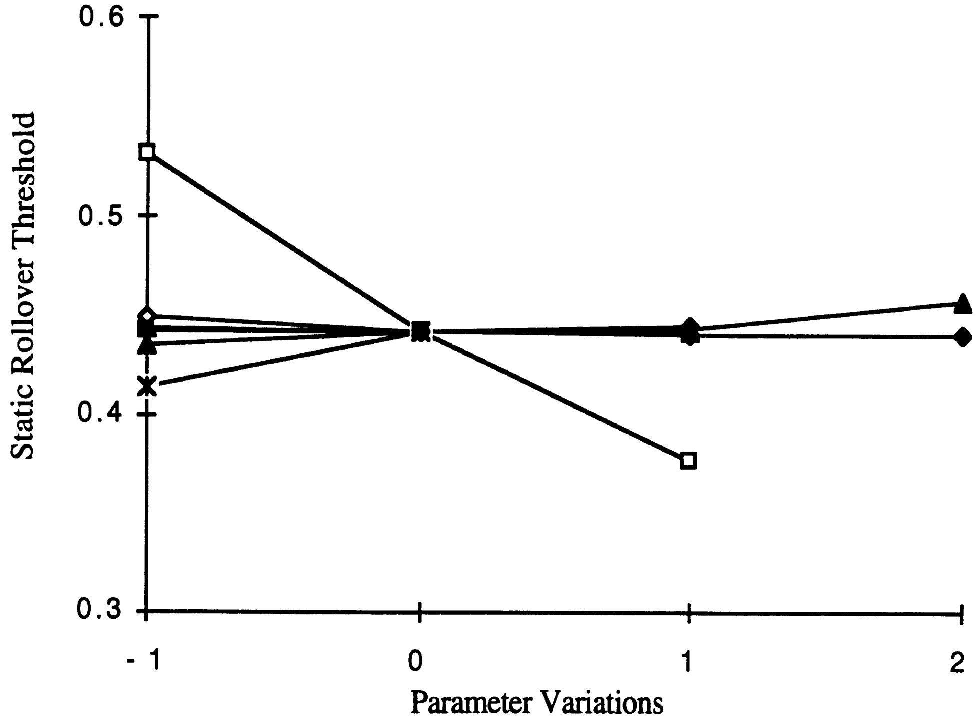


Figure C-44. Sensitivity of static rollover threshold: 32'x32' eight-axle 2C1-train double

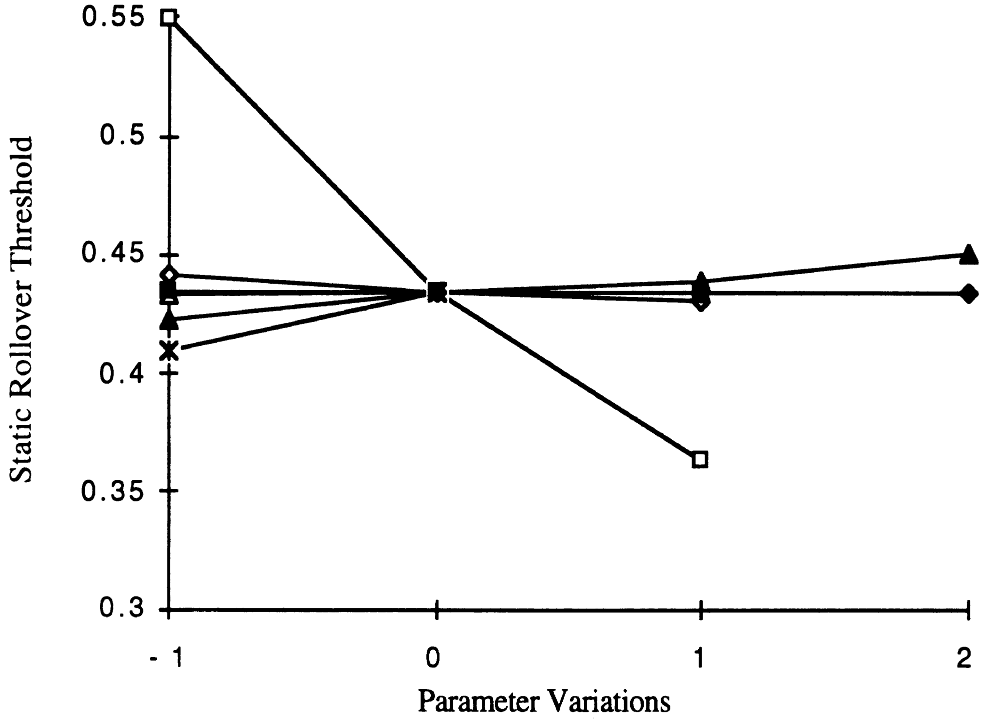


Figure C-45. Sensitivity of static rollover threshold: 38'x20' seven-axle 2C1-train double

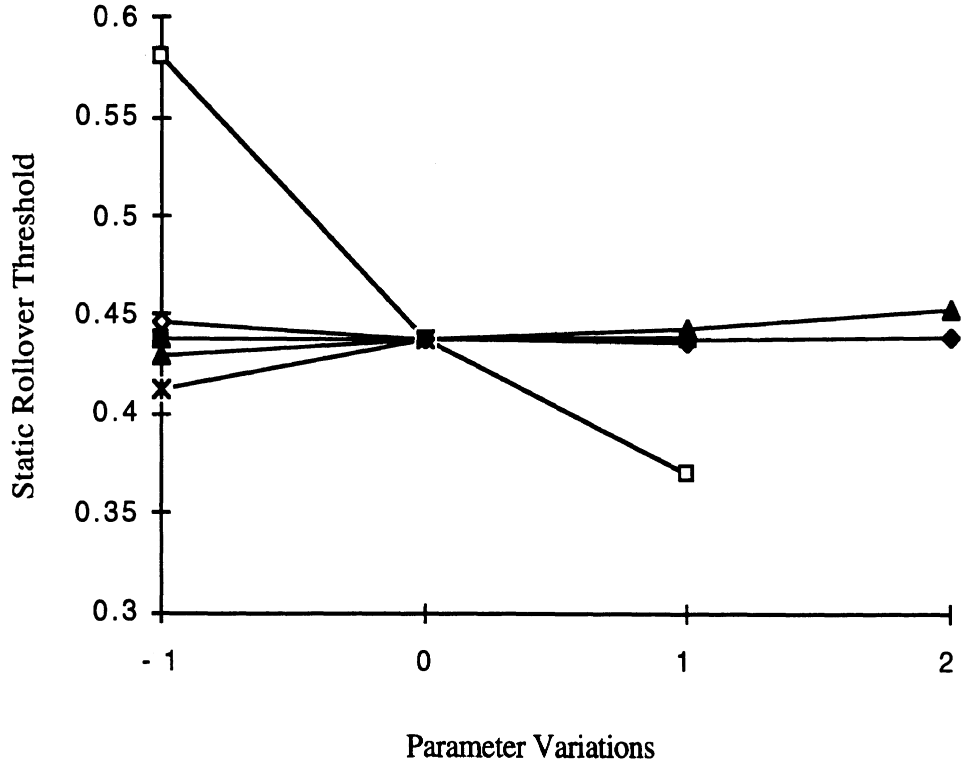


Figure C-46. Sensitivity of static rollover threshold: 45'x28' seven-axle 2C1-train double

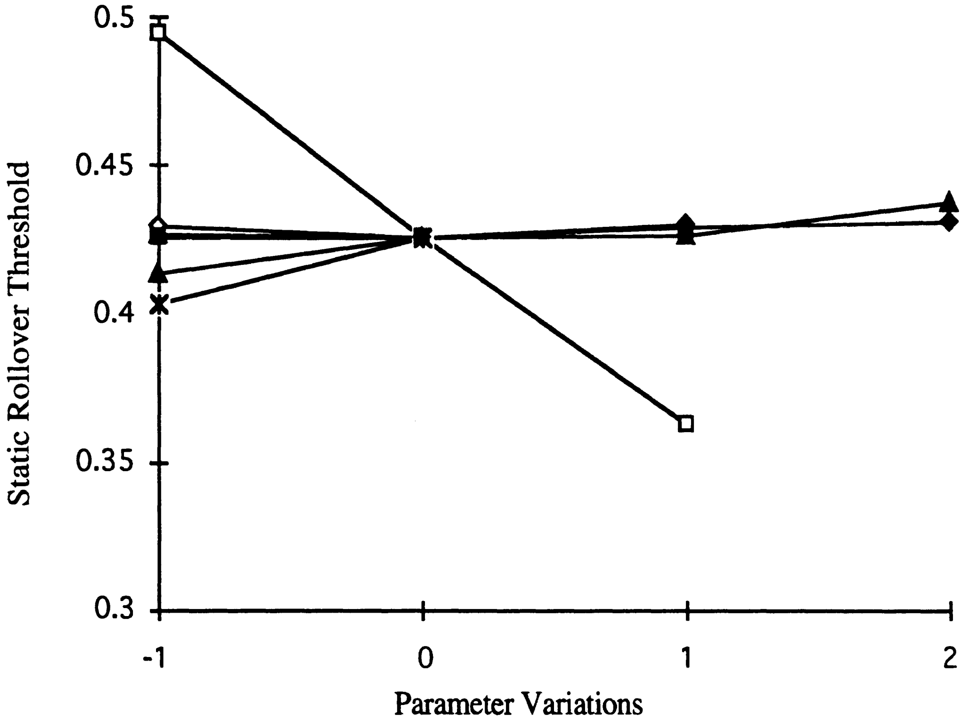


Figure C-47. Sensitivity of static rollover threshold: 28'x28'x28' seven-axle 2C1-train triple

Sensitivity Plots of High-Speed Steady-State Offtracking

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

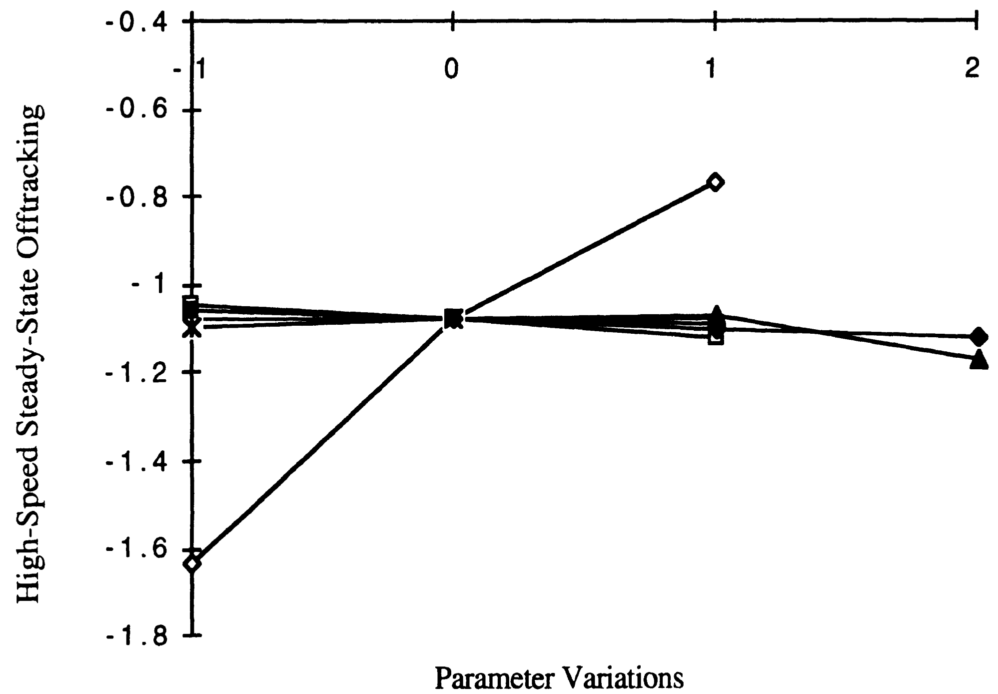


Figure C-48. Sensitivity of high-speed steady-state offtracking: 28'x28' five-axle 2C1-train double

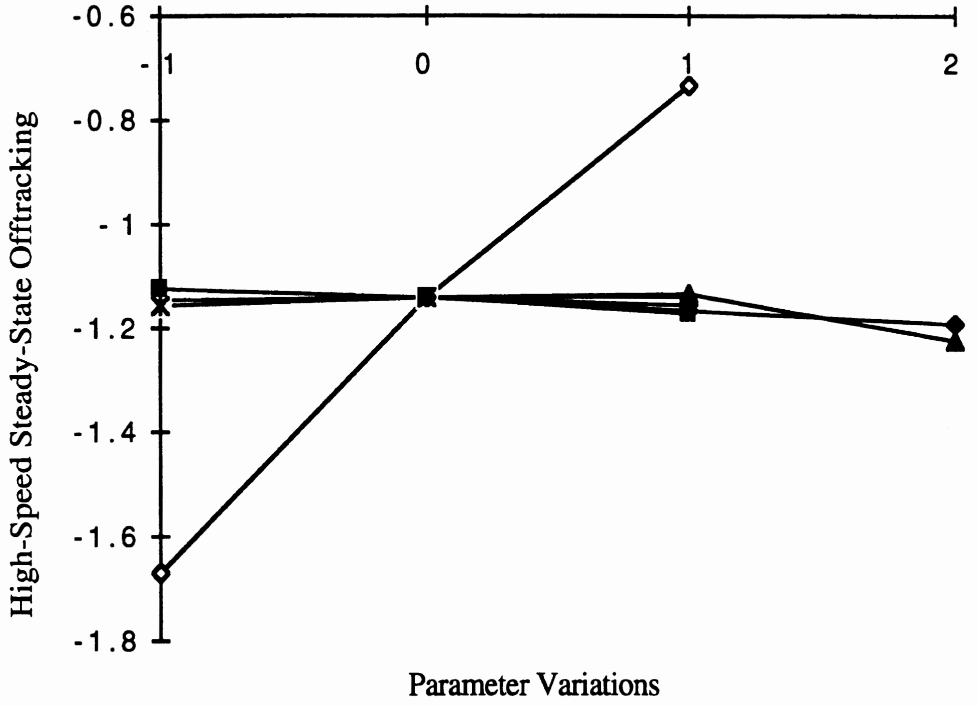


Figure C-49. Sensitivity of high-speed steady-state offtracking: 32'x32' eight-axle 2C1-train double

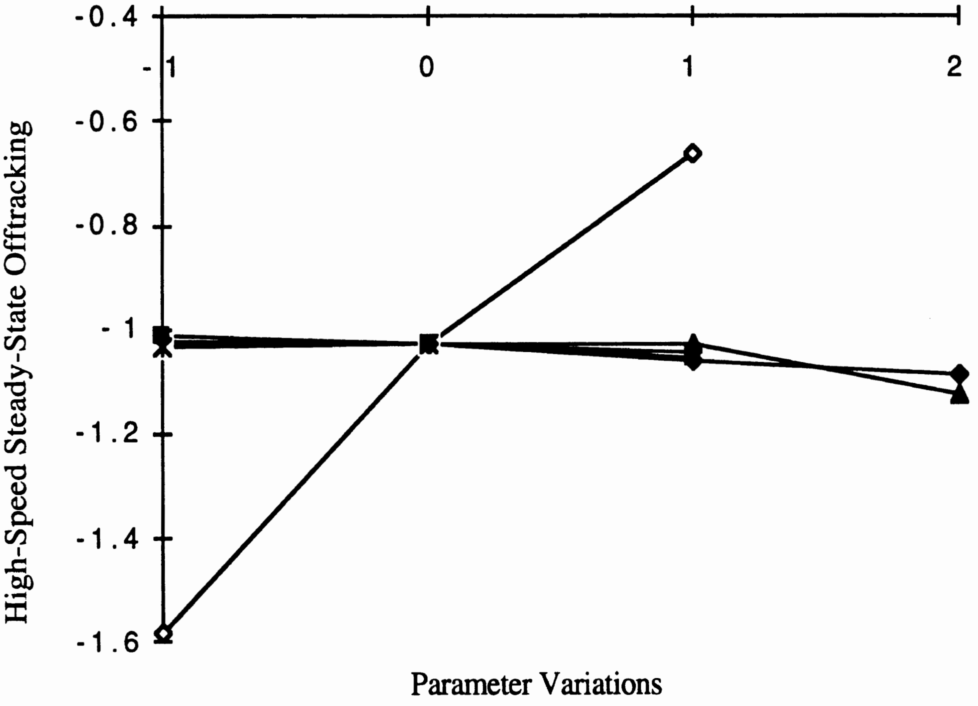


Figure C-50. Sensitivity of high-speed steady-state offtracking: 38'x20' seven-axle 2C1-train double

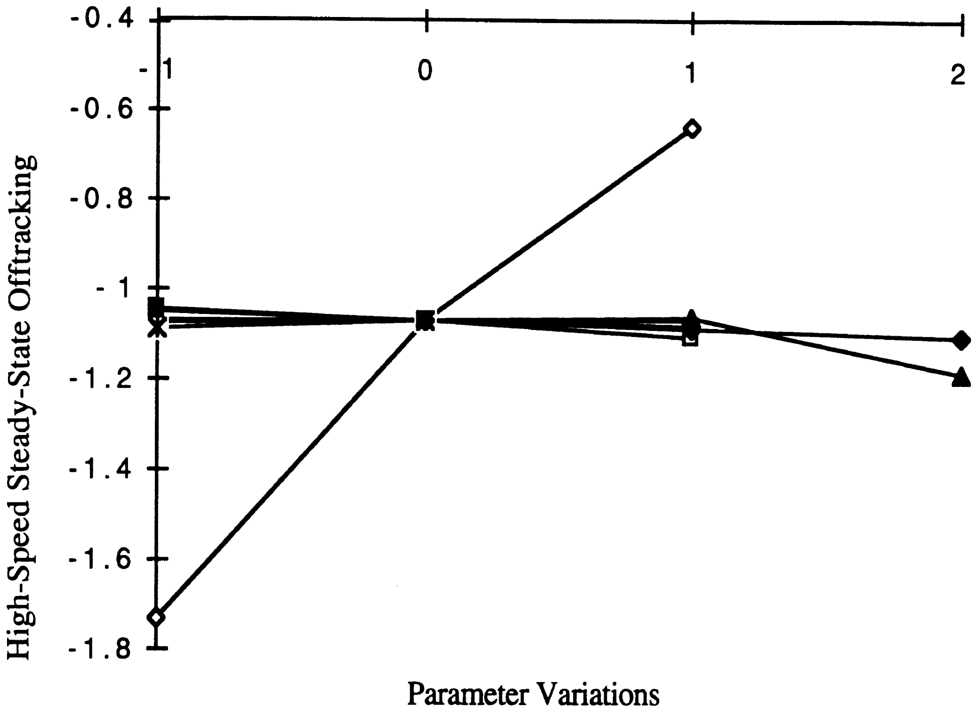


Figure C-51. Sensitivity of high-speed steady-state offtracking: 45'x28' seven-axle 2C1-train double

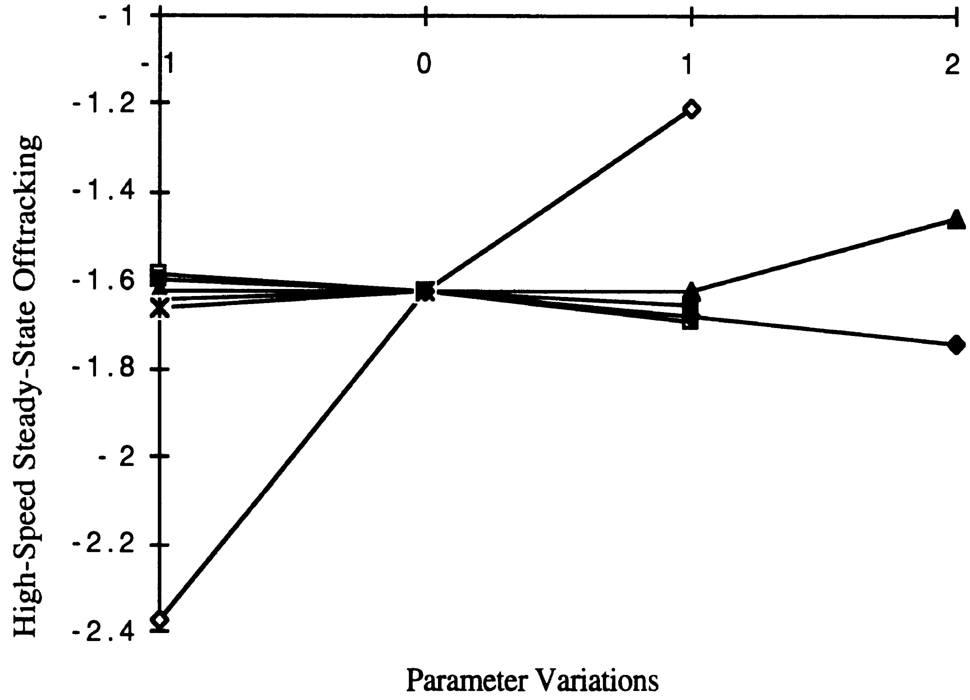


Figure C-52. Sensitivity of high-speed steady-state offtracking: 28'x28'x28' seven-axle 2C1-train triple

Sensitivity Plots of Rearward Amplification

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

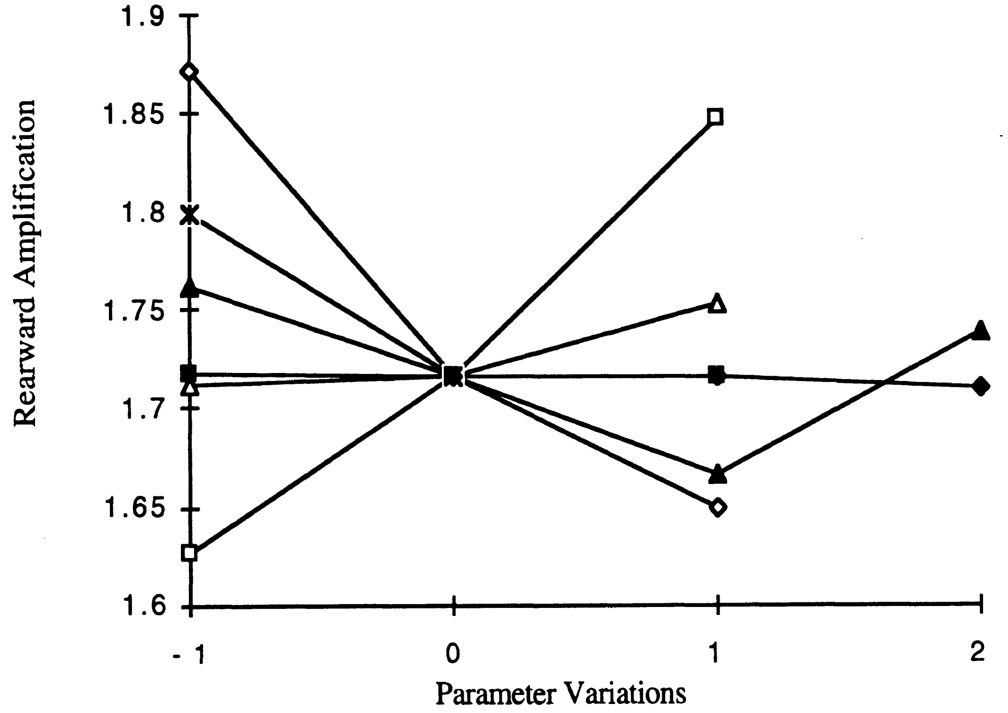


Figure C-53. Sensitivity of rearward amplification: 28'x28' five-axle 2C1-train double

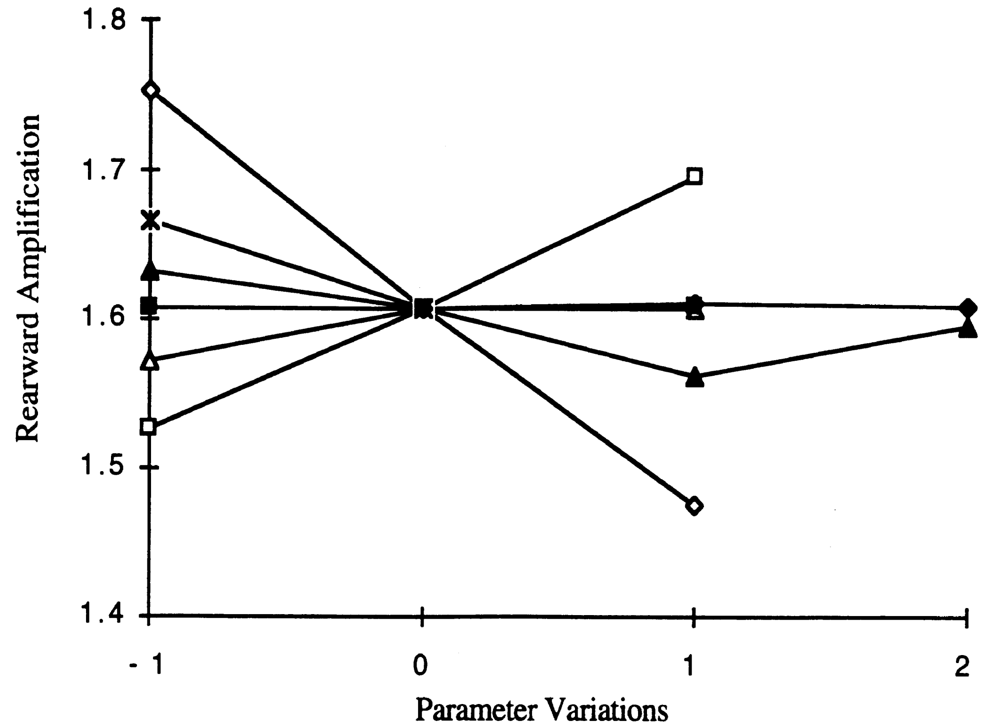


Figure C-54. Sensitivity of rearward amplification: 32'x32' eight-axle 2C1-train double

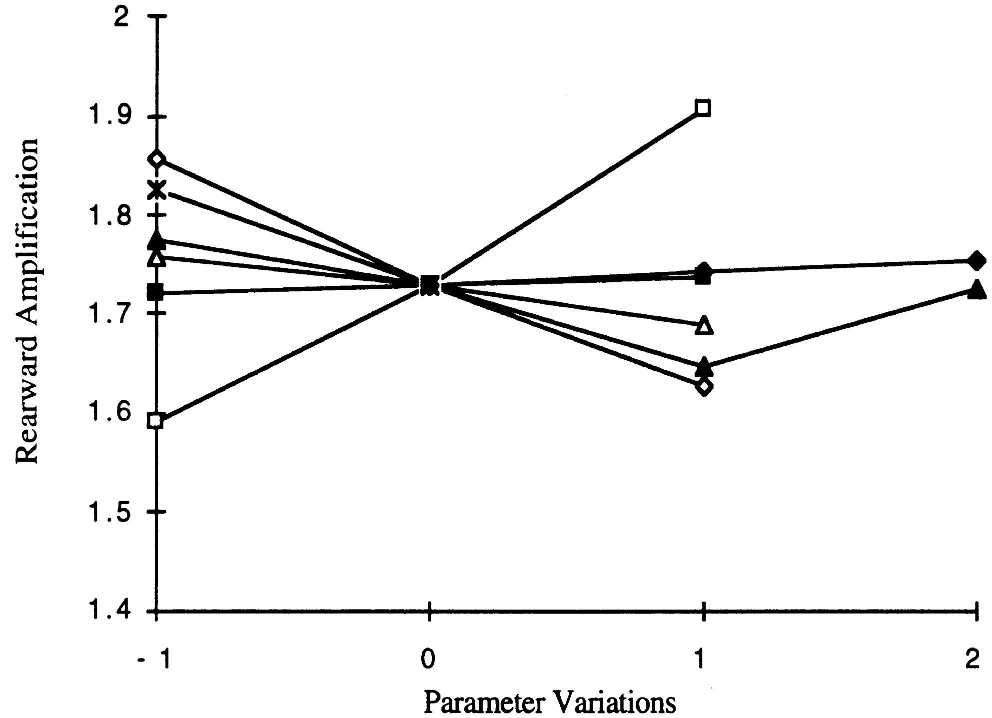


Figure C-55. Sensitivity of rearward amplification: 38'x20' seven-axle 2C1-train double

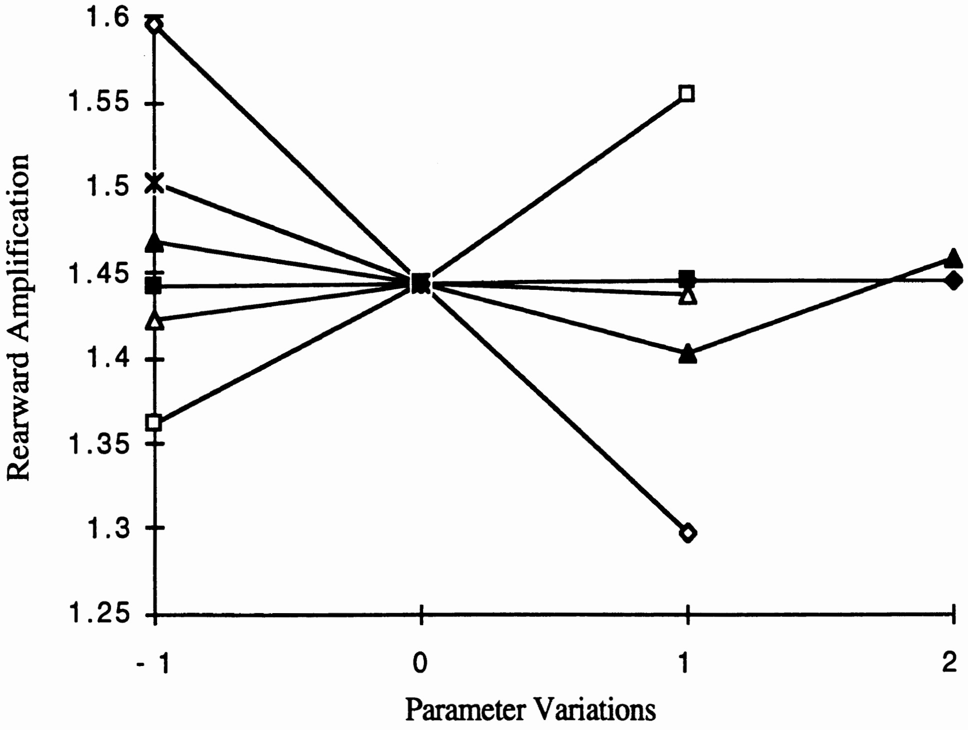


Figure C-56. Sensitivity of rearward amplification: 45'x28' seven-axle 2C1-train double

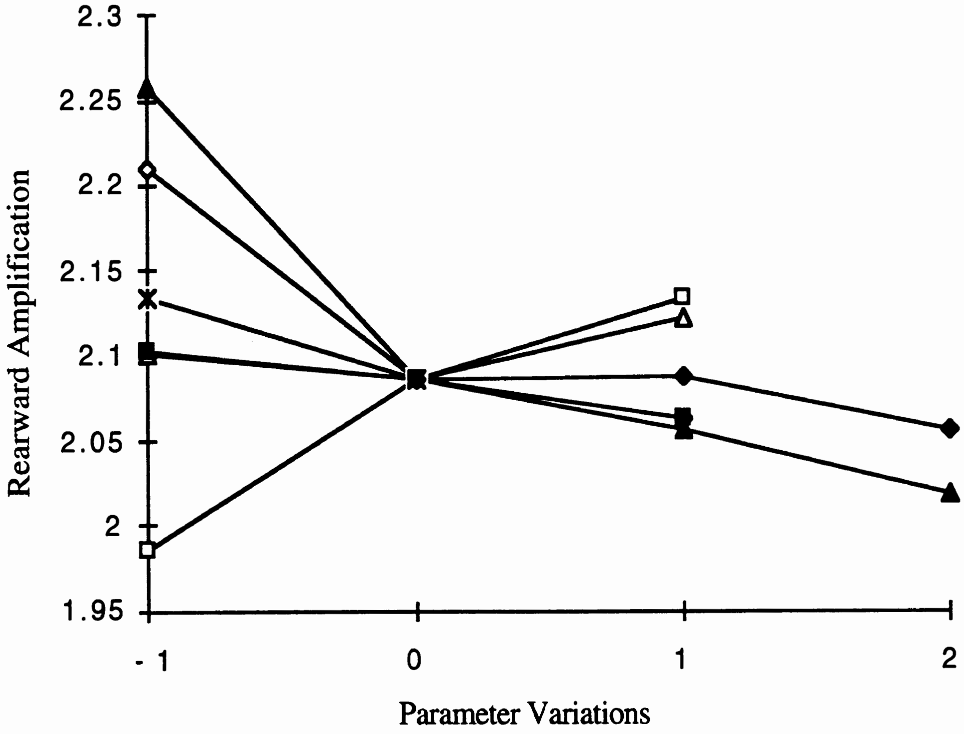


Figure C-57. Sensitivity of rearward amplification: 28'x28'x28' seven-axle 2C1-train triple

Sensitivity Plots of Dynamic-Load-Transfer Ratio

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✳	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

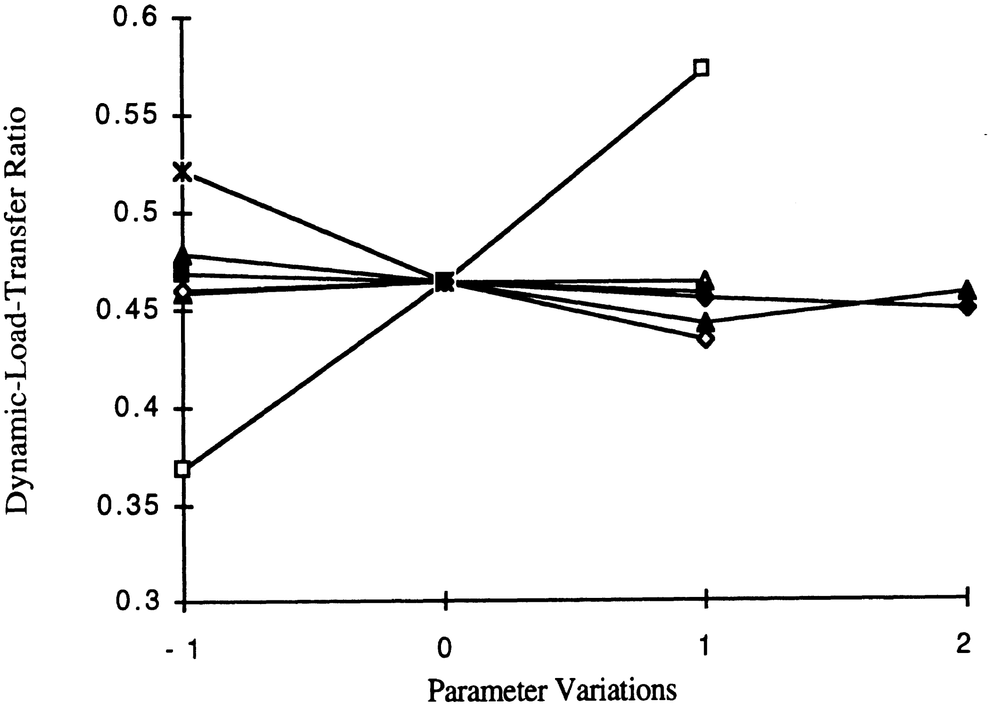


Figure C-58. Sensitivity of dynamic-load-transfer ratio: 28'x28' five-axle 2C1-train double

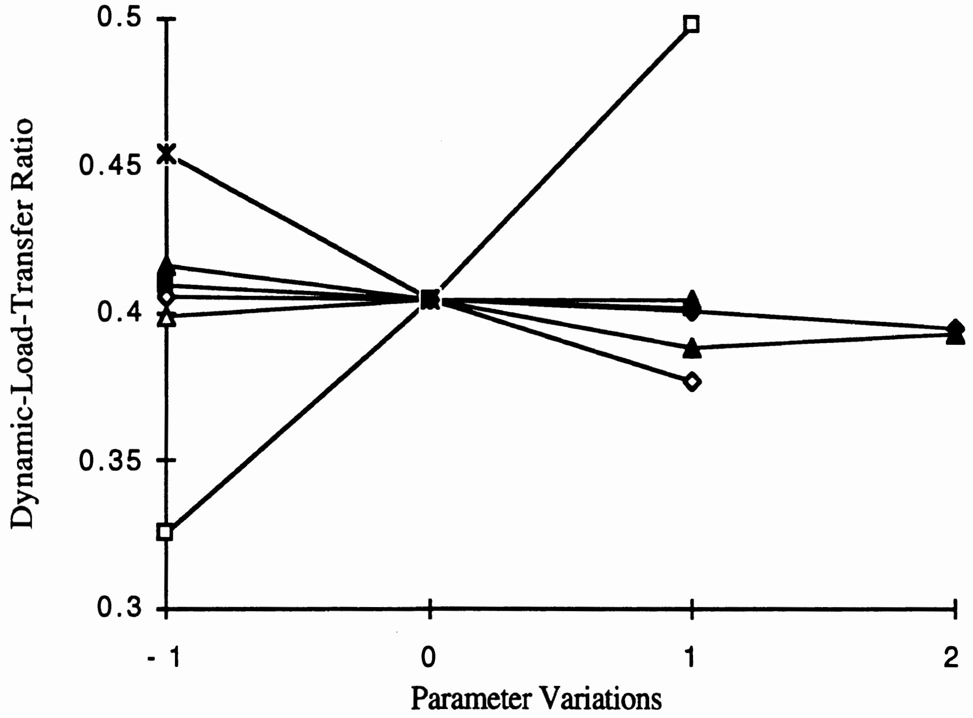


Figure C-59. Sensitivity of dynamic-load-transfer ratio: 32'x32' eight-axle 2C1-train double

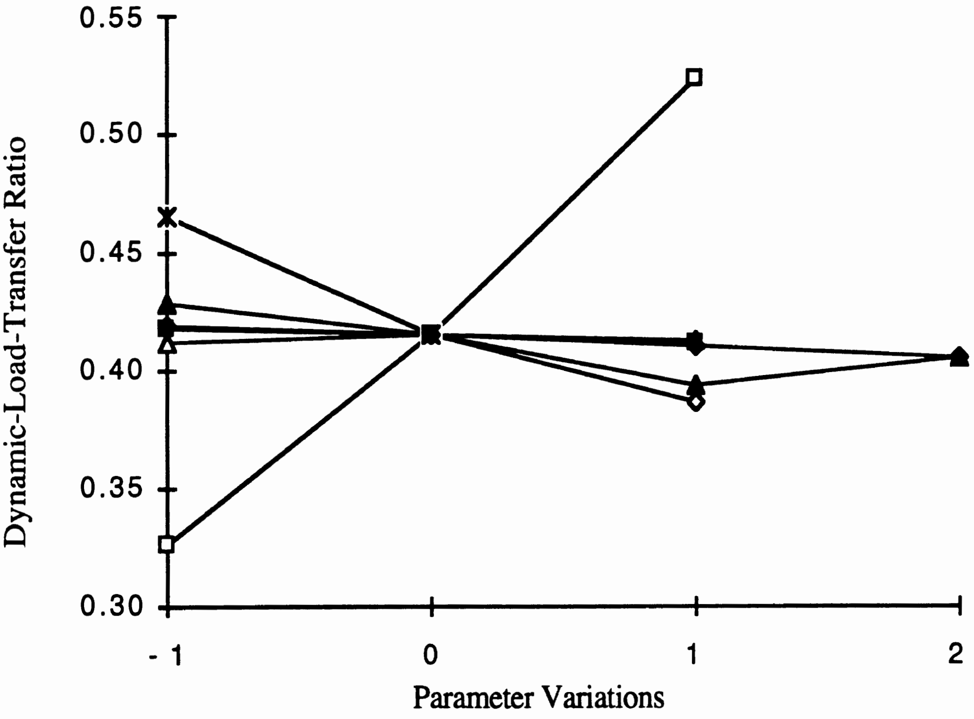


Figure C-60. Sensitivity of dynamic-load-transfer ratio: 38'x20' seven-axle 2C1-train double

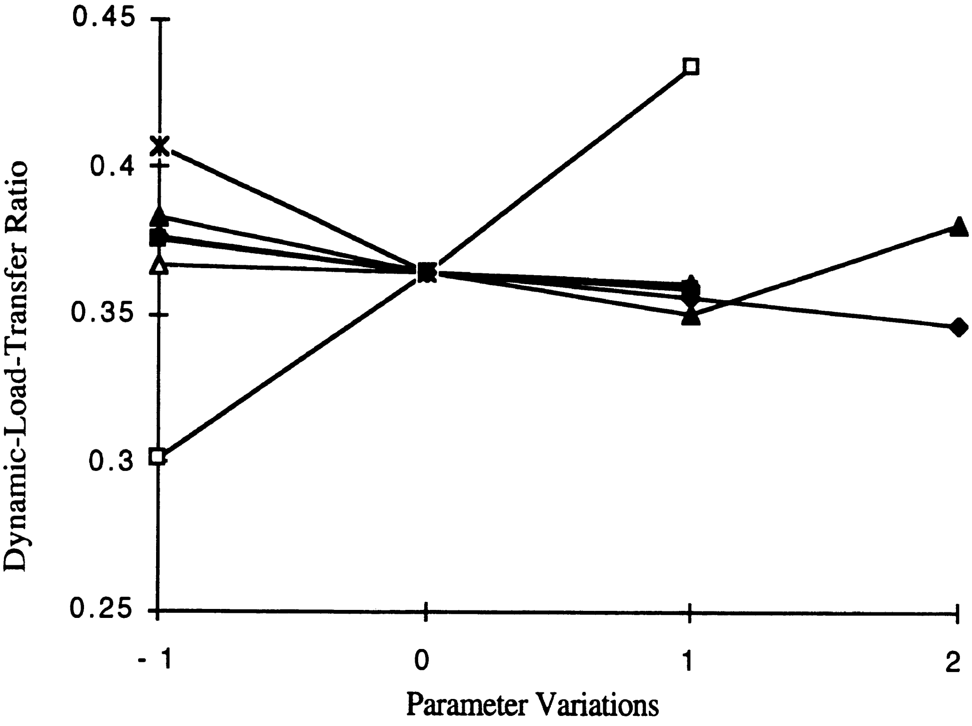


Figure C-61. Sensitivity of dynamic-load-transfer ratio: 45'x28' seven-axle 2C1-train double

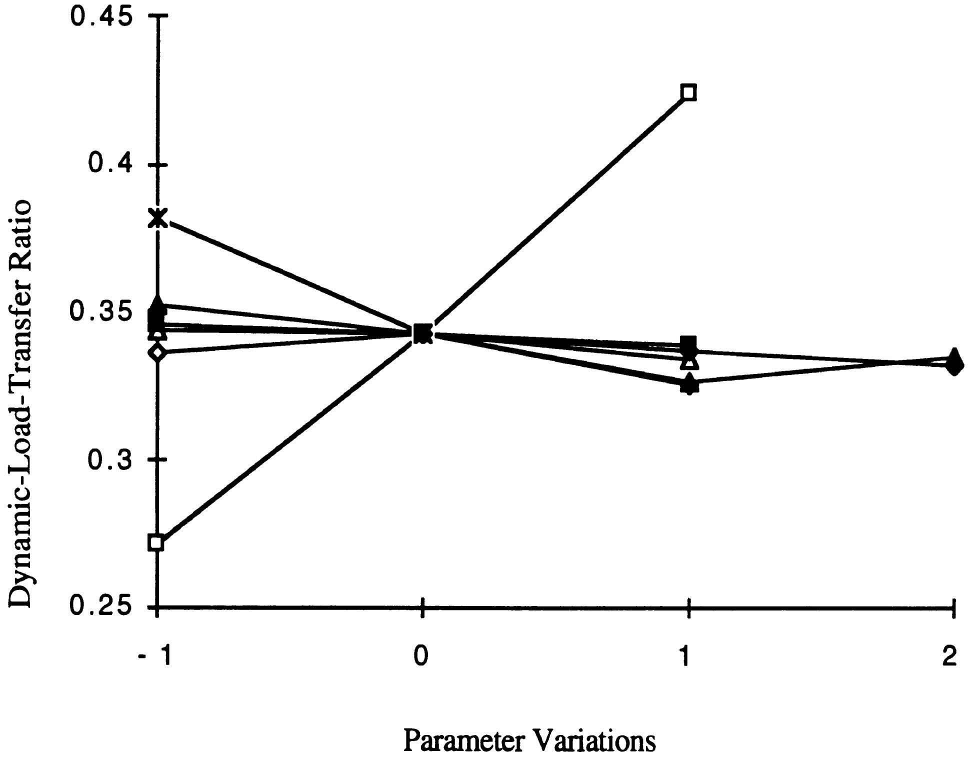


Figure C-62. Sensitivity of dynamic-load-transfer ratio: 28'x28'x28' seven-axle 2C1-train triple

Sensitivity Plots of Transient High-Speed Offtracking

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

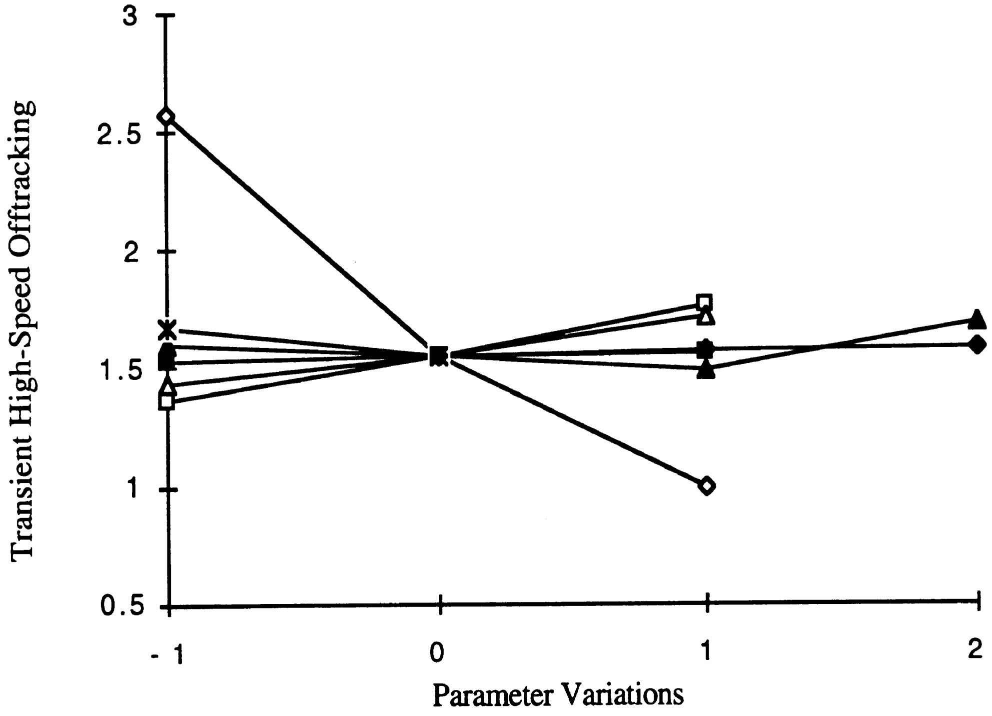


Figure C-63. Sensitivity of transient high-speed offtracking: 28'x28' five-axle 2C1-train double

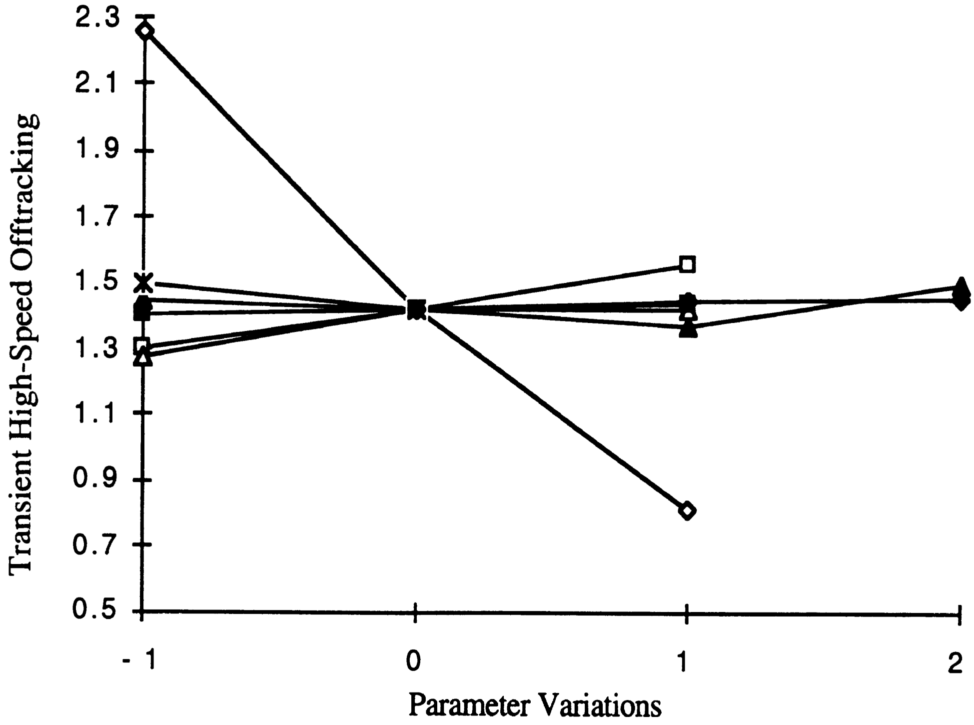


Figure C-64. Sensitivity of transient high-speed offtracking: 32'x32' eight-axle 2C1-train double

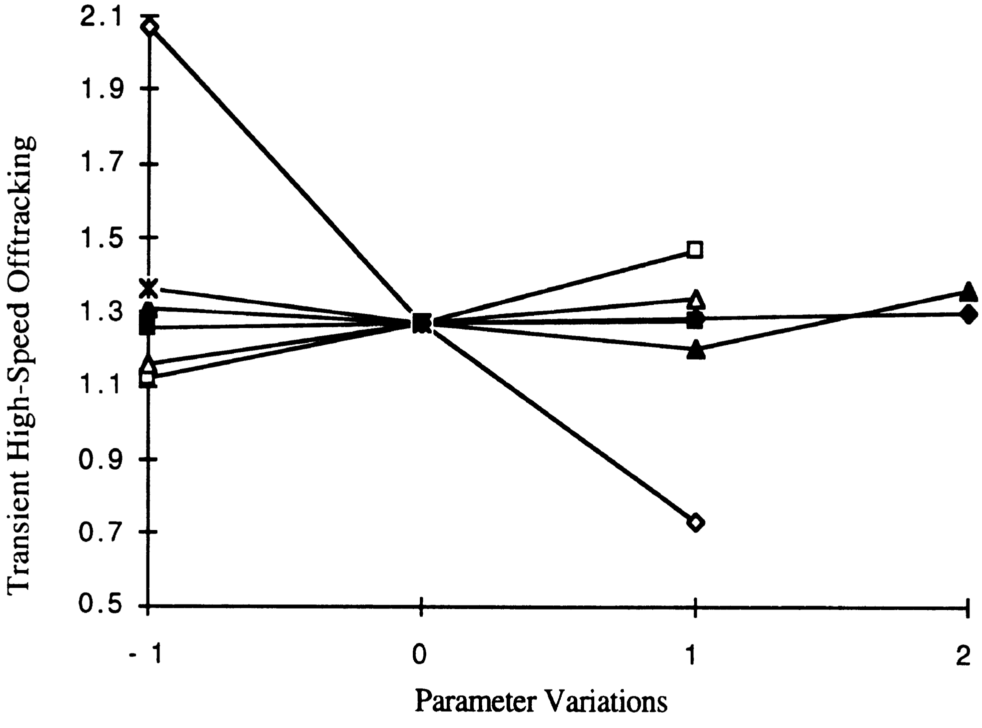


Figure C-65. Sensitivity of transient high-speed offtracking: 38'x20' seven-axle 2C1-train double

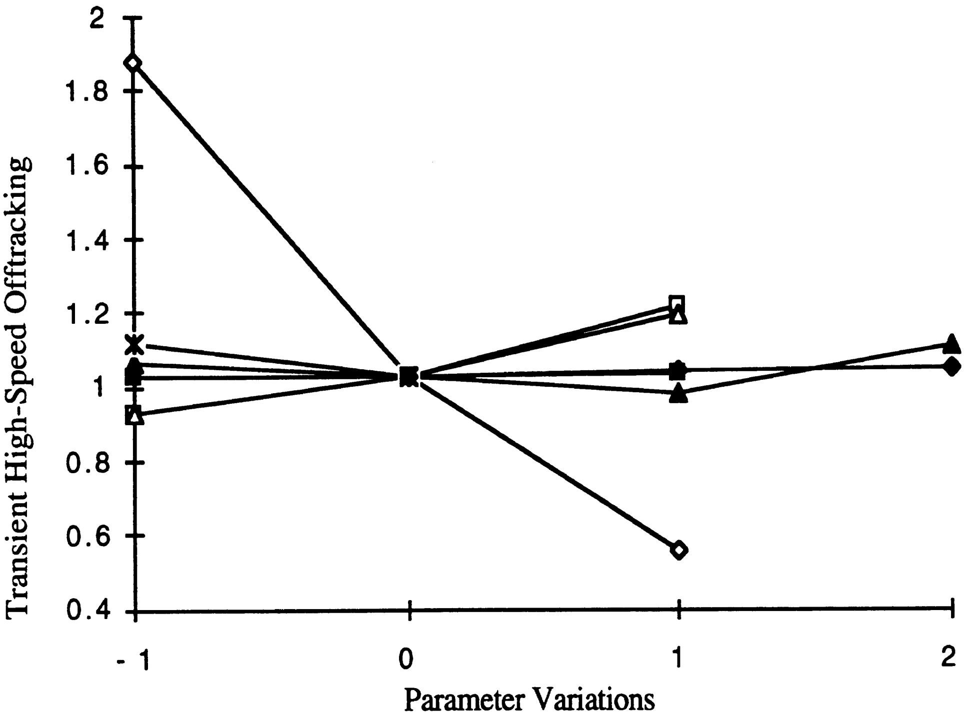


Figure C-66. Sensitivity of transient high-speed offtracking: 45'x28' seven-axle 2C1-train double

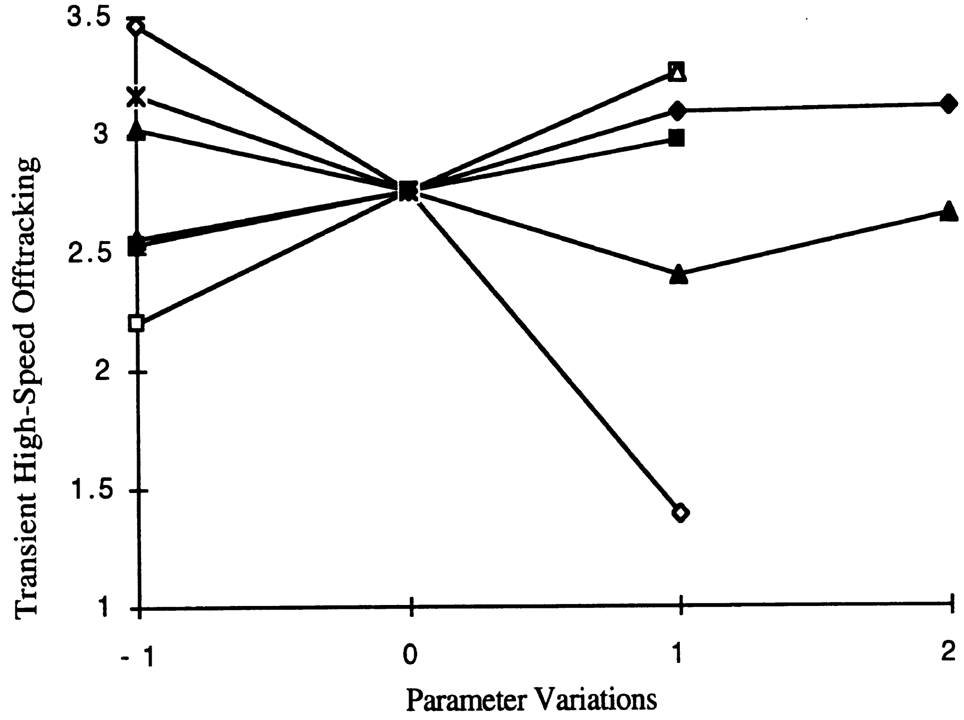


Figure C-67. Sensitivity of transient high-speed offtracking: 28'x28'x28' seven-axle 2C1-train triple

Sensitivity Plots of Damping Ratio in the RTAC-B Maneuver

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

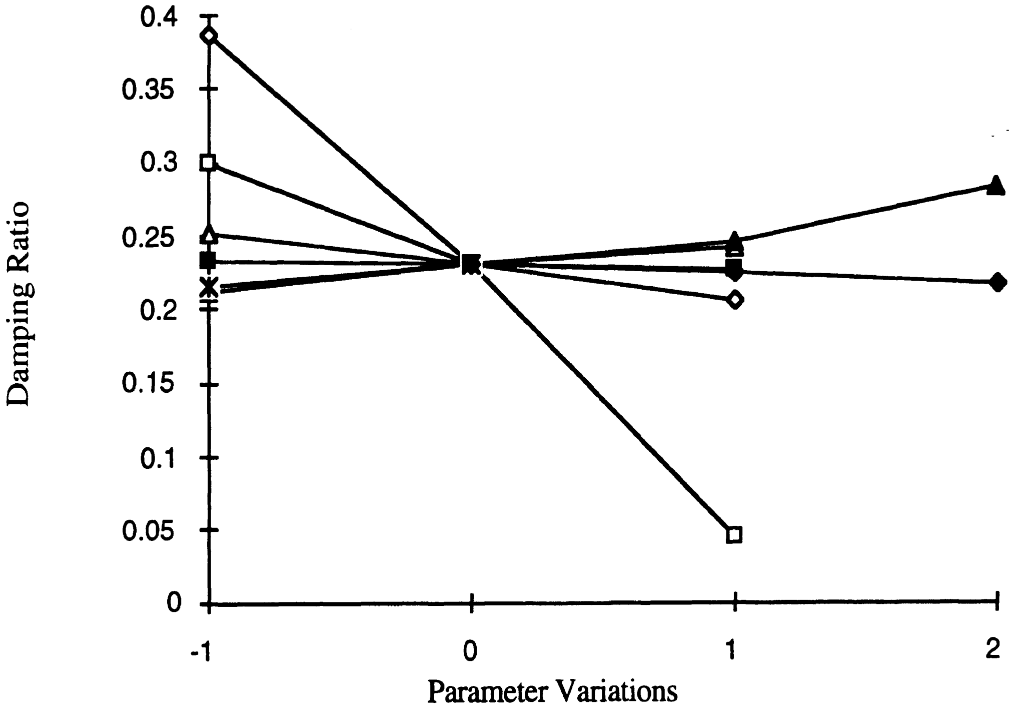


Figure C-68. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28' five-axle 2C1-train double

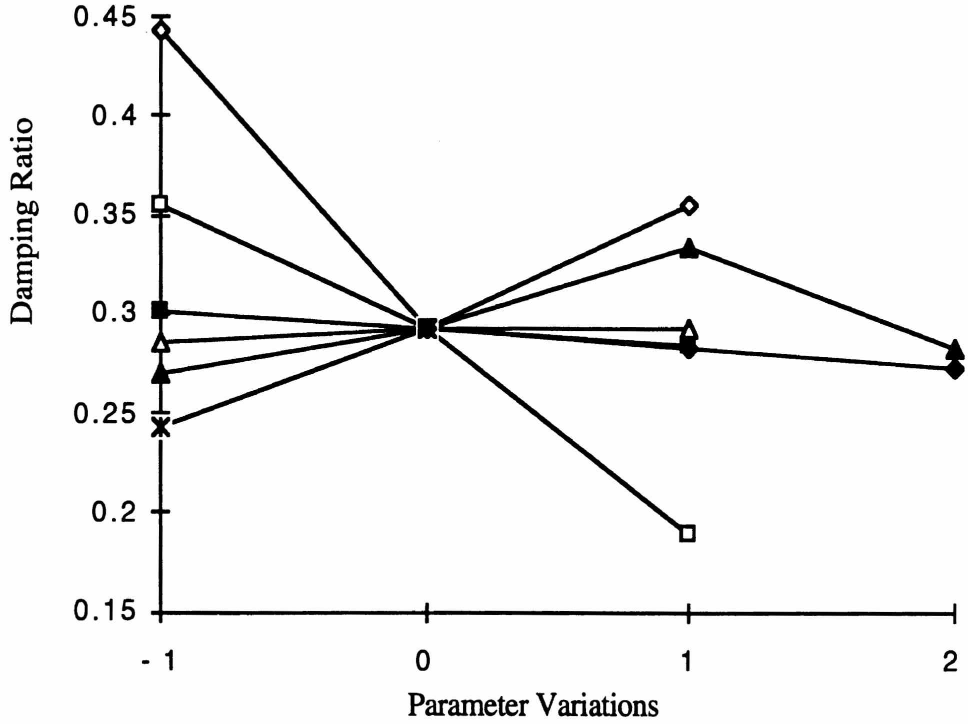


Figure C-69. Sensitivity of damping ratio in the RTAC-B maneuver: 32'x32' eight-axle 2C1-train double

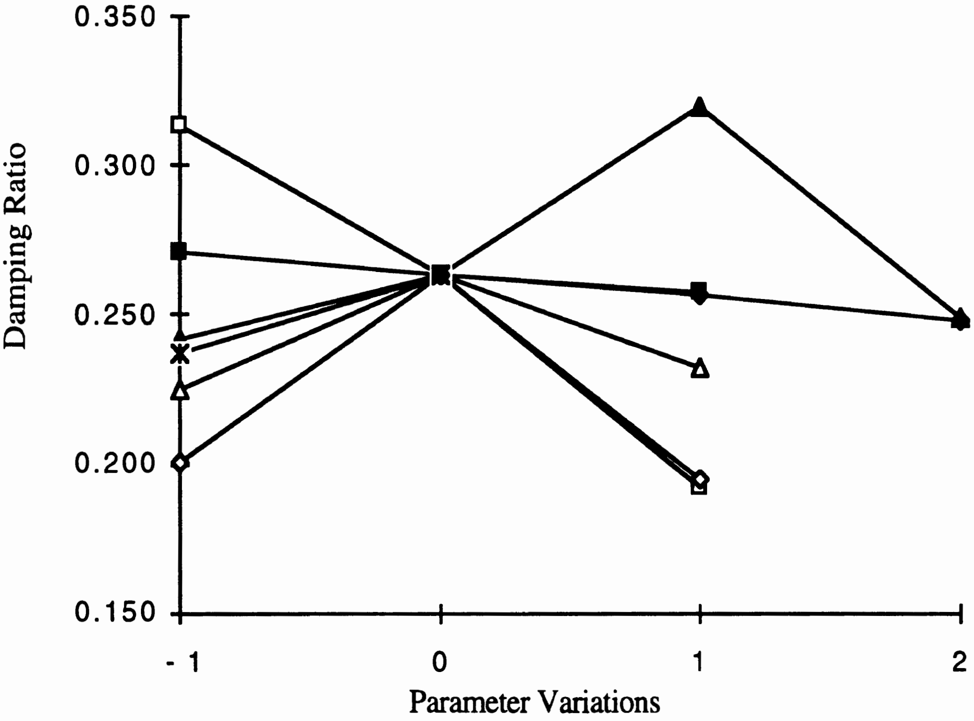


Figure C-70. Sensitivity of damping ratio in the RTAC-B maneuver: 38'x20' seven-axle 2C1-train double

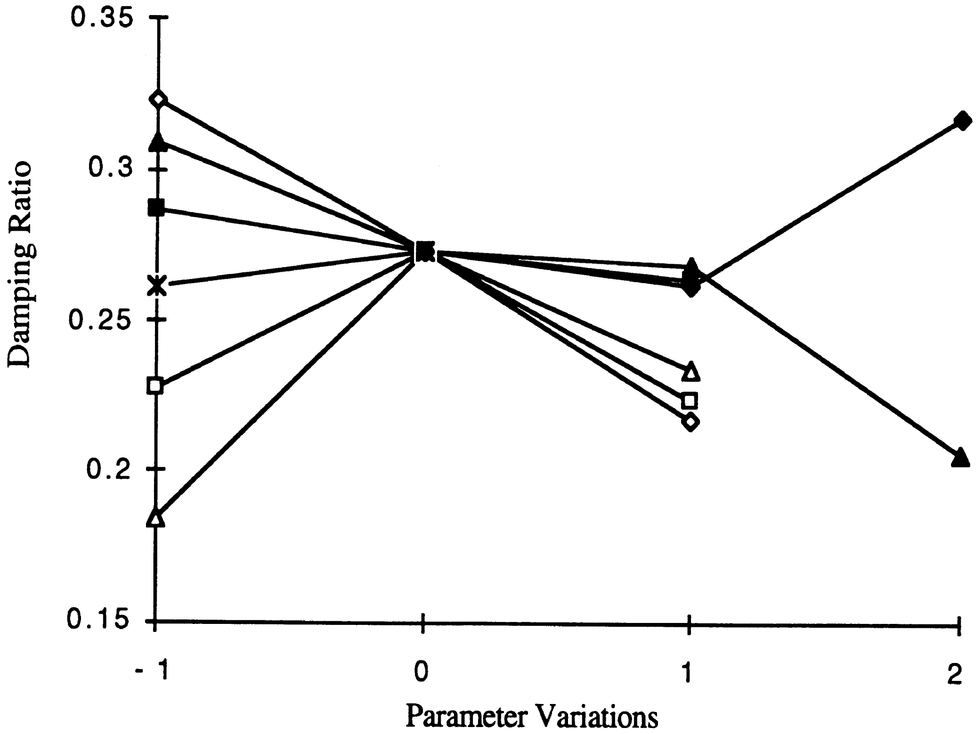


Figure C-71. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x28' seven-axle 2C1-train double

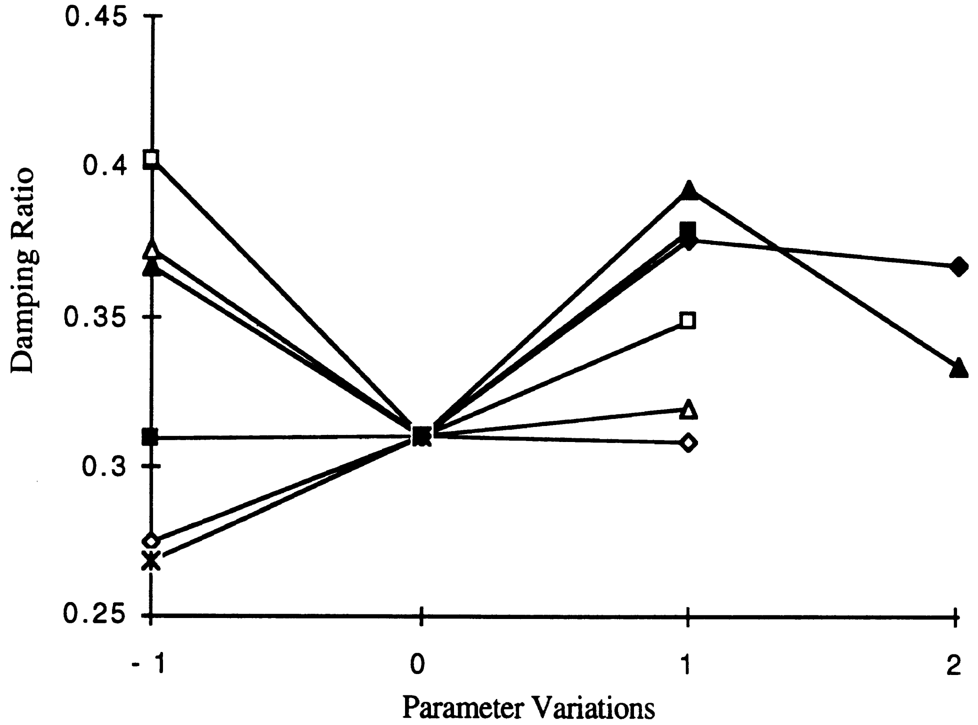


Figure C-72. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28'x28' seven-axle 2C1-train triple

SENSITIVITY STUDY RESULTS FOR THE 2C2-DOLLY

Table C-4. Performance measures obtained with the 2C2-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio
28x28bas2C2	0.431	-1.115	1.730	0.458	1.585	0.240
28x28do12C2	0.431	-1.148	1.729	0.449	1.607	0.236
28x28do22C2	0.431	-1.176	1.721	0.442	1.620	0.227
28x28pl12C2	0.365	-1.161	1.852	0.565	1.804	0.030
28x28pl22C2	0.527	-1.088	1.636	0.363	1.394	0.308
28x28pl32C2	0.432	-1.116	1.774	0.454	1.768	0.223
28x28pl42C2	0.432	-1.115	1.715	0.453	1.451	0.253
28x28se12C2	0.432	-1.137	1.729	0.452	1.598	0.236
28x28se22C2	0.432	-1.095	1.728	0.463	1.568	0.241
28x28sp22C2	0.422	-1.119	1.774	0.471	1.634	0.114
28x28sp32C2	0.434	-1.112	1.679	0.437	1.524	0.255
28x28ss42C2	0.451	-1.213	1.746	0.452	1.728	0.310
28x28su12C2	0.395	-1.137	1.811	0.514	1.704	0.224
28x28tl12C2	0.423	-0.794	1.651	0.431	1.015	0.205
28x28tl22C2	0.424	-1.733	1.887	0.444	2.674	0.364
32x32bas2C2	0.445	-1.176	1.619	0.402	1.446	0.289
32x32do12C2	0.447	-1.204	1.623	0.397	1.469	0.277
32x32do22C2	0.446	-1.233	1.621	0.390	1.485	0.262
32x32pl12C2	0.372	-1.206	1.708	0.493	1.574	0.182
32x32pl22C2	0.516	-1.155	1.534	0.322	1.330	0.351
32x32pl32C2	0.445	-1.176	1.619	0.402	1.446	0.289
32x32pl42C2	0.446	-1.177	1.578	0.395	1.296	0.290
32x32se12C2	0.445	-1.193	1.622	0.398	1.461	0.279
32x32se22C2	0.442	-1.152	1.614	0.405	1.428	0.299
32x32sp22C2	0.431	-1.179	1.644	0.413	1.474	0.266
32x32sp32C2	0.451	-1.170	1.574	0.384	1.397	0.329
32x32ss42C2	0.464	-1.258	1.612	0.390	1.520	0.286
32x32su12C2	0.408	-1.191	1.677	0.450	1.516	0.240
32x32tl12C2	0.440	-0.755	1.474	0.375	0.828	0.358
32x32tl22C2	0.439	-1.749	1.778	0.398	2.321	0.430
38x20bas2C2	0.427	-1.068	1.731	0.411	1.290	0.263
38x20do12C2	0.427	-1.103	1.747	0.406	1.313	0.257
38x20do22C2	0.427	-1.140	1.758	0.402	1.331	0.248
38x20pl12C2	0.359	-1.095	1.904	0.519	1.485	0.193
38x20pl22C2	0.530	-1.063	1.593	0.323	1.147	0.310
38x20pl32C2	0.427	-1.068	1.683	0.409	1.361	0.233
38x20pl42C2	0.426	-1.068	1.755	0.409	1.177	0.223
38x20se12C2	0.426	-1.088	1.739	0.408	1.303	0.257
38x20se22C2	0.427	-1.048	1.721	0.415	1.275	0.271
38x20sp22C2	0.416	-1.071	1.775	0.424	1.331	0.241
38x20sp32C2	0.432	-1.067	1.646	0.390	1.223	0.323
38x20ss42C2	0.444	-1.164	1.728	0.402	1.385	0.248
38x20su12C2	0.404	-1.074	1.826	0.462	1.384	0.236
38x20tl12C2	0.428	-0.686	1.626	0.385	0.736	0.195
38x20tl22C2	0.435	-1.719	1.872	0.410	2.134	0.048
45x28bas2C2	0.432	-1.114	1.443	0.340	1.041	0.274
45x28do12C2	0.432	-1.141	1.446	0.335	1.054	0.262
45x28do22C2	0.432	-1.166	1.448	0.329	1.064	0.323
45x28pl12C2	0.364	-1.149	1.554	0.421	1.232	0.226
45x28pl22C2	0.534	-1.094	1.363	0.270	0.935	0.222
45x28pl32C2	0.432	-1.113	1.445	0.330	1.208	0.240
45x28pl42C2	0.432	-1.110	1.421	0.342	0.939	0.181
45x28se12C2	0.432	-1.131	1.444	0.336	1.048	0.264
45x28se22C2	0.432	-1.094	1.441	0.343	1.033	0.287
45x28sp22C2	0.425	-1.119	1.468	0.350	1.082	0.313
45x28sp32C2	0.437	-1.111	1.404	0.324	0.989	0.268
45x28ss42C2	0.448	-1.232	1.457	0.333	1.129	0.200
45x28su12C2	0.408	-1.130	1.503	0.379	1.127	0.262
45x28tl12C2	0.434	-0.661	1.297	0.326	0.559	0.217
45x28tl22C2	0.440	-1.858	1.607	0.331	1.919	0.310
3X28BAS2C2	0.417	-1.703	2.119	0.366	3.132	0.309
3X28DO12C2	0.420	-1.768	2.118	0.356	3.106	0.375
3X28DO22C2	0.418	-1.839	2.102	0.351	2.833	0.362
3X28PL12C2	0.360	-1.772	2.164	0.434	3.540	0.341
3X28PL22C2	0.472	-1.662	2.035	0.298	2.691	0.407
3X28PL32C2	0.416	-1.701	2.149	0.358	3.772	0.309
3X28PL42C2	0.400	-1.705	2.119	0.365	3.077	0.375
3X28SE12C2	0.418	-1.739	2.109	0.359	3.150	0.375
3X28SE22C2	0.418	-1.670	2.117	0.371	3.017	0.310
3X28SP22C2	0.403	-1.724	2.260	0.383	3.378	0.356
3X28SP32C2	0.418	-1.698	2.100	0.349	2.839	0.390
3X28SS42C2	0.422	-1.534	2.053	0.376	3.080	0.330
3X28SU12C2	0.390	-1.736	2.138	0.405	3.545	0.271
3X28TI12C2	0.423	-1.260	2.074	0.362	1.658	0.309
3X28TI22C2	0.423	-2.580	2.256	0.368	4.597	0.280

Sensitivity Plots of Static Rollover Threshold

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

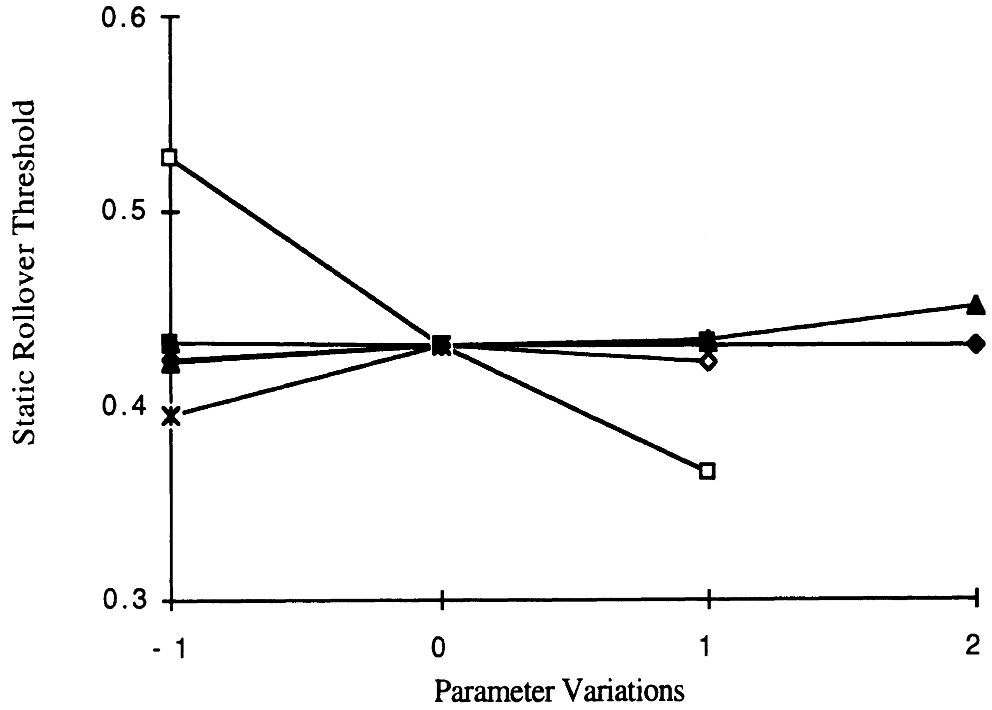


Figure C-73. Sensitivity of static rollover threshold: 28'x28' five-axle 2C2-train double

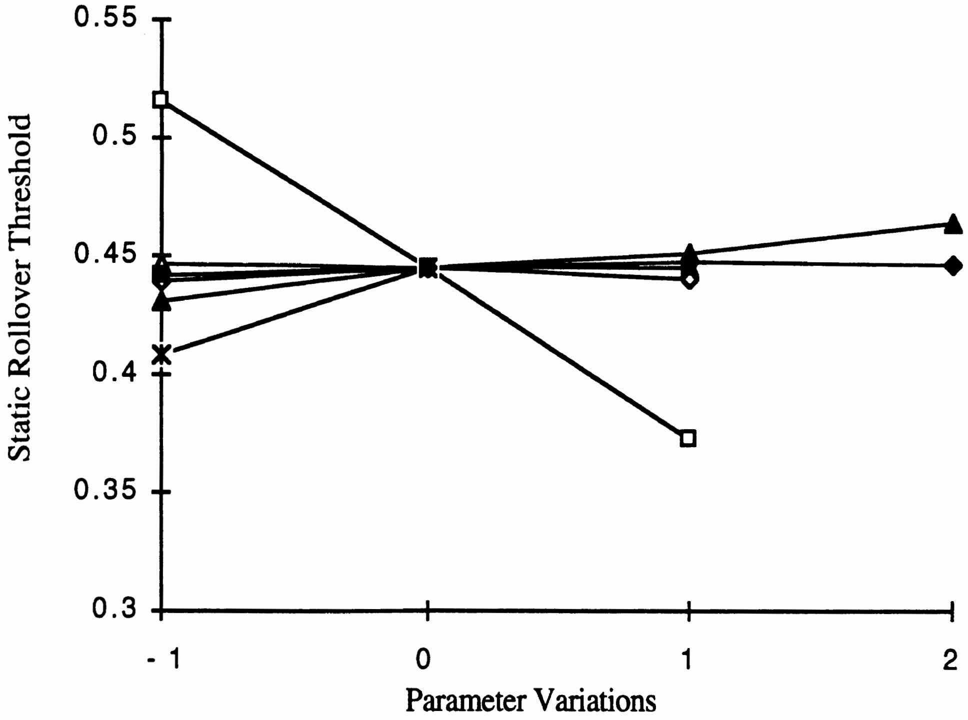


Figure C-74. Sensitivity of static rollover threshold: 32'x32' eight-axle 2C2-train double

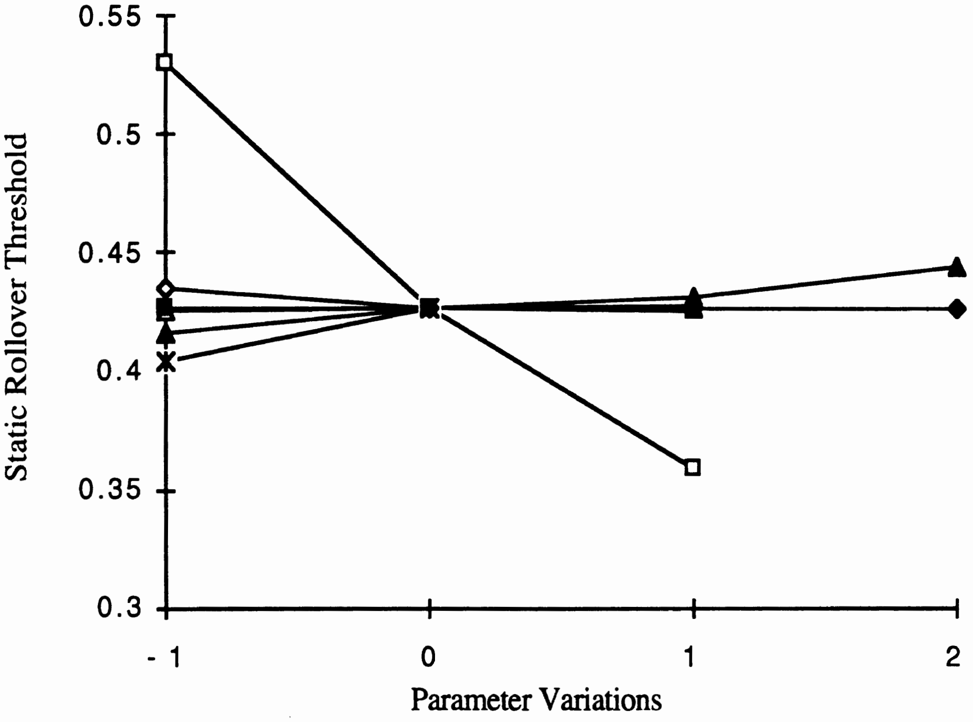


Figure C-75. Sensitivity of static rollover threshold: 38'x20' seven-axle 2C2-train double

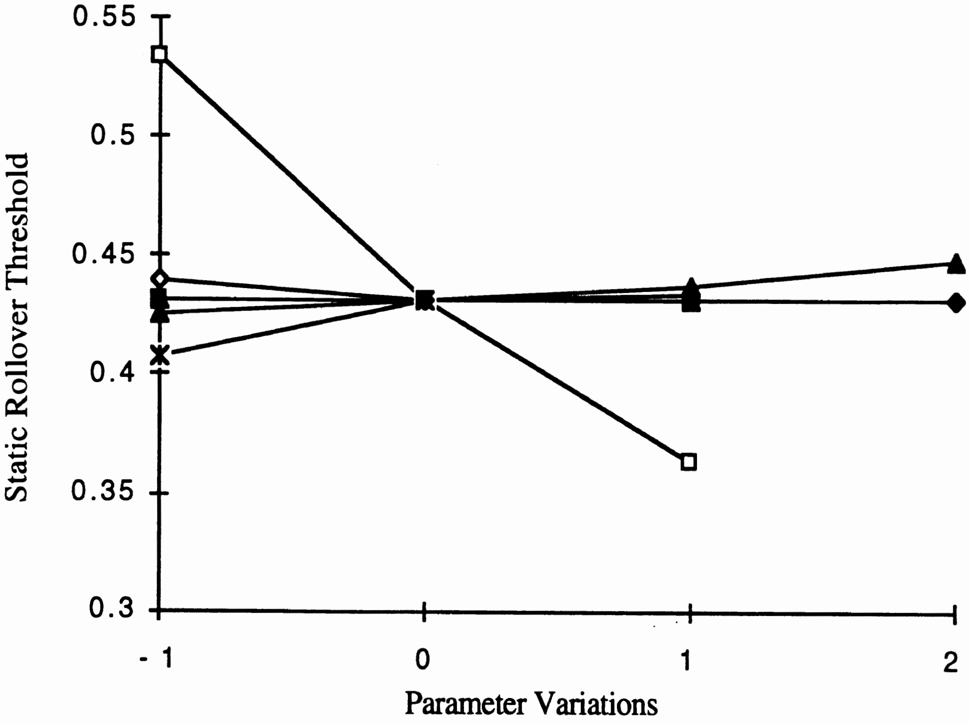


Figure C-76. Sensitivity of static rollover threshold: 45'x28' seven-axle 2C2-train double

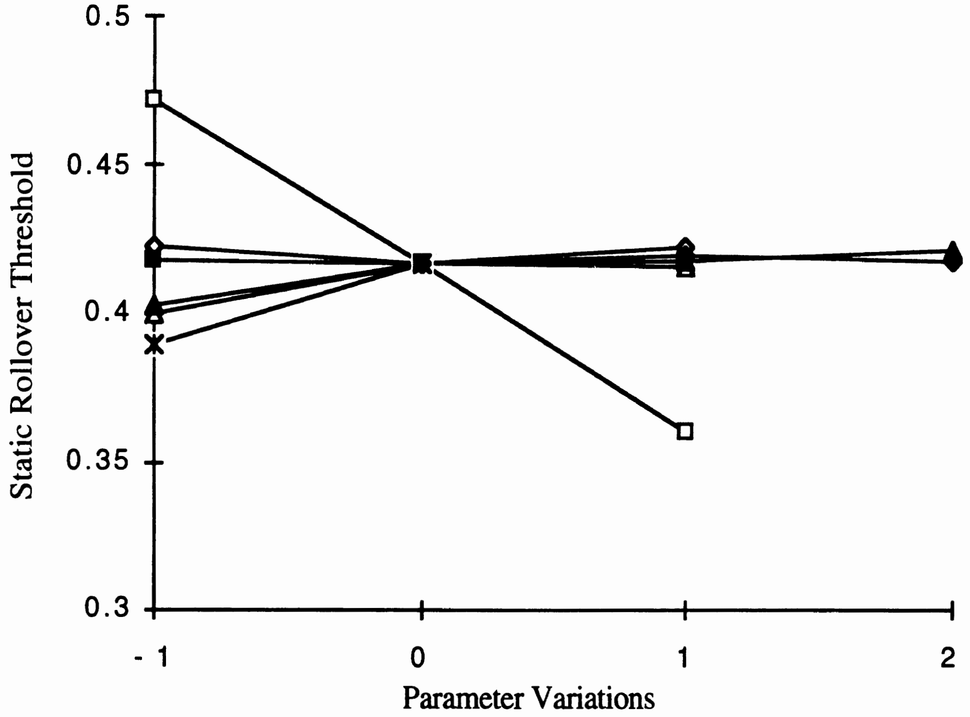


Figure C-77. Sensitivity of static rollover threshold: 28'x28'x28' seven-axle 2C2-train triple

Sensitivity Plots of High-Speed Steady-State Offtracking

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✱	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

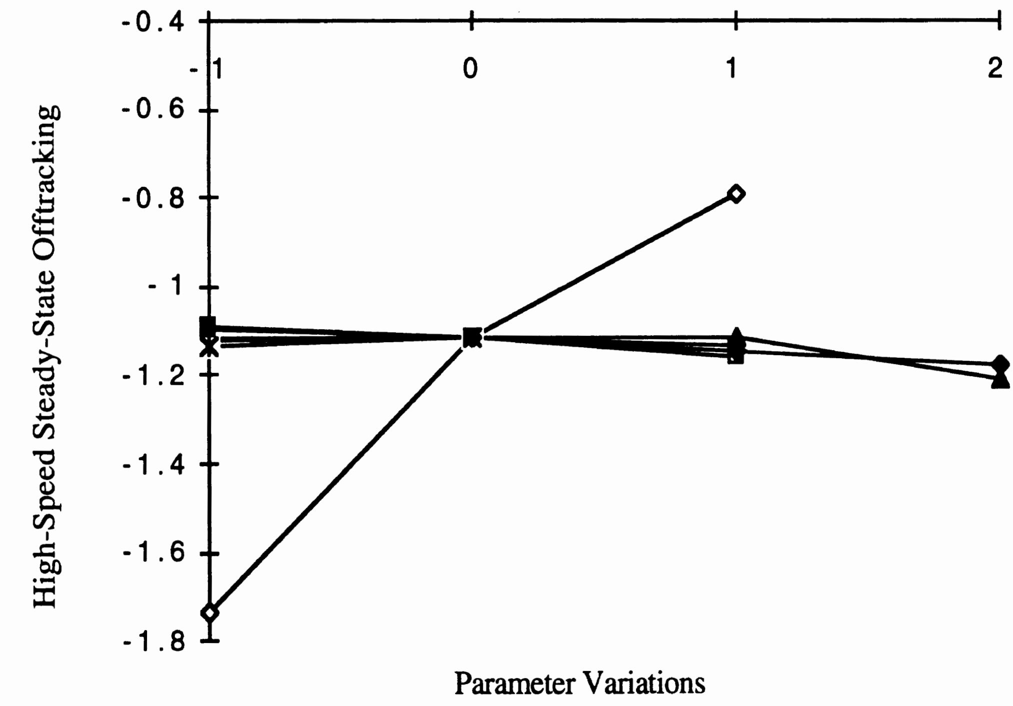


Figure C-78. Sensitivity of high-speed steady-state offtracking: 28'x28' five-axle 2C2-train double

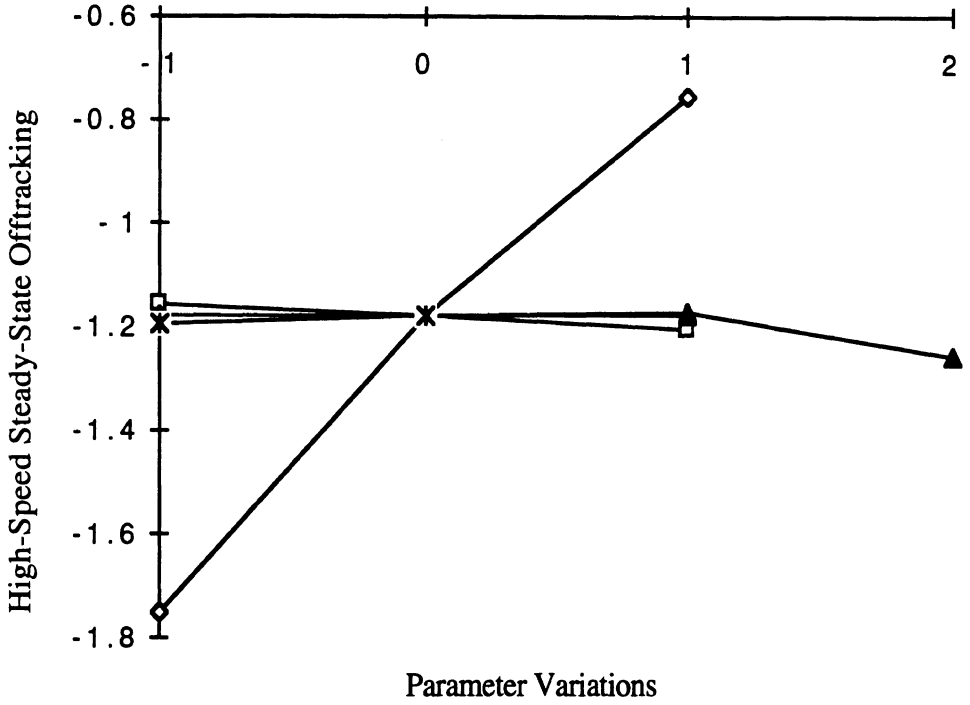


Figure C-79. Sensitivity of high-speed steady-state offtracking: 32'x32' eight-axle 2C2-train double

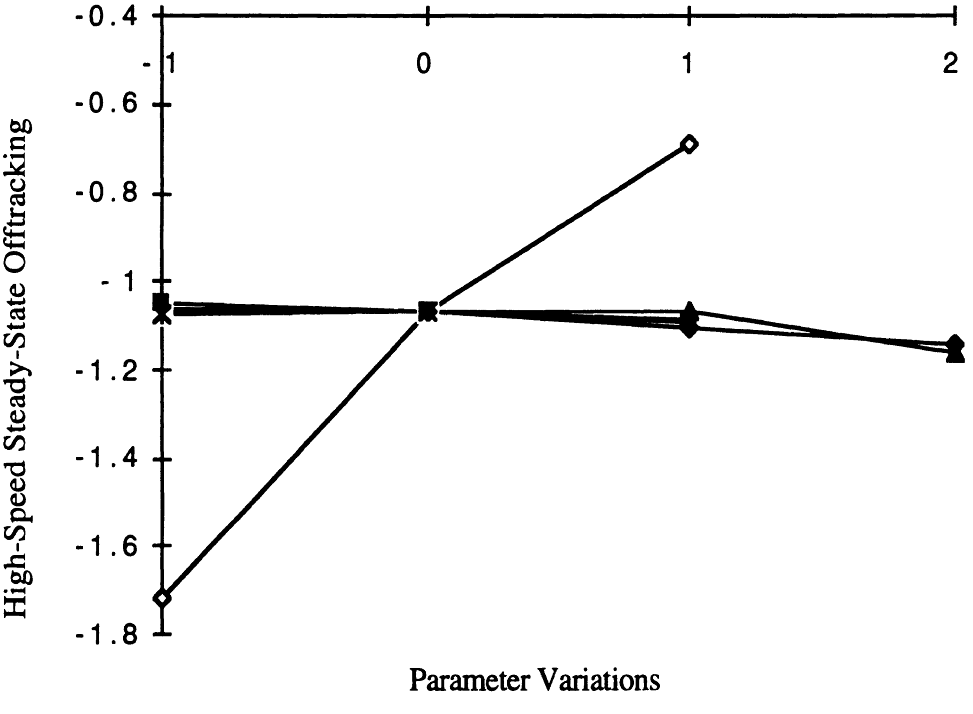


Figure C-80. Sensitivity of high-speed steady-state offtracking: 38'x20' seven-axle 2C2-train double

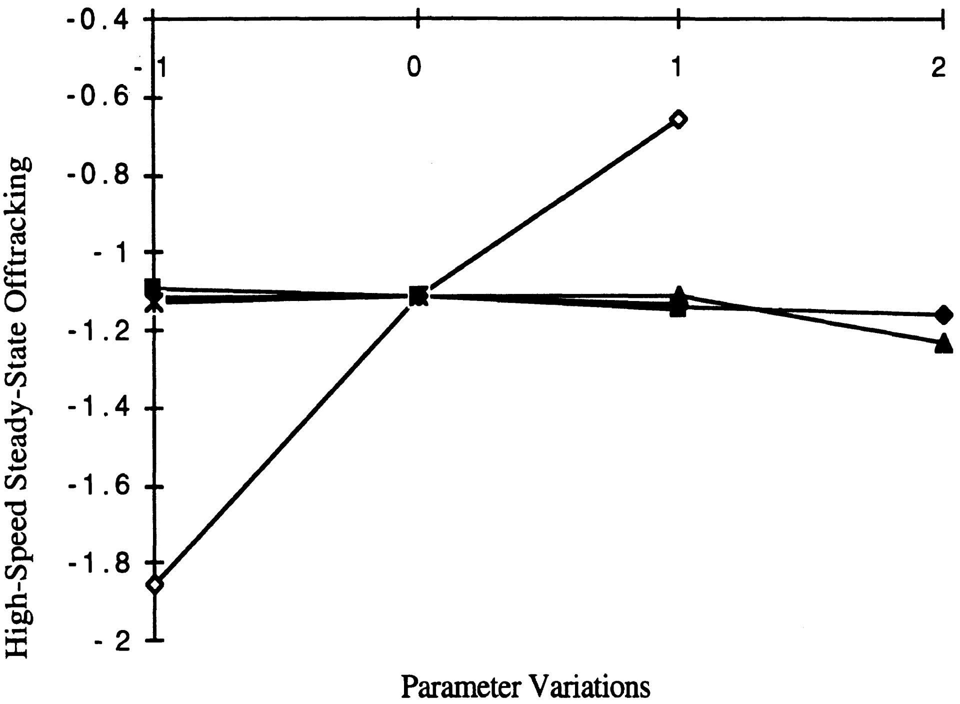


Figure C-81. Sensitivity of high-speed steady-state offtracking: 45'x28' seven-axle 2C2-train double

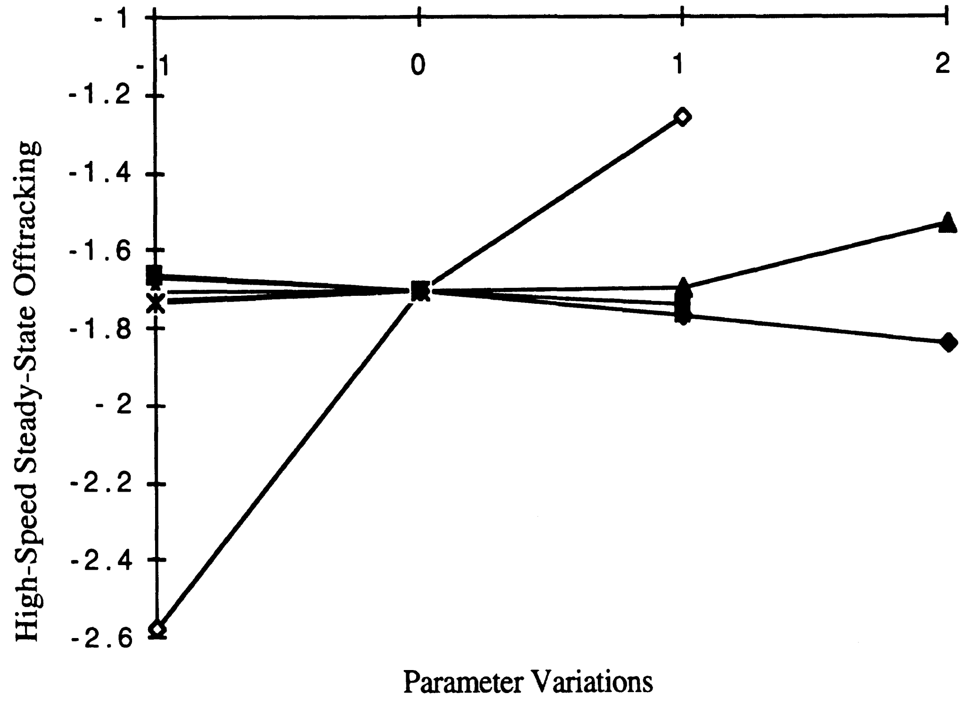


Figure C-82. Sensitivity of high-speed steady-state offtracking: 28'x28'x28' seven-axle 2C2-train triple

Sensitivity Plots of Rearward Amplification

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

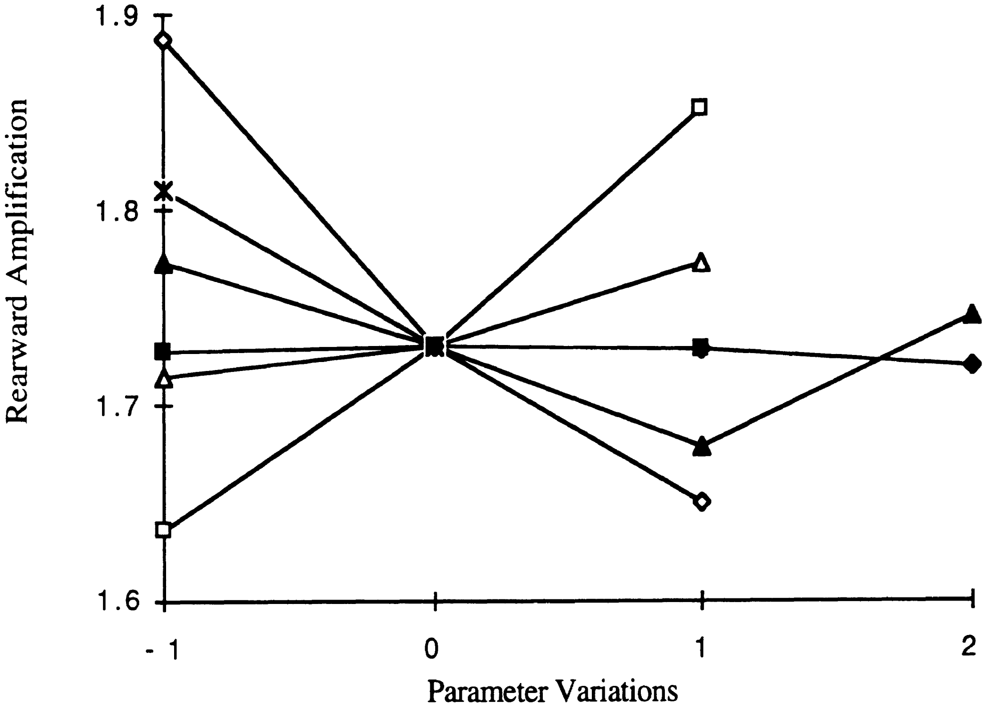


Figure C-83. Sensitivity of rearward amplification: 28'x28' five-axle 2C2-train double

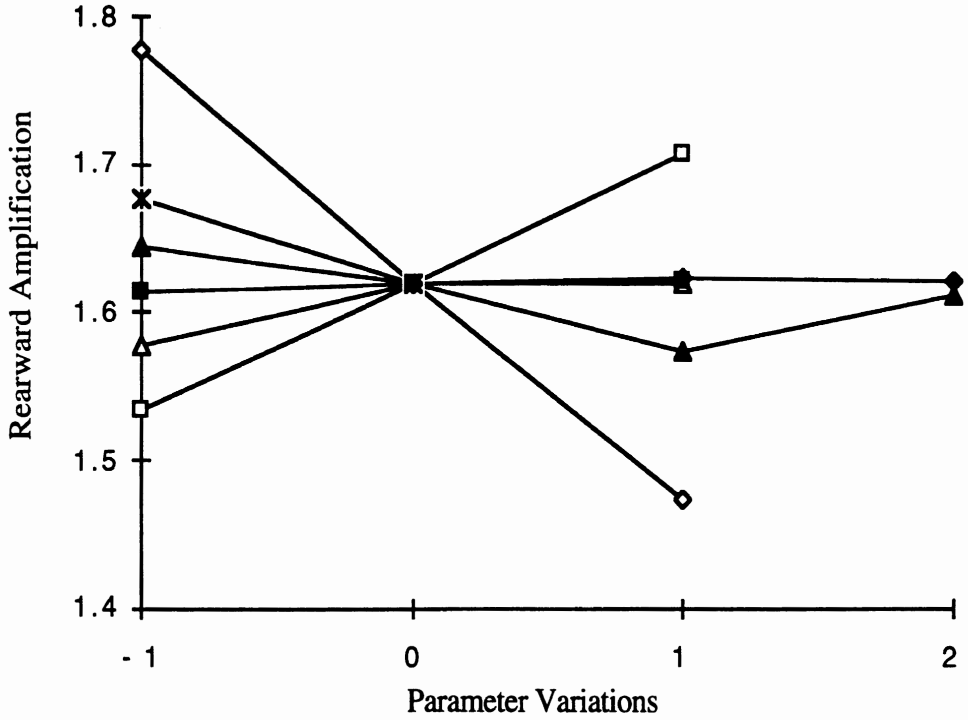


Figure C-84. Sensitivity of rearward amplification: 32'x32' eight-axle 2C2-train double

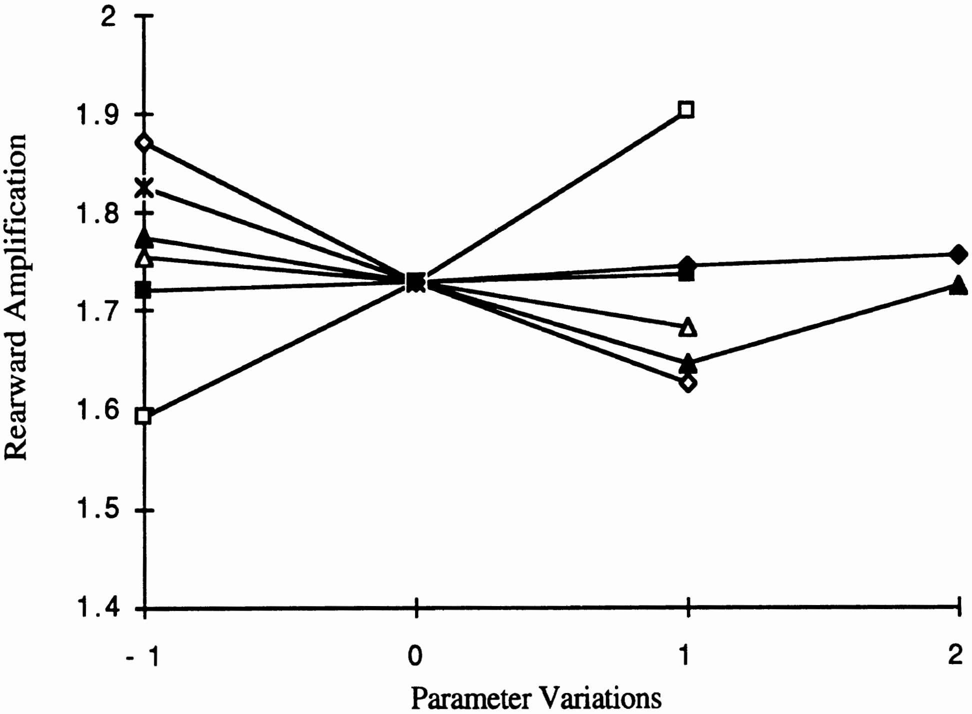


Figure C-85. Sensitivity of rearward amplification: 38'x20' seven-axle 2C2-train double

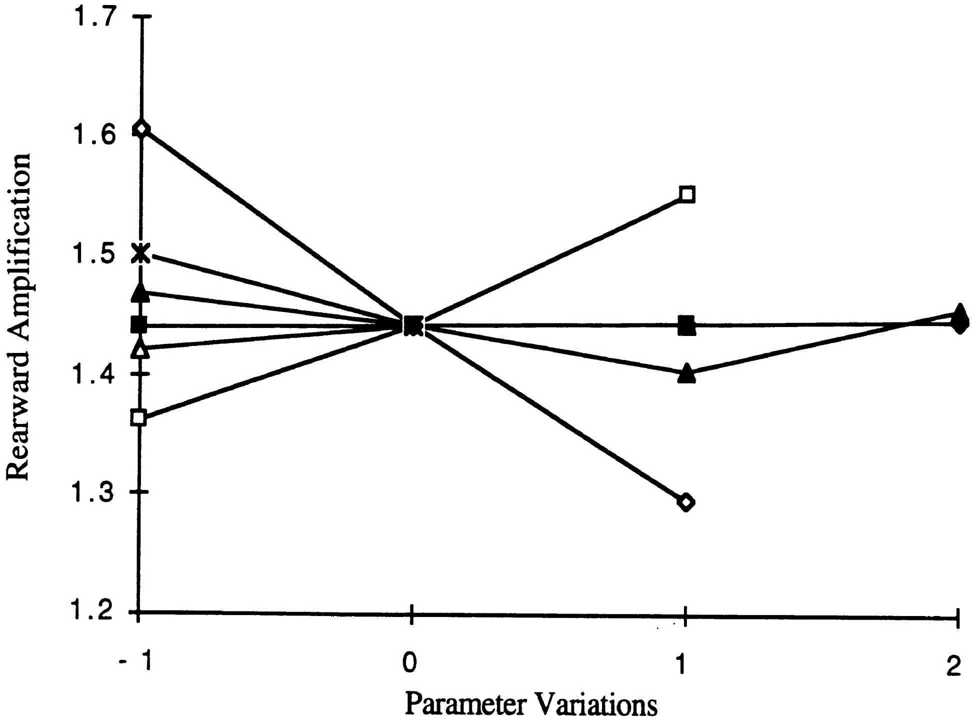


Figure C-86. Sensitivity of rearward amplification: 45'x28' seven-axle 2C2-train double

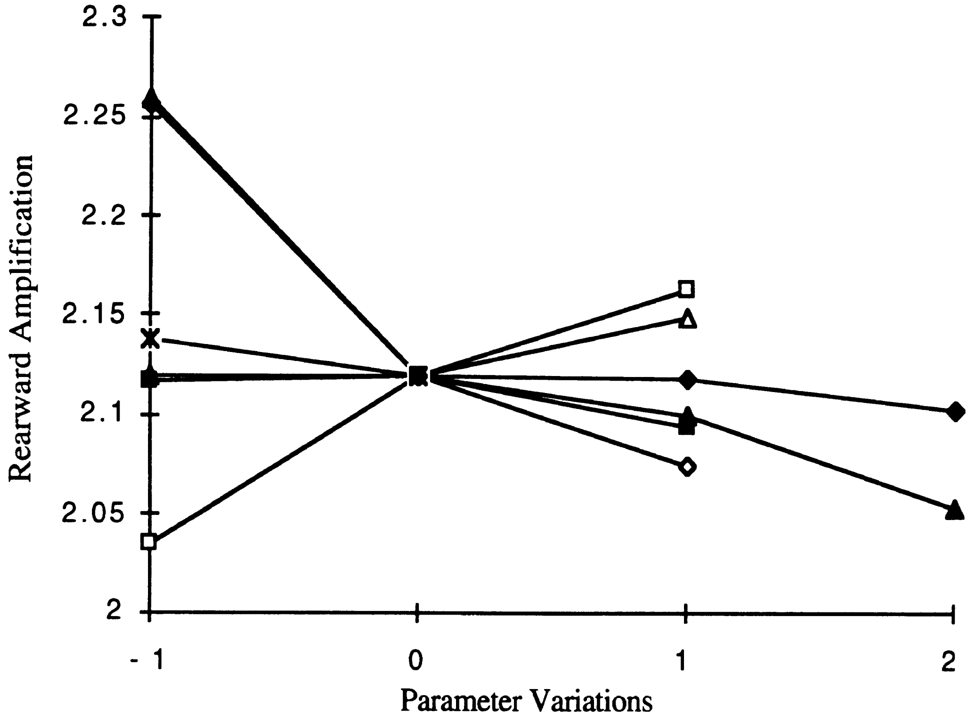


Figure C-87. Sensitivity of rearward amplification: 28'x28'x28' seven-axle 2C2-train triple

Sensitivity Plots of Dynamic-Load-Transfer Ratio

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

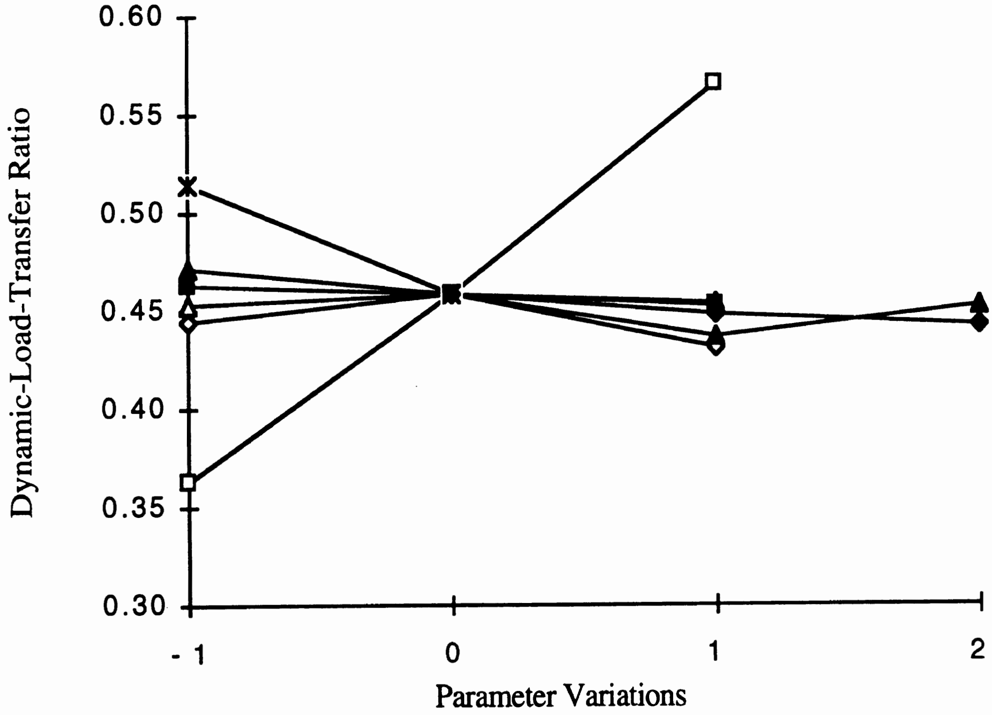


Figure C-88. Sensitivity of dynamic-load-transfer ratio: 28'x28' five-axle 2C2-train double

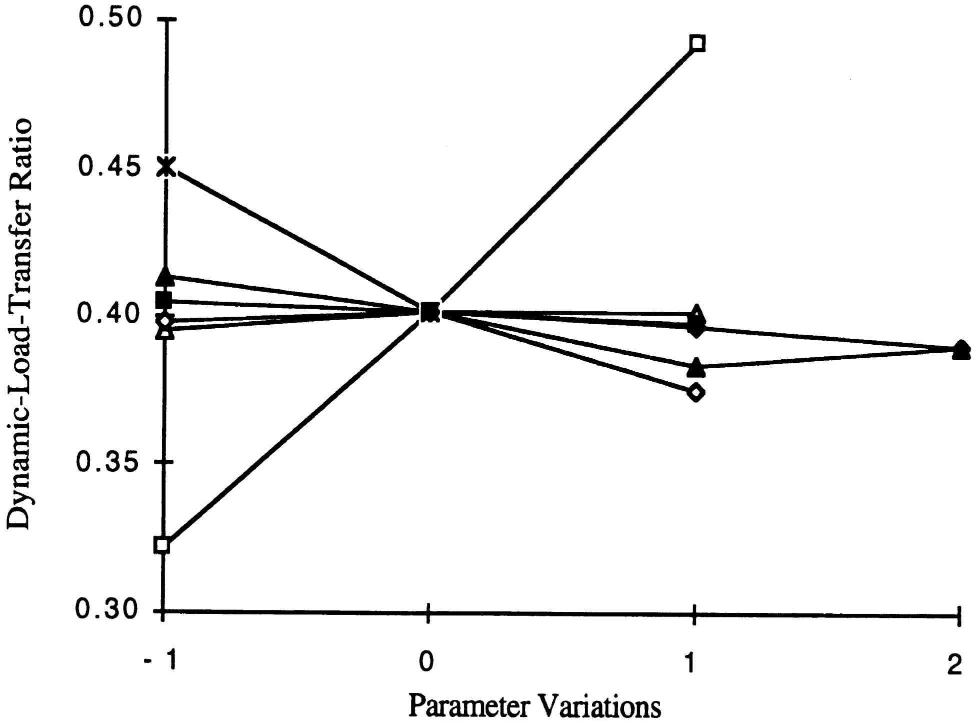


Figure C-89. Sensitivity of dynamic-load-transfer ratio: 32'x32' eight-axle 2C2-train double

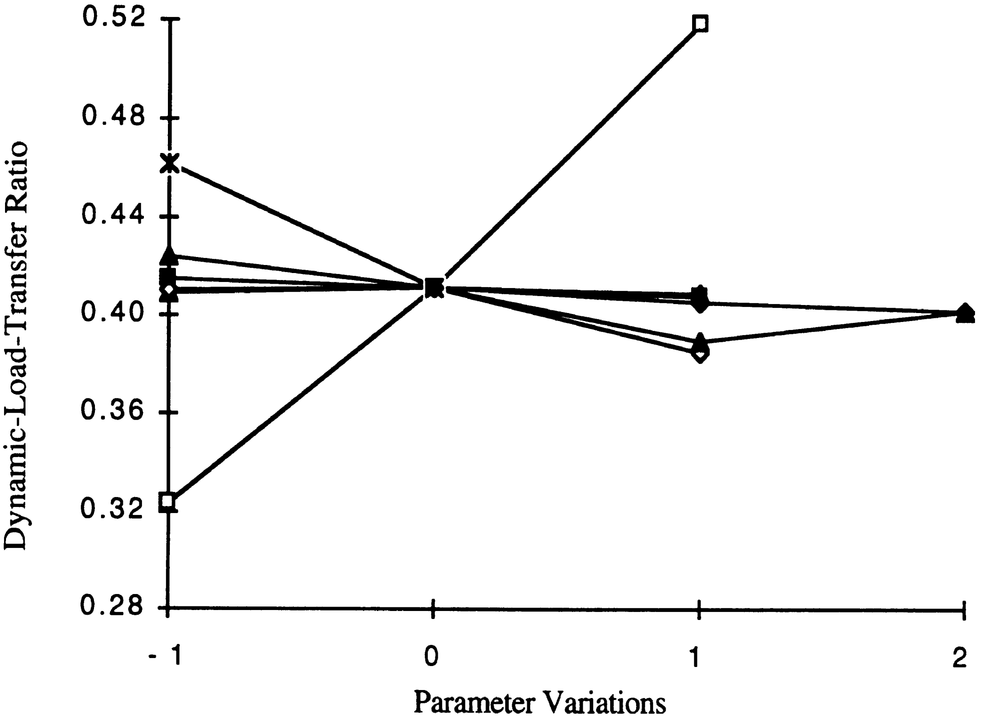


Figure C-90. Sensitivity of dynamic-load-transfer ratio: 38'x20' seven-axle 2C2-train double

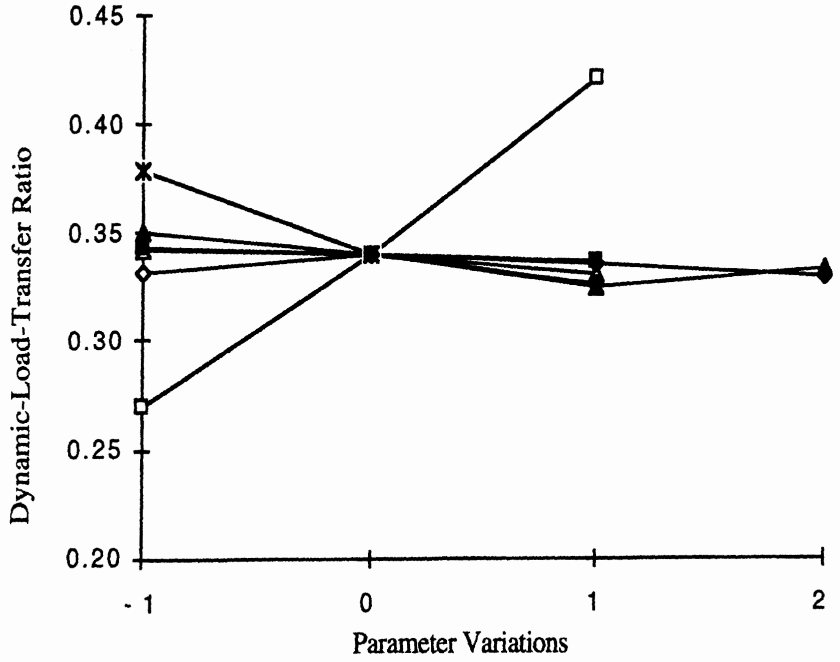


Figure C-91. Sensitivity of dynamic-load-transfer ratio: 45'x28' seven-axle 2C2-train double

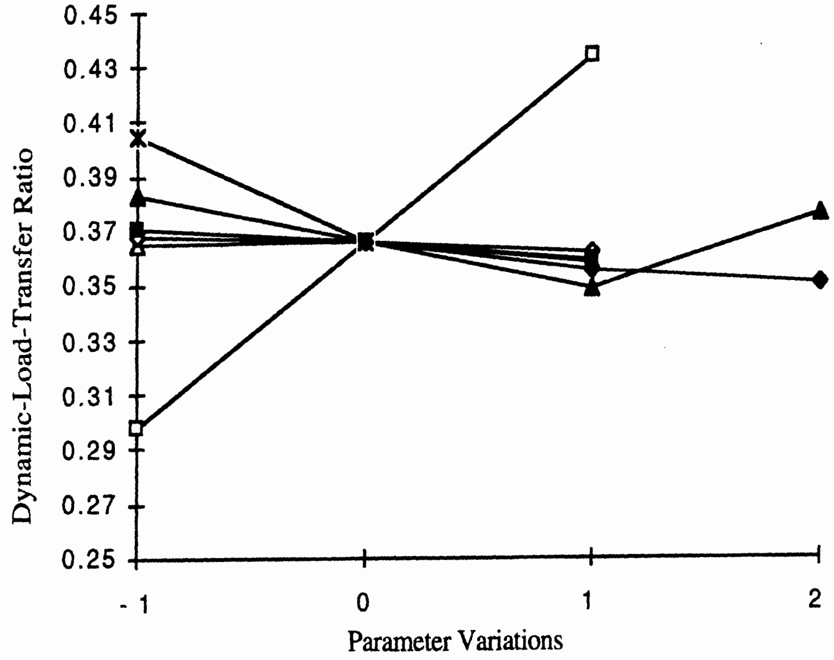


Figure C-92. Sensitivity of dynamic-load-transfer ratio: 28'x28'x28' seven-axle 2C2-train triple

Sensitivity Plots of Transient High-Speed Offtracking

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

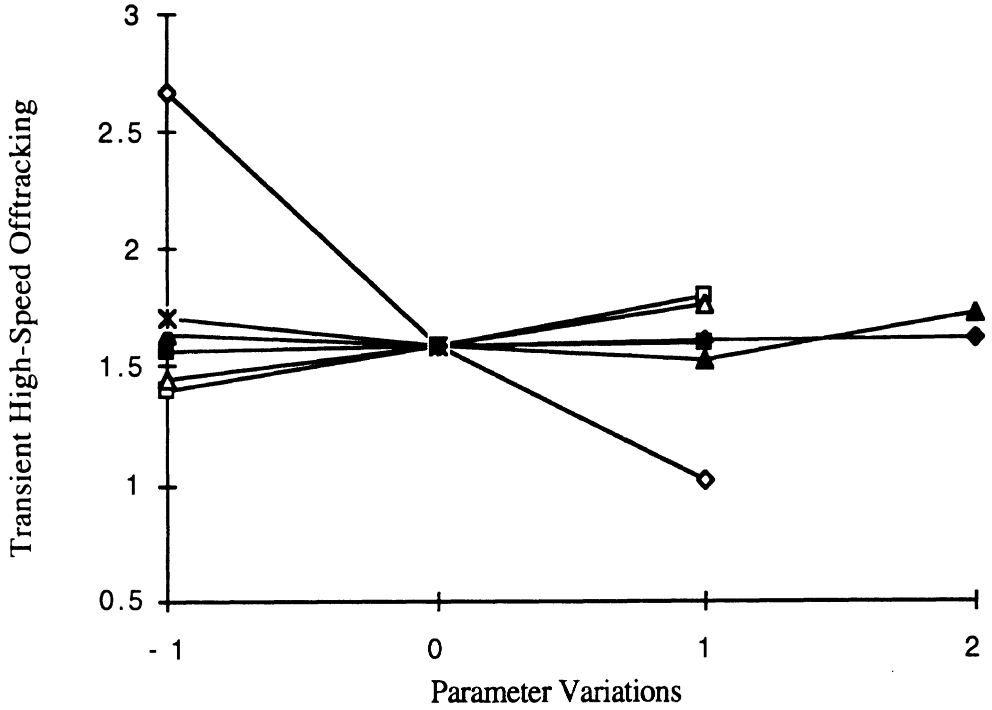


Figure C-93. Sensitivity of transient high-speed offtracking: 28'x28' five-axle 2C2-train double

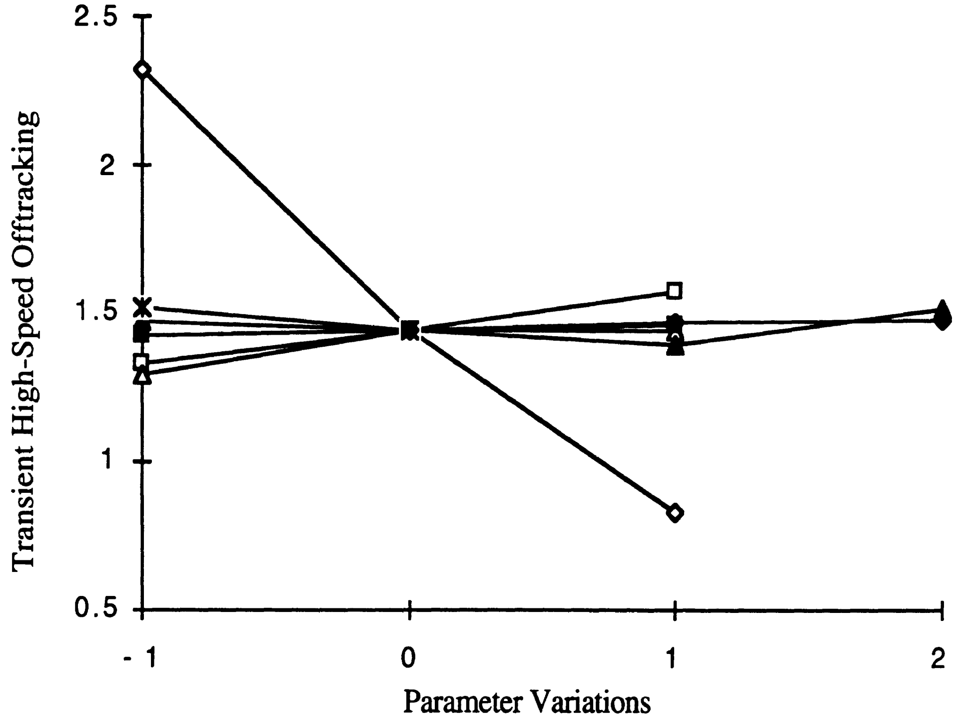


Figure C-94. Sensitivity of transient high-speed offtracking: 32'x32' eight-axle 2C2-train double

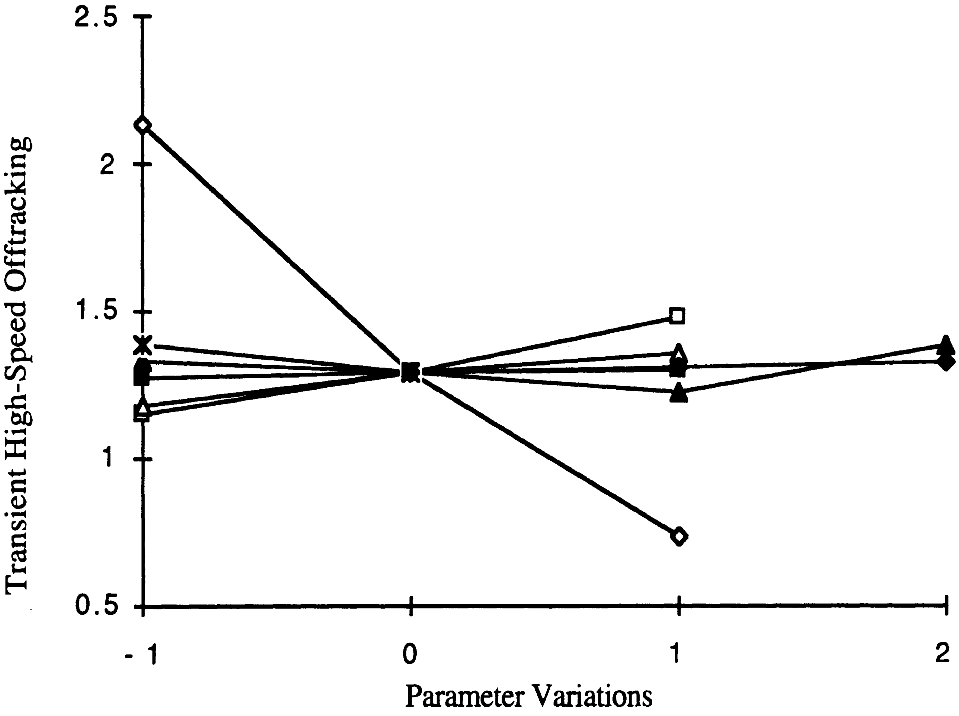


Figure C-95. Sensitivity of transient high-speed offtracking: 38'x20' seven-axle 2C2-train double

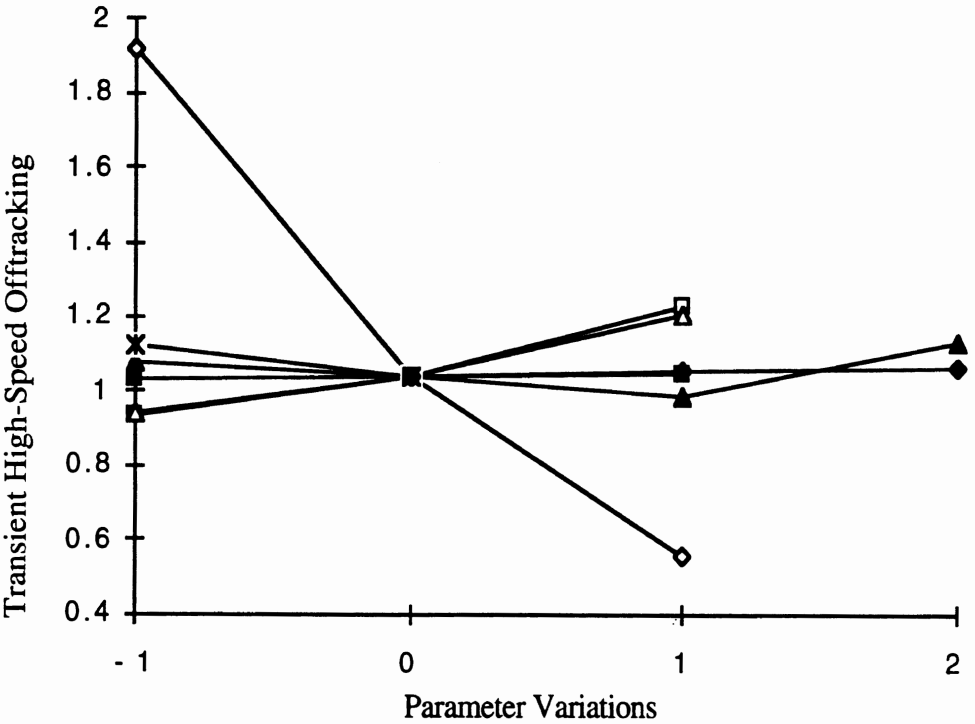


Figure C-96. Sensitivity of transient high-speed offtracking: 45'x28' seven-axle 2C2-train double

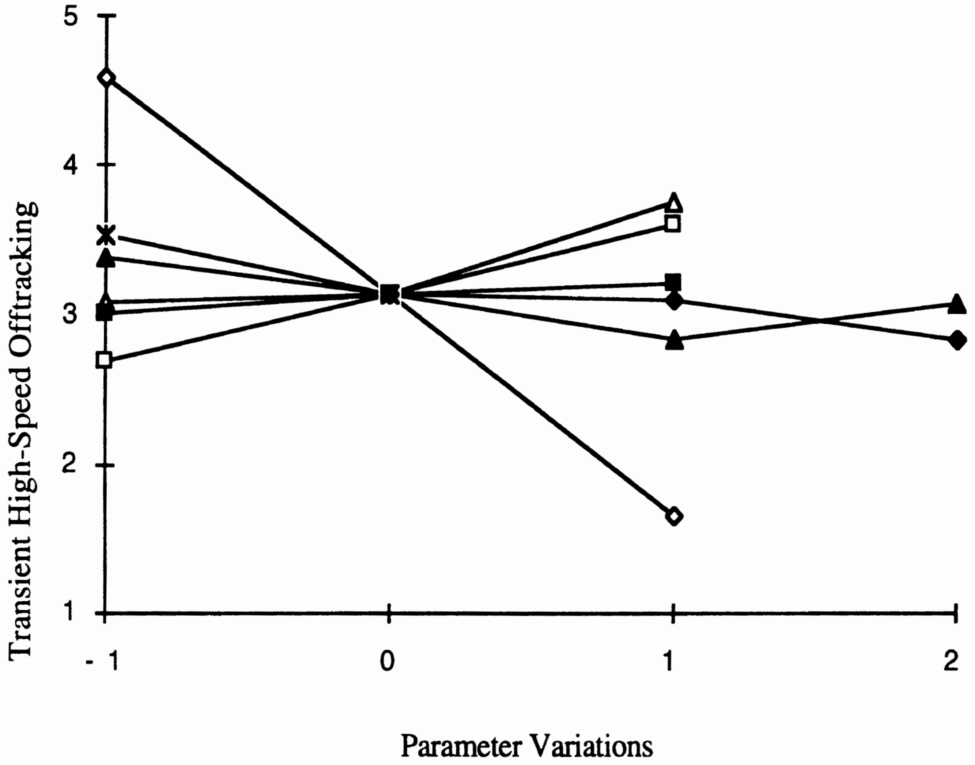


Figure C-97. Sensitivity of transient high-speed offtracking: 28'x28'x28' seven-axle 2C2-train triple

Sensitivity Plots of Damping Ratio in the RTAC-B Maneuver

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

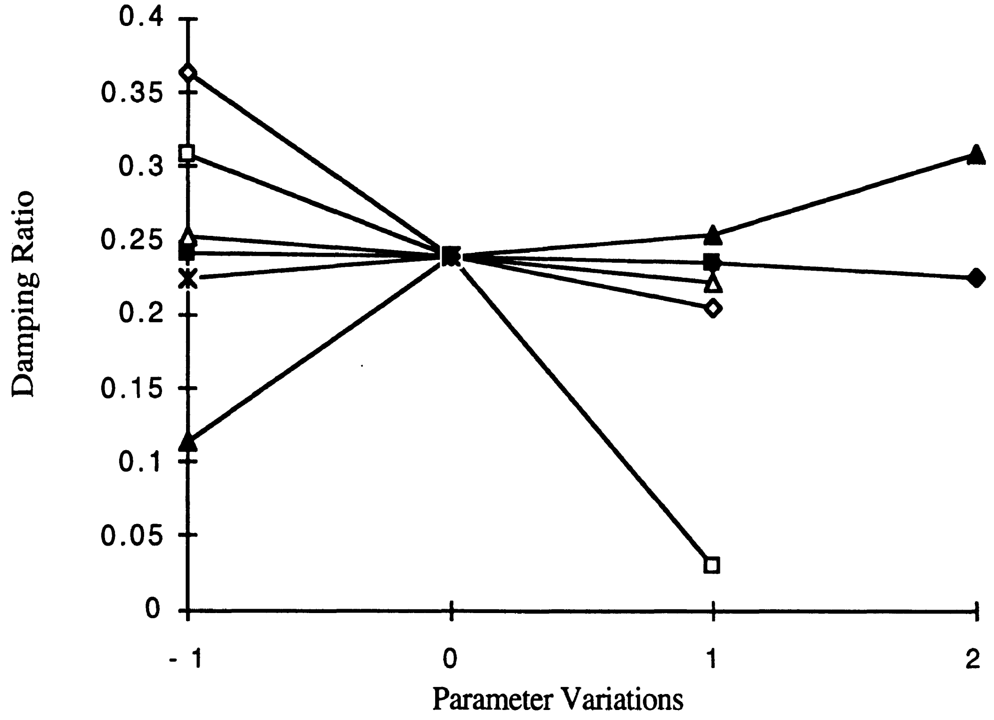


Figure C-98. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28' five-axle 2C2-train double

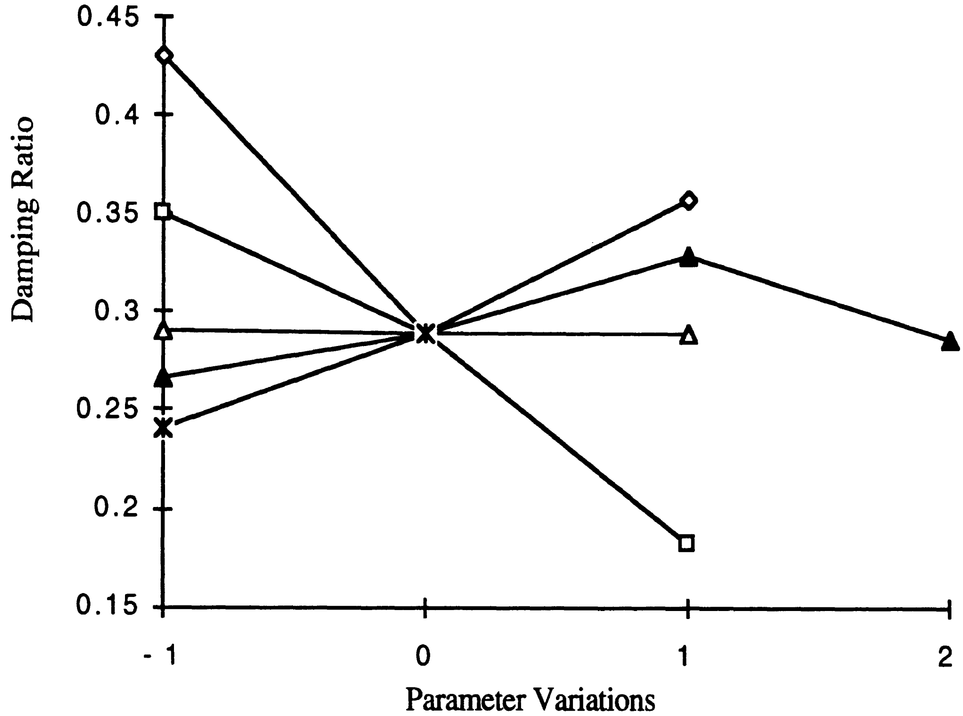


Figure C-99. Sensitivity of damping ratio in the RTAC-B maneuver: 32'x32' eight-axle 2C2-train double

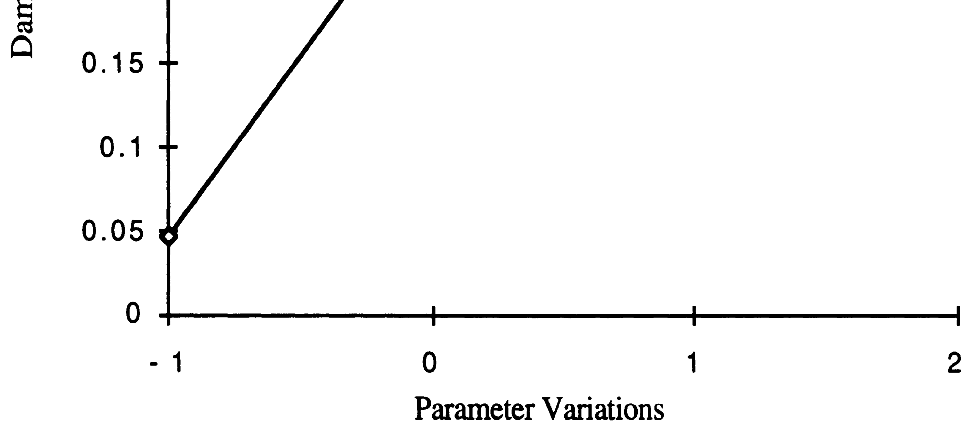


Figure C-100. Sensitivity of damping ratio in the RTAC-B maneuver: 38'x20' seven-axle 2C2-train double

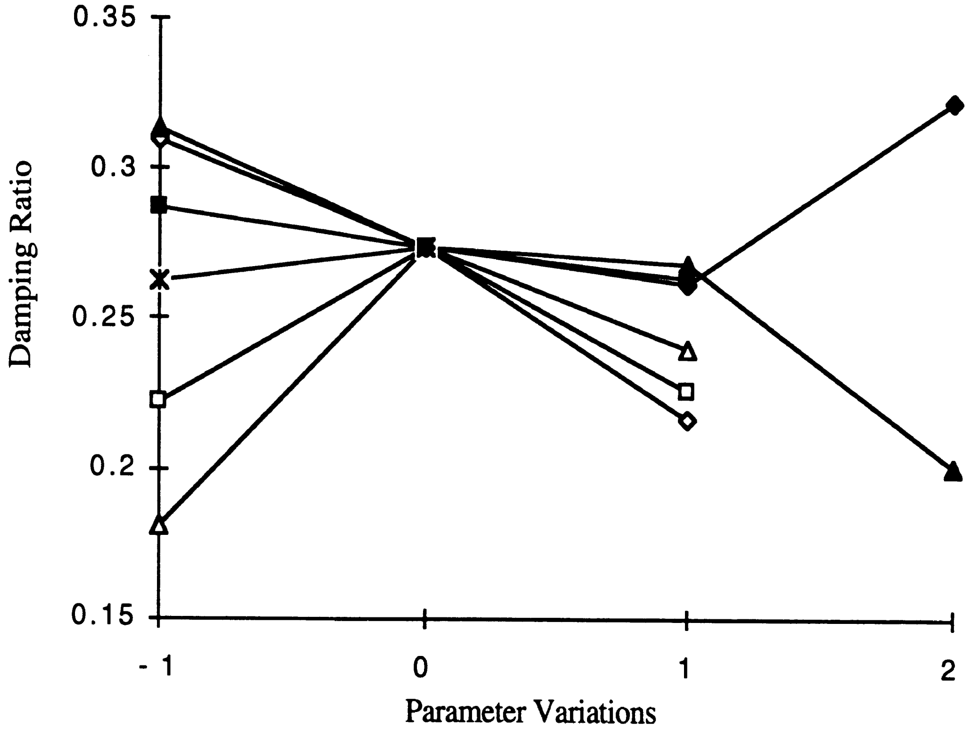


Figure C-101. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x28' seven-axle 2C2-train double

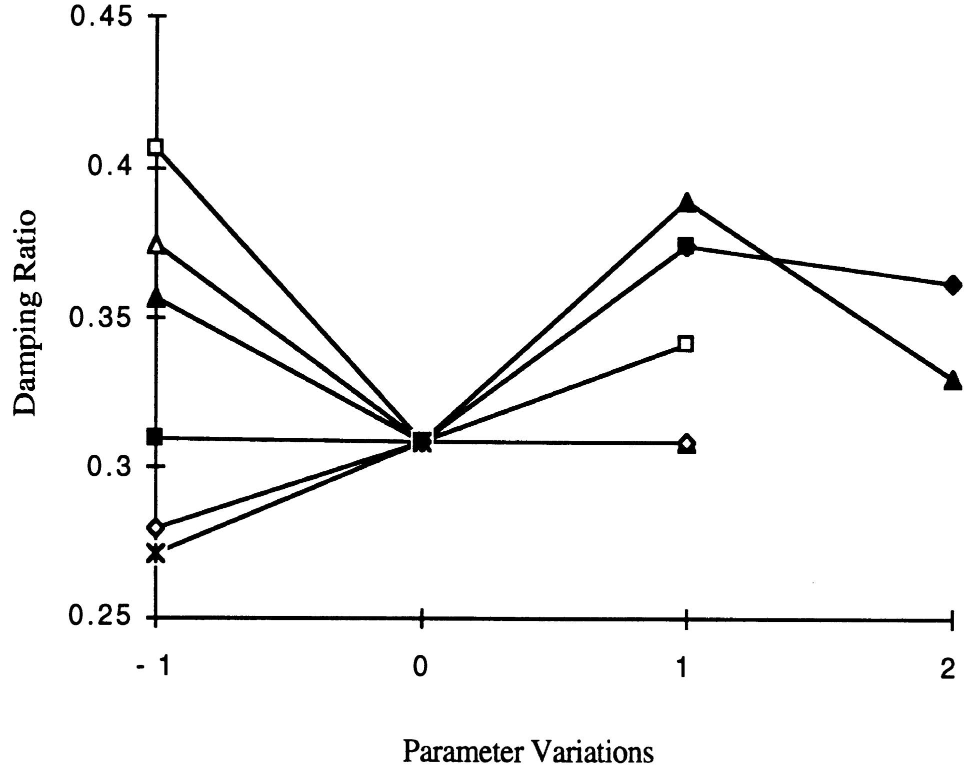


Figure C-102. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28'x28' seven-axle 2C2-train triple

SENSITIVITY STUDY RESULTS FOR THE 2C3-DOLLY

Table C-5. Performance measures obtained with the 2C3-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio
28x28bas2C3	0.448	-1.194	1.963	0.496	1.968	0.193
28x28do12C3	0.448	-1.255	1.995	0.492	2.076	0.194
28x28do22C3	0.450	-1.307	2.037	0.485	2.200	0.195
28x28pl12C3	0.367	-1.238	2.014	0.602	2.193	0.107
28x28pl22C3	0.539	-1.165	1.866	0.396	1.762	0.247
28x28pl32C3	0.449	-1.200	1.982	0.491	2.185	0.171
28x28pl42C3	0.448	-1.192	1.903	0.486	1.787	0.248
28x28se12C3	0.448	-1.219	1.960	0.491	1.989	0.192
28x28se22C3	0.448	-1.169	1.962	0.500	1.943	0.196
28x28sp22C3	0.442	-1.198	1.989	0.510	2.014	0.172
28x28sp32C3	0.454	-1.189	1.908	0.472	1.907	0.216
28x28ss42C3	0.460	-1.289	1.991	0.492	2.129	0.228
28x28su12C3	0.407	-1.215	2.015	0.556	2.084	0.163
28x28ti12C3	0.442	-0.769	1.762	0.458	1.128	0.480
28x28ti22C3	0.445	-2.019	2.214	0.522	3.648	0.187
32x32bas2C3	0.455	-1.283	1.817	0.428	1.784	0.266
32x32do12C3	0.455	-1.342	1.850	0.426	1.895	0.259
32x32do22C3	0.455	-1.396	1.864	0.420	2.007	0.256
32x32pl12C3	0.378	-1.310	1.856	0.523	1.952	0.205
32x32pl22C3	0.629	-1.262	1.728	0.342	1.669	0.302
32x32pl32C3	0.455	-1.283	1.817	0.428	1.784	0.266
32x32pl42C3	0.455	-1.284	1.750	0.418	1.584	0.313
32x32se12C3	0.455	-1.304	1.820	0.424	1.807	0.263
32x32se22C3	0.456	-1.253	1.812	0.430	1.758	0.266
32x32sp22C3	0.448	-1.285	1.832	0.439	1.809	0.253
32x32sp32C3	0.458	-1.276	1.767	0.407	1.737	0.291
32x32ss42C3	0.475	-1.362	1.796	0.415	1.868	0.294
32x32su12C3	0.415	-1.295	1.856	0.481	1.851	0.241
32x32ti12C3	0.457	-0.779	1.551	0.390	0.941	0.347
32x32ti22C3	0.456	-2.049	2.063	0.456	3.237	0.256
38x20bas2C3	0.447	-1.150	1.964	0.452	1.664	0.347
38x20do12C3	0.447	-1.206	2.016	0.452	1.759	0.293
38x20do22C3	0.447	-1.267	2.079	0.452	1.858	0.306
38x20pl12C3	0.368	-1.180	2.117	0.559	1.865	0.184
38x20pl22C3	0.585	-1.144	1.828	0.354	1.490	0.250
38x20pl32C3	0.446	-1.150	1.882	0.442	1.726	0.210
38x20pl42C3	0.447	-1.151	2.000	0.446	1.495	0.204
38x20se12C3	0.447	-1.175	1.977	0.450	1.694	0.300
38x20se22C3	0.446	-1.126	1.950	0.454	1.633	0.378
38x20sp22C3	0.436	-1.155	1.998	0.465	1.709	0.270
38x20sp32C3	0.449	-1.149	1.885	0.425	1.584	0.313
38x20ss42C3	0.467	-1.245	1.980	0.444	1.782	0.238
38x20su12C3	0.411	-1.157	2.045	0.507	1.773	0.284
38x20ti12C3	0.447	-0.681	1.774	0.412	0.869	0.131
38x20ti22C3	0.446	-1.923	2.245	0.467	3.001	0.238
45x28bas2C3	0.450	-1.213	1.603	0.358	1.338	0.310
45x28do12C3	0.450	-1.265	1.636	0.355	1.402	0.310
45x28do22C3	0.450	-1.318	1.668	0.351	1.470	0.311
45x28pl12C3	0.374	-1.246	1.726	0.441	1.551	0.293
45x28pl22C3	0.581	-1.197	1.523	0.284	1.207	0.393
45x28pl32C3	0.450	-1.211	1.591	0.340	1.565	0.298
45x28pl42C3	0.449	-1.213	1.587	0.360	1.184	0.430
45x28se12C3	0.450	-1.235	1.611	0.355	1.354	0.306
45x28se22C3	0.449	-1.189	1.595	0.361	1.320	0.313
45x28sp22C3	0.439	-1.218	1.634	0.368	1.382	0.263
45x28sp32C3	0.453	-1.210	1.567	0.341	1.276	0.355
45x28ss42C3	0.470	-1.330	1.623	0.352	1.451	0.371
45x28su12C3	0.414	-1.227	1.667	0.401	1.436	0.241
45x28ti12C3	0.449	-0.654	1.380	0.340	0.655	0.210
45x28ti22C3	0.454	-1.992	1.630	0.332	2.110	0.393
3X28BAS2C3	0.450	-1.823	2.551	0.421	3.848	0.122
3X28DO12C3	0.451	-1.974	3.919	0.427	6.020	0.096
3X28DO22C3	0.455	-2.060	3.495	0.438	NA	0.567
3X28PL12C3	0.377	-1.905	3.036	0.496	4.803	0.135
3X28PL22C3	0.550	-1.798	2.532	0.352	3.160	NA
3X28PL32C3	0.445	-1.847	3.735	0.427	7.793	0.591
3X28PL42C3	0.450	-1.844	2.542	0.413	2.945	0.187
3X28SE12C3	0.449	-1.856	2.634	0.417	4.707	0.109
3X28SE22C3	0.450	-1.791	2.571	0.426	3.432	0.137
3X28SP22C3	0.430	-1.839	2.752	0.446	4.874	0.119
3X28SP32C3	0.451	-1.818	2.568	0.407	3.628	0.120
3X28SS42C3	0.462	-1.655	2.739	0.437	3.322	0.120
3X28SU12C3	0.416	-1.851	2.675	0.470	4.168	0.123
3X28TI12C3	0.450	-1.213	2.309	0.394	2.042	0.189
3X28TI22C3	0.452	-3.058	3.221	0.377	4.220	.038

Sensitivity Plots of Static Rollover Threshold

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

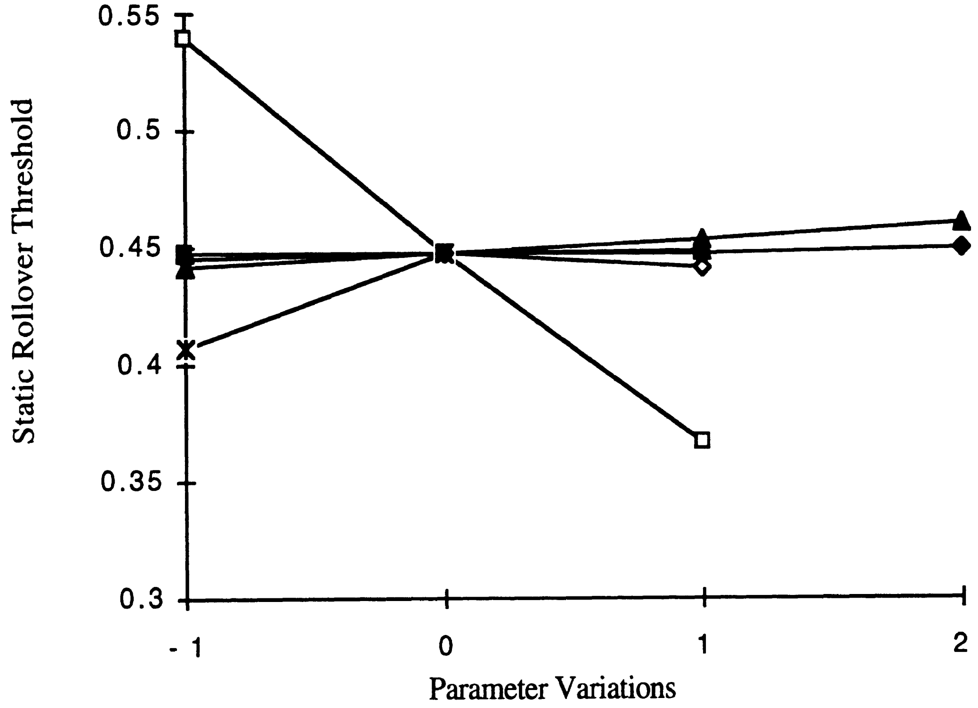


Figure C-103. Sensitivity of static rollover threshold: 28'x28' five-axle 2C3-train double

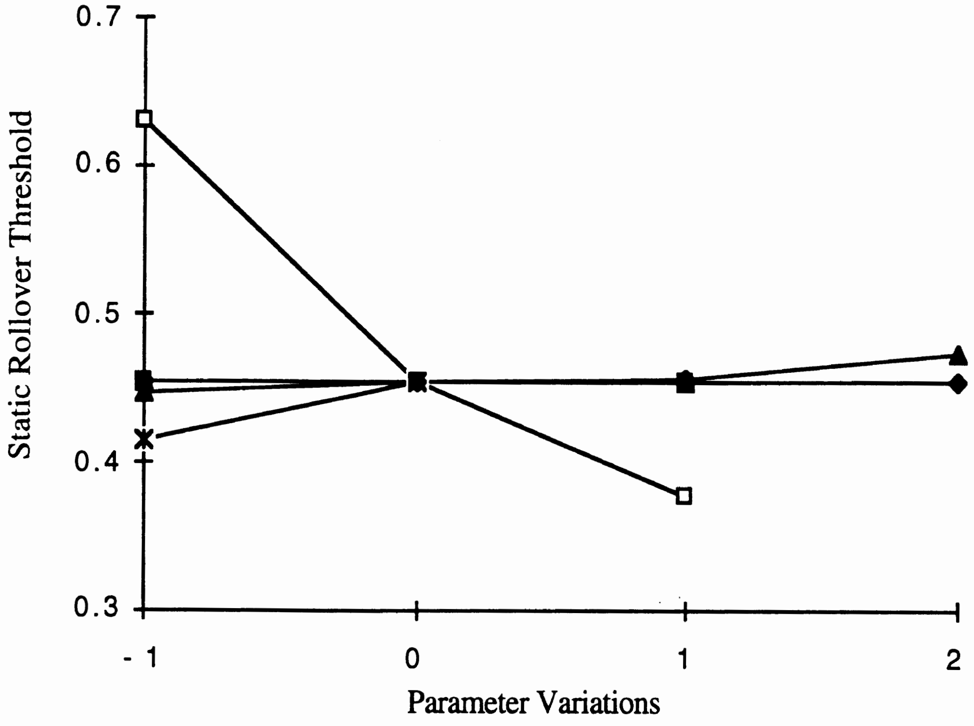


Figure C-104. Sensitivity of static rollover threshold: 32'x32' eight-axle 2C3-train double

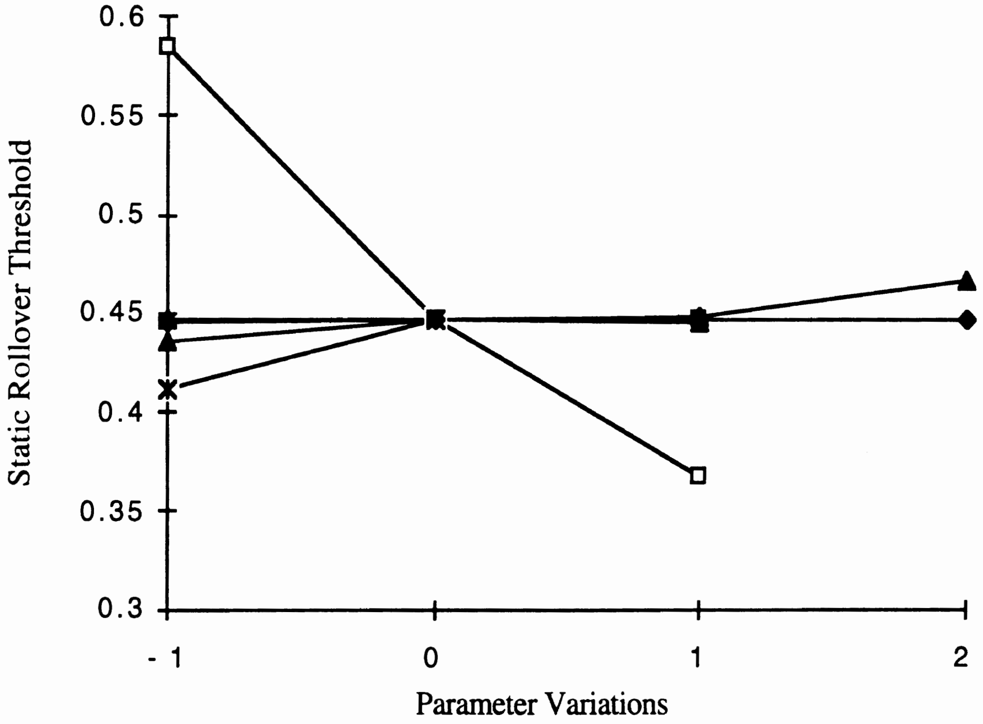


Figure C-105. Sensitivity of static rollover threshold: 38'x20' seven-axle 2C3-train double

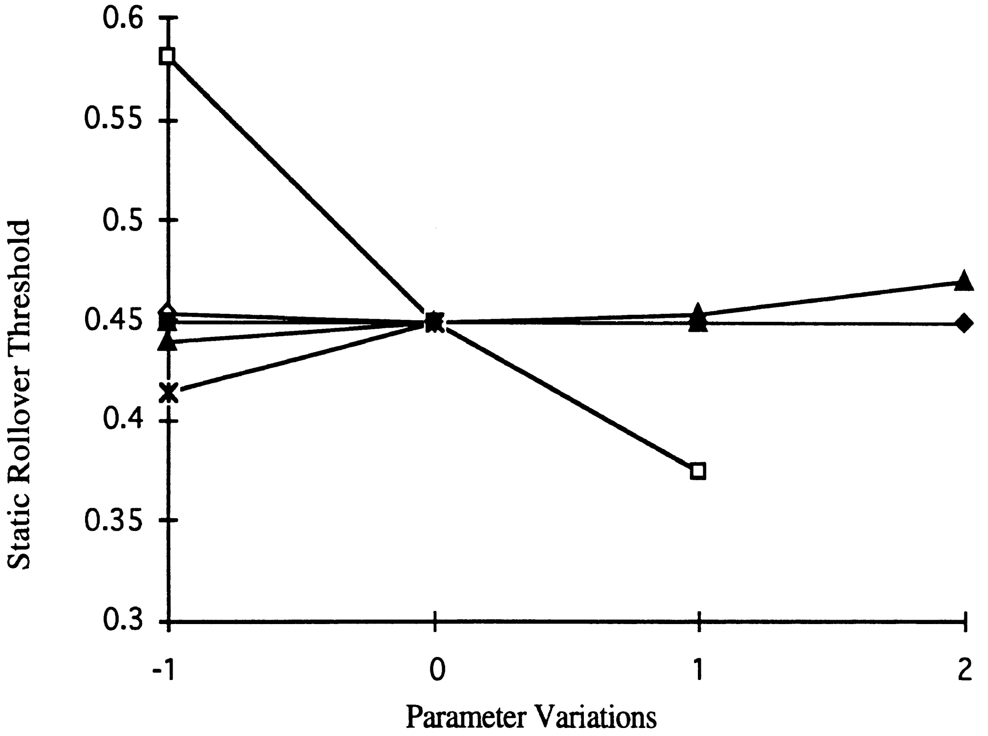


Figure C-106. Sensitivity of static rollover threshold: 45'x28' seven-axle 2C3-train double

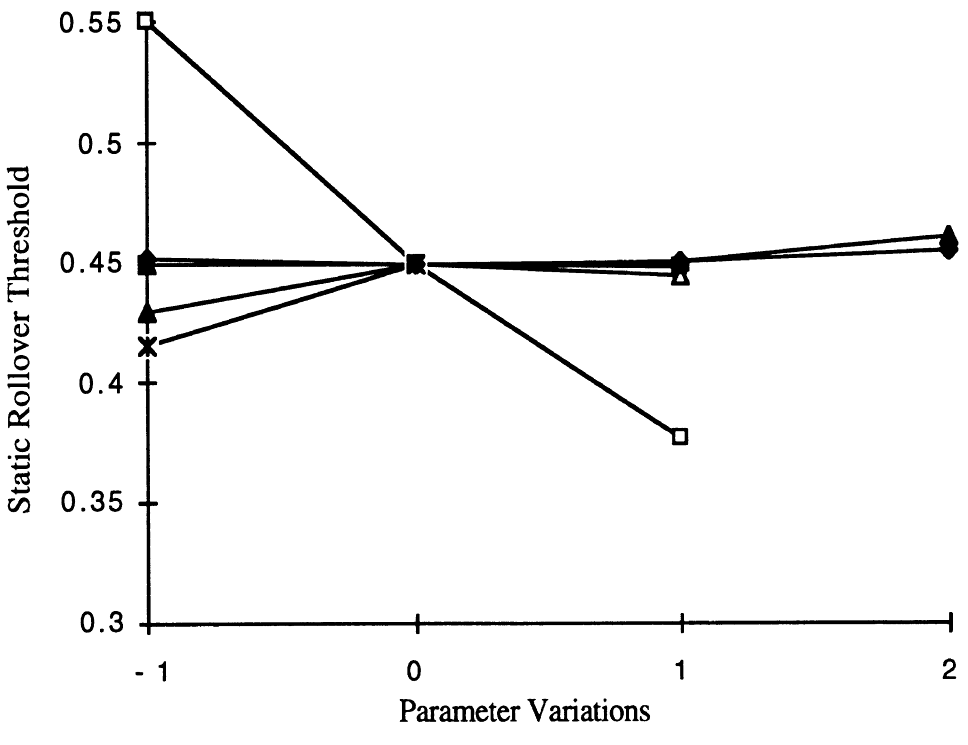


Figure C-107. Sensitivity of static rollover threshold: 28'x28'x28' seven-axle 2C3-train triple

Sensitivity Plots of High-Speed Steady-State Offtracking

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✱	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

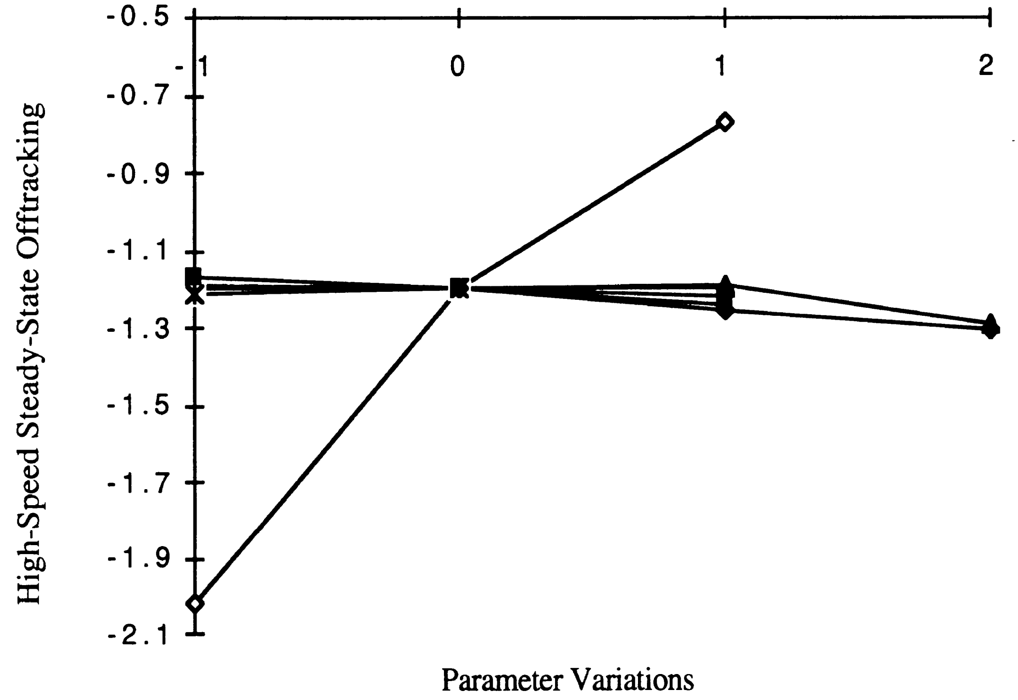


Figure C-108. Sensitivity of high-speed steady-state offtracking: 28'x28' five-axle 2C3-train double

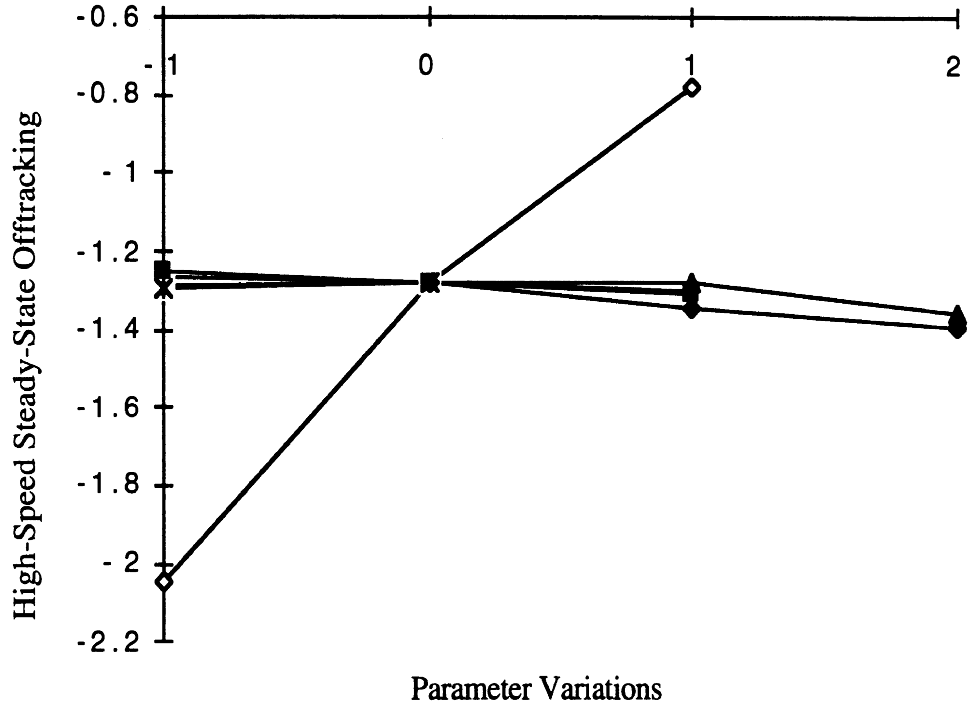


Figure C-109. Sensitivity of high-speed steady-state offtracking: 32'x32' eight-axle 2C3-train double

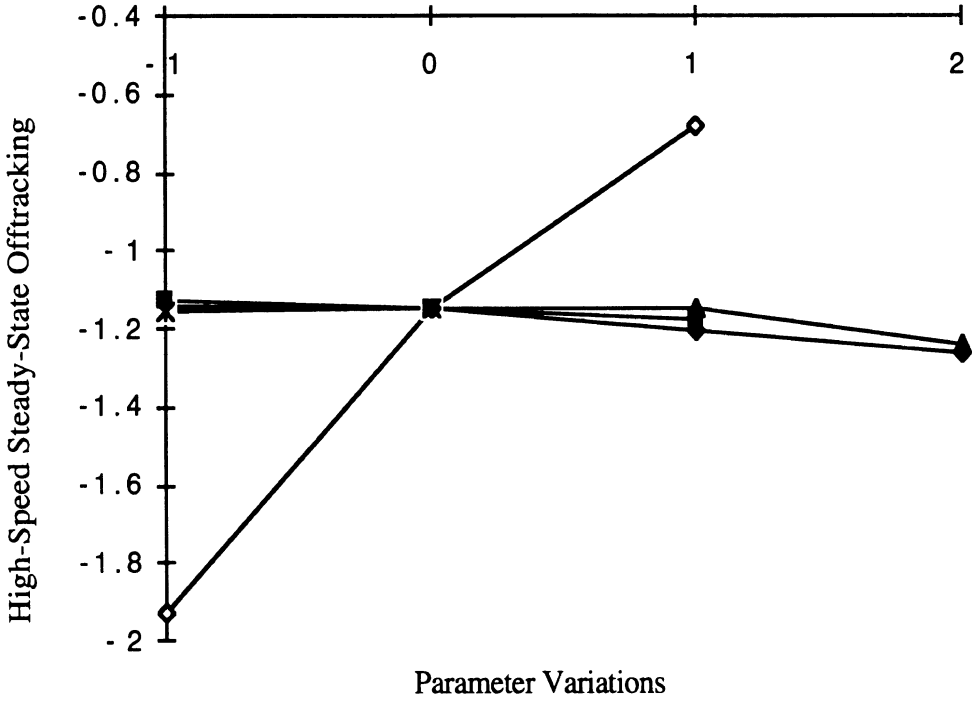


Figure C-110. Sensitivity of high-speed steady-state offtracking: 38'x20' seven-axle 2C3-train double

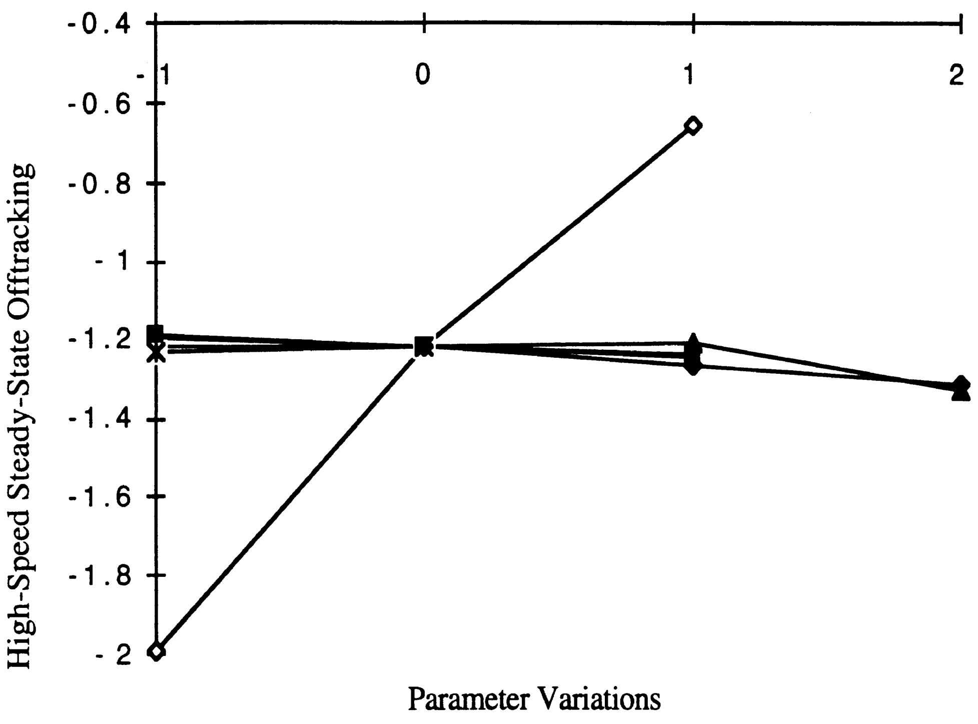


Figure C-111. Sensitivity of high-speed steady-state offtracking: 45'x28' seven-axle 2C3-train double

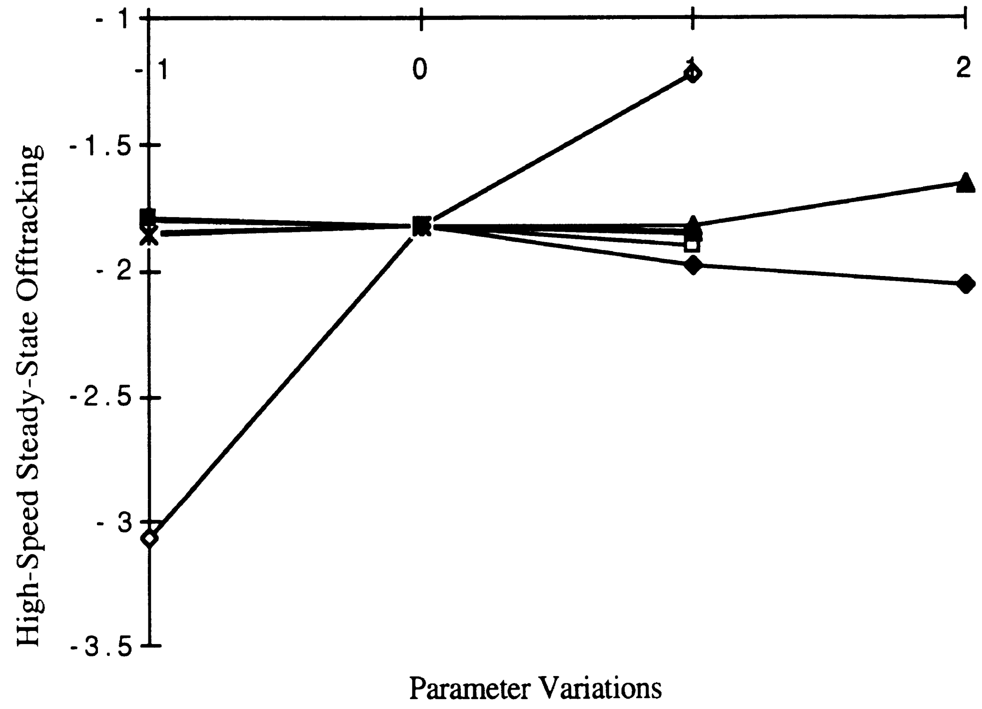


Figure C-112. Sensitivity of high-speed steady-state offtracking: 28'x28'x28' seven-axle 2C3-train triple

Sensitivity Plots of Rearward Amplification

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

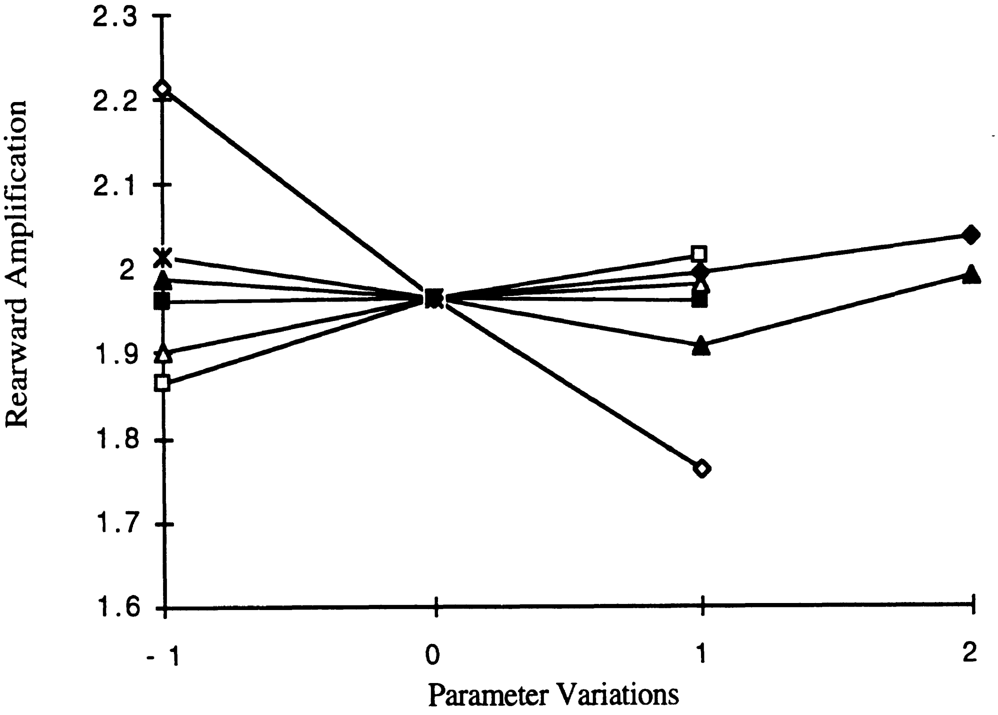


Figure C-113. Sensitivity of rearward amplification: 28'x28' five-axle 2C3-train double

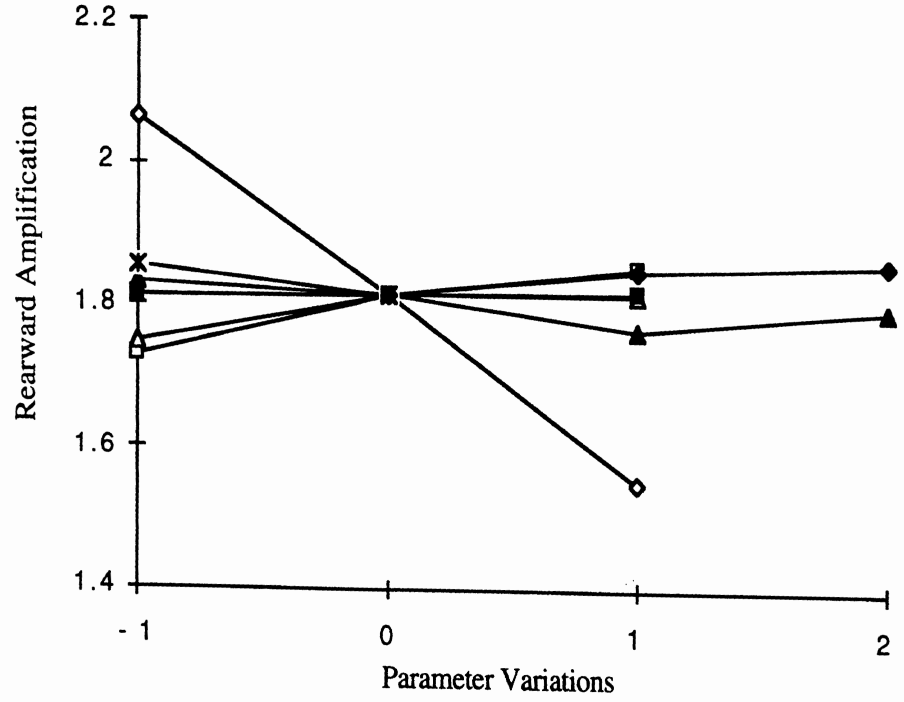


Figure C-114. Sensitivity of rearward amplification: 32'x32' eight-axle 2C3-train double

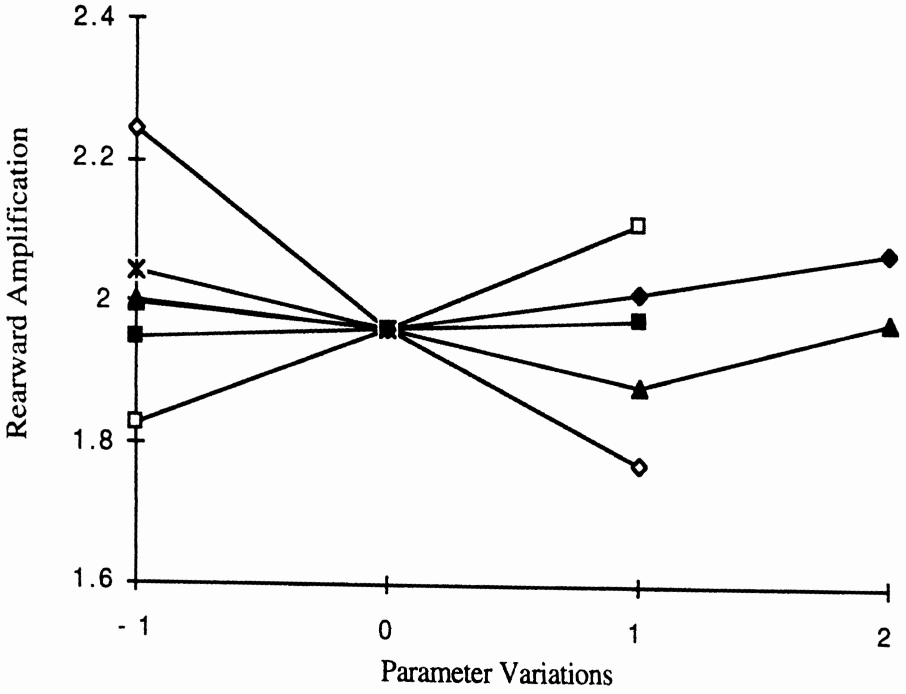


Figure C-115. Sensitivity of rearward amplification: 38'x20' seven-axle 2C3-train double

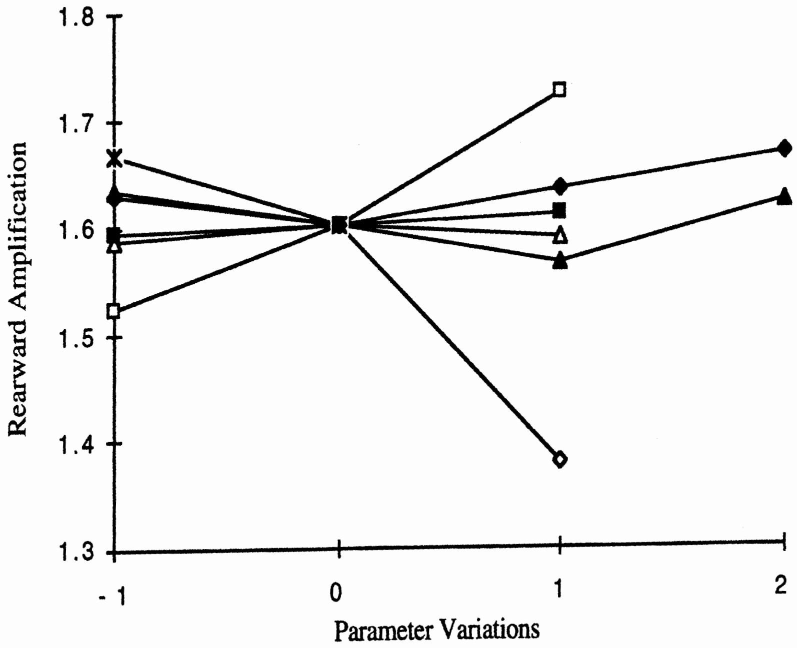


Figure C-116. Sensitivity of rearward amplification: 45'x28' seven-axle 2C3-train double

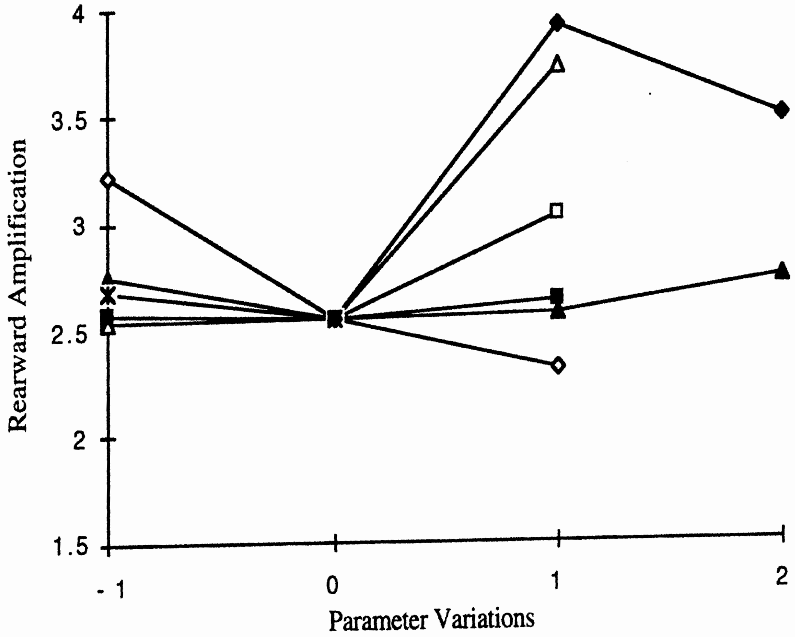


Figure C-117. Sensitivity of rearward amplification: 28'x28'x28' seven-axle 2C3-train triple

Sensitivity Plots of Dynamic-Load-Transfer Ratio

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

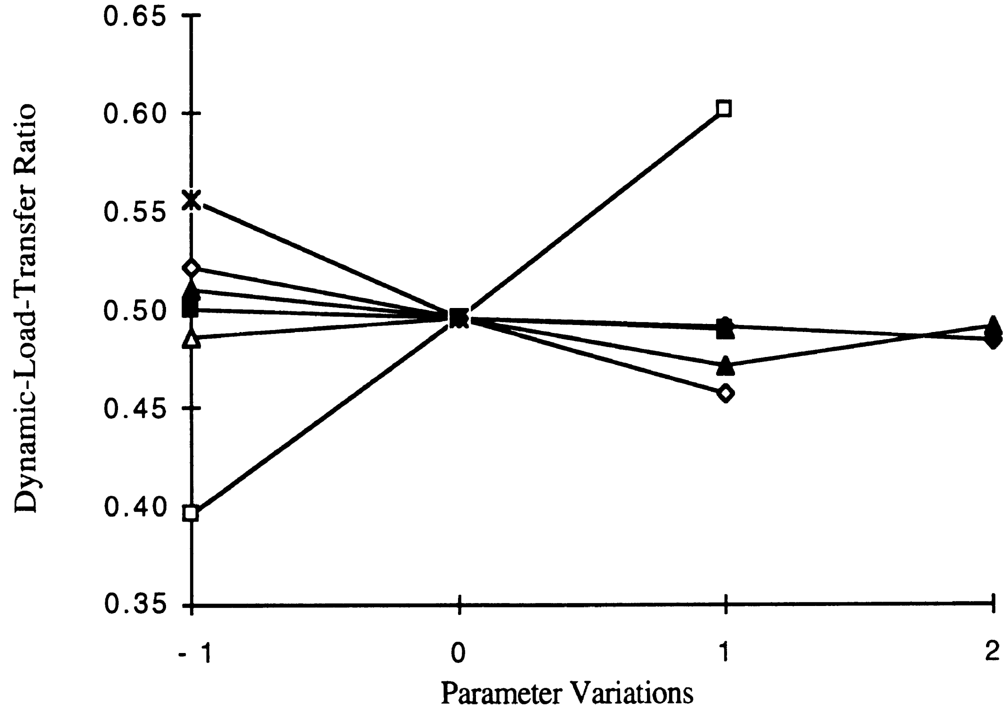


Figure C-118. Sensitivity of dynamic-load-transfer ratio: 28'x28' five-axle 2C3-train double

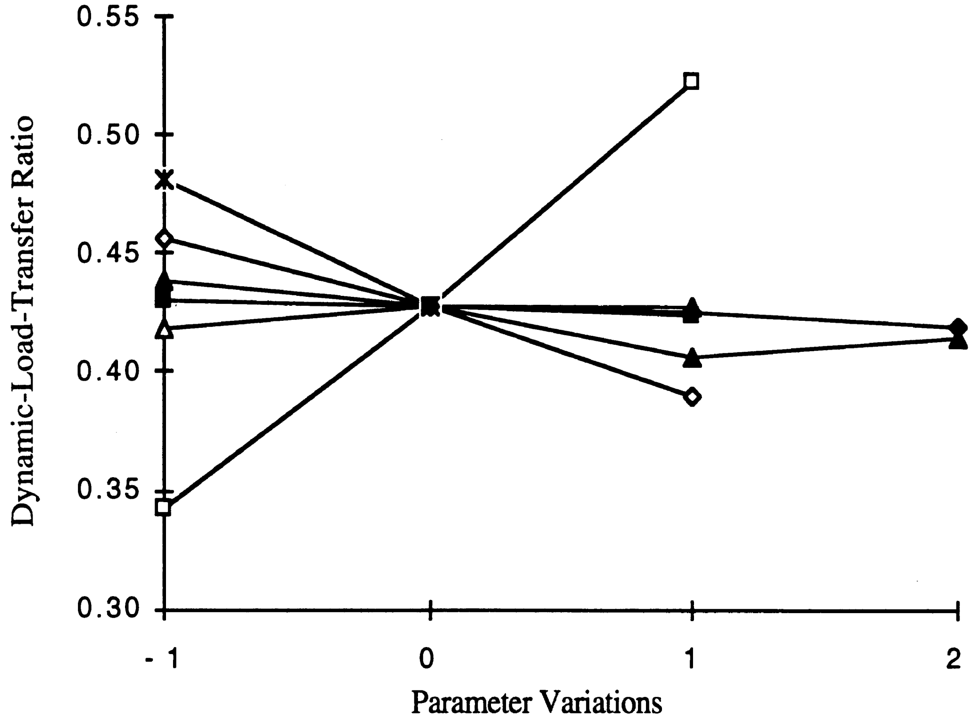


Figure C-119. Sensitivity of dynamic-load-transfer ratio: 32'x32' eight-axle 2C3-train double

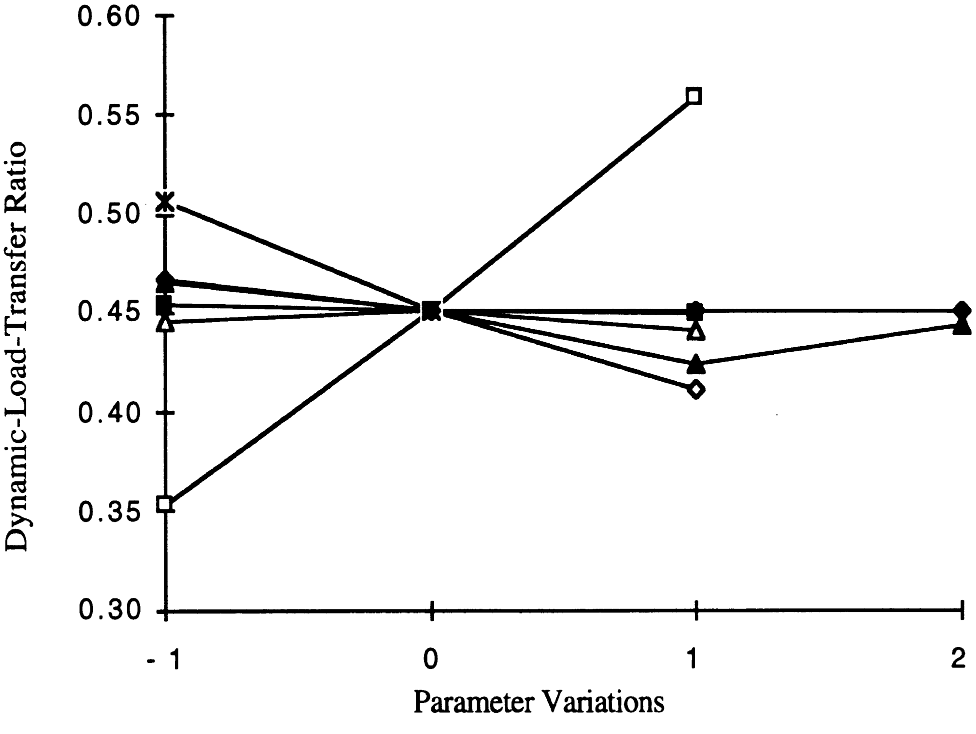


Figure C-120. Sensitivity of dynamic-load-transfer ratio: 38'x20' seven-axle 2C3-train double

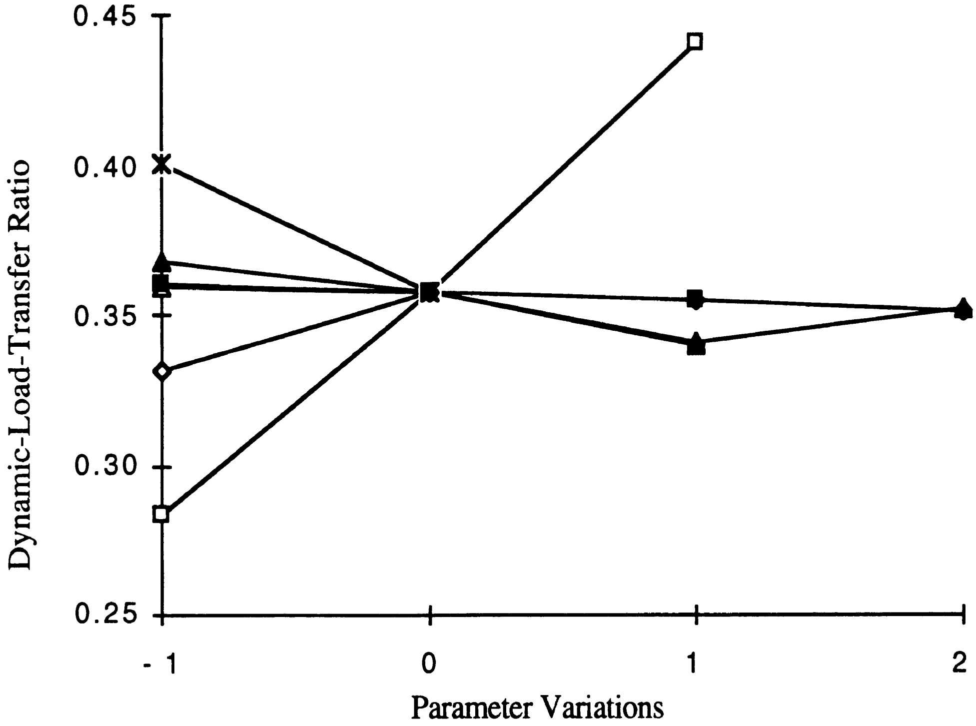


Figure C-121. Sensitivity of dynamic-load-transfer ratio: 45'x28' seven-axle 2C3-train double

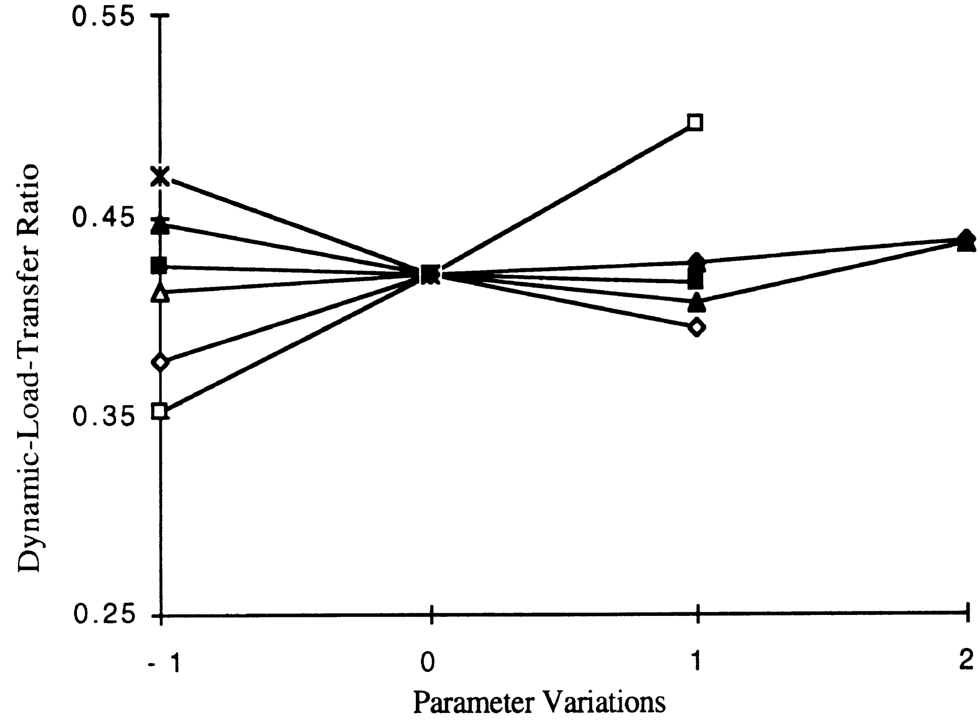


Figure C-122. Sensitivity of dynamic-load-transfer ratio: 28'x28'x28' seven-axle 2C3-train triple

Sensitivity Plots of Transient High-Speed Offtracking

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
─□─	Payload cg height, inches	70	85	100	None
─△─	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
─◇─	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
─▲─	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
─✱─	Overall axle width, inches	96	102	None	None
─■─	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
─◆─	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

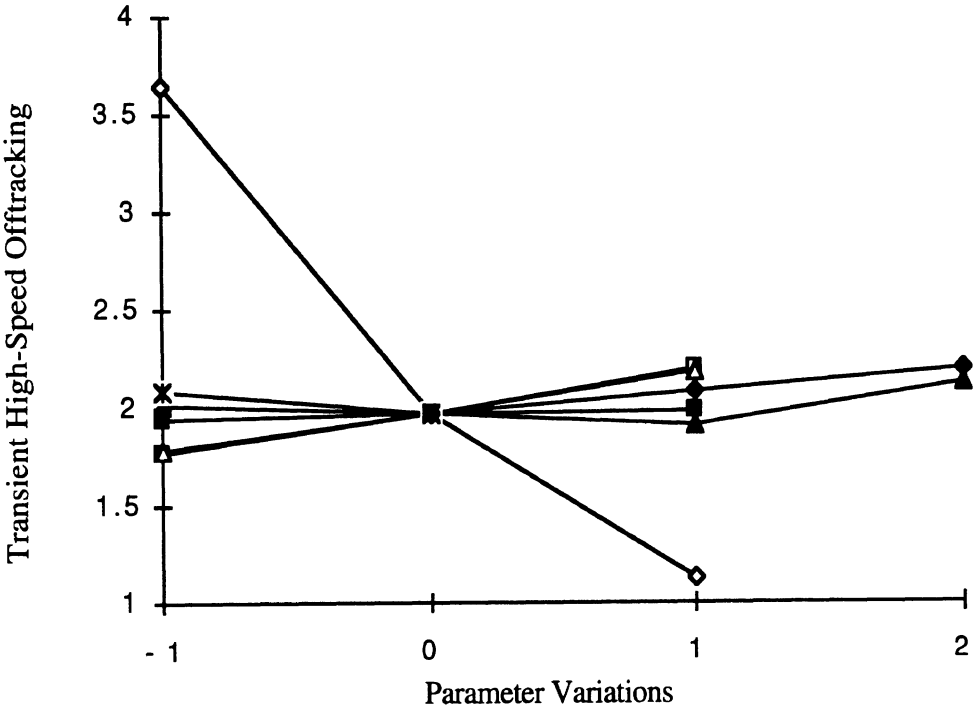


Figure C-123. Sensitivity of transient high-speed offtracking: 28'x28' five-axle 2C3-train double

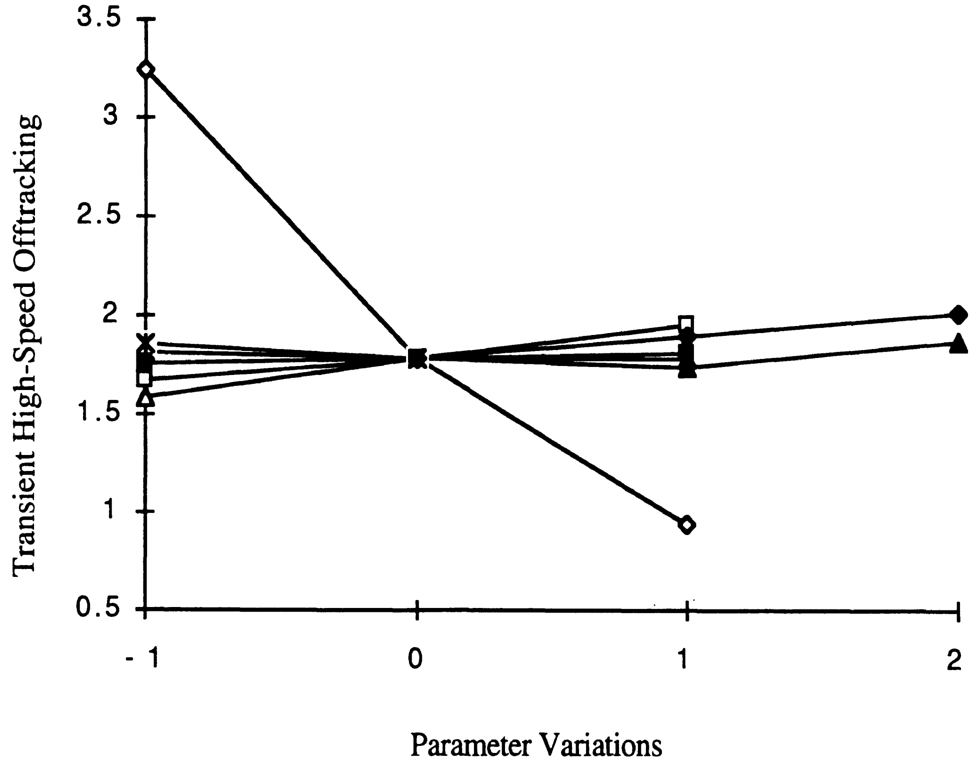


Figure C-124. Sensitivity of transient high-speed offtracking: 32'x32' eight-axle 2C3-train double

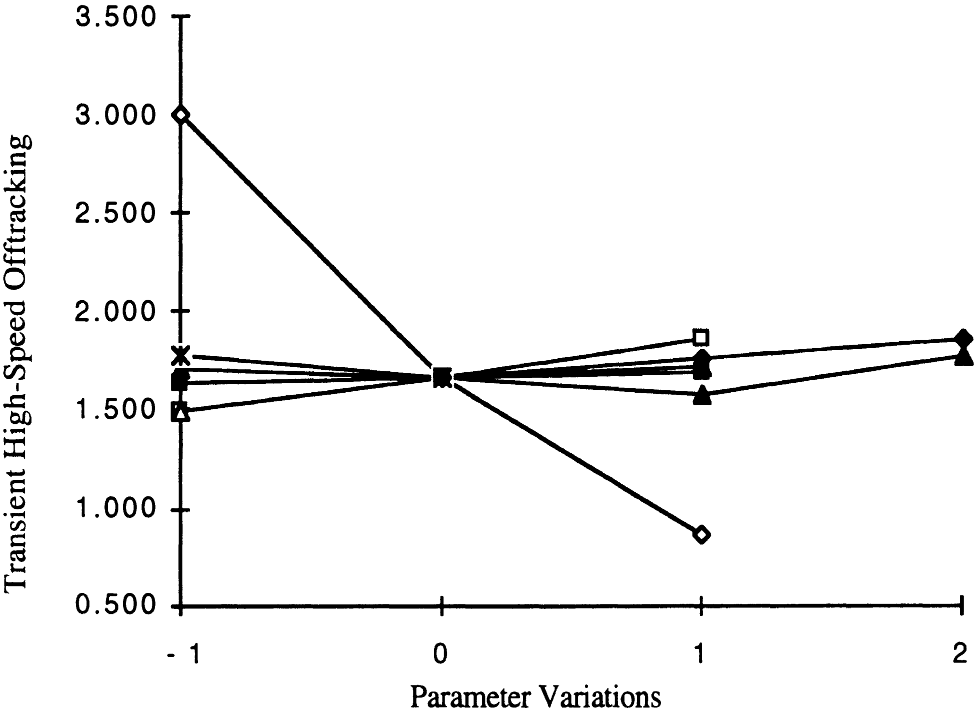


Figure C-125. Sensitivity of transient high-speed offtracking: 38'x20' seven-axle 2C3-train double

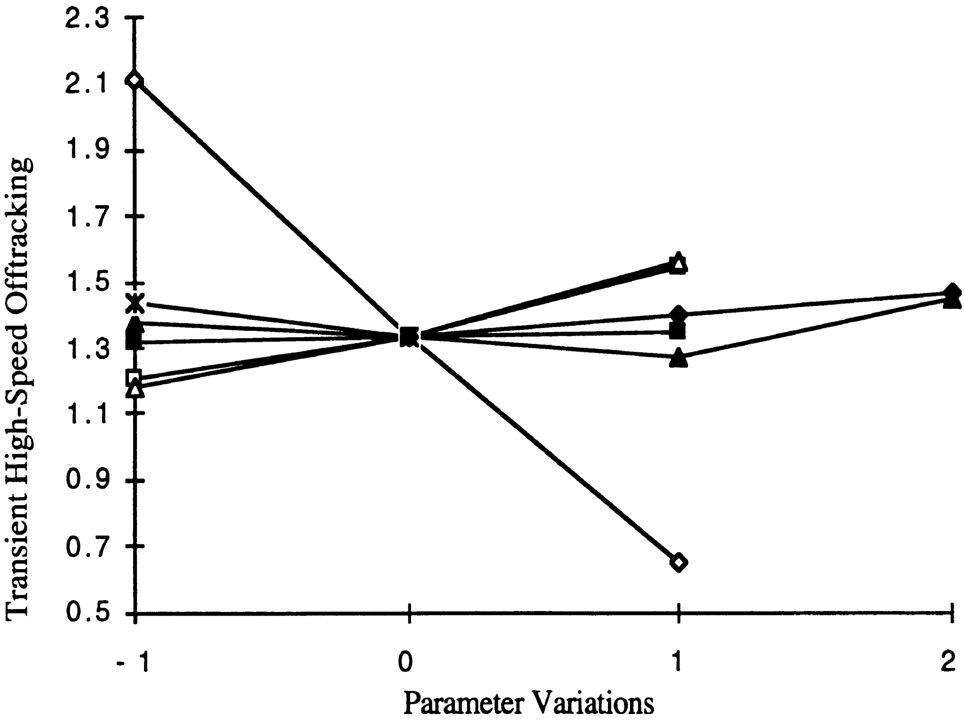


Figure C-126. Sensitivity of transient high-speed offtracking: 45'x28' seven-axle 2C3-train double

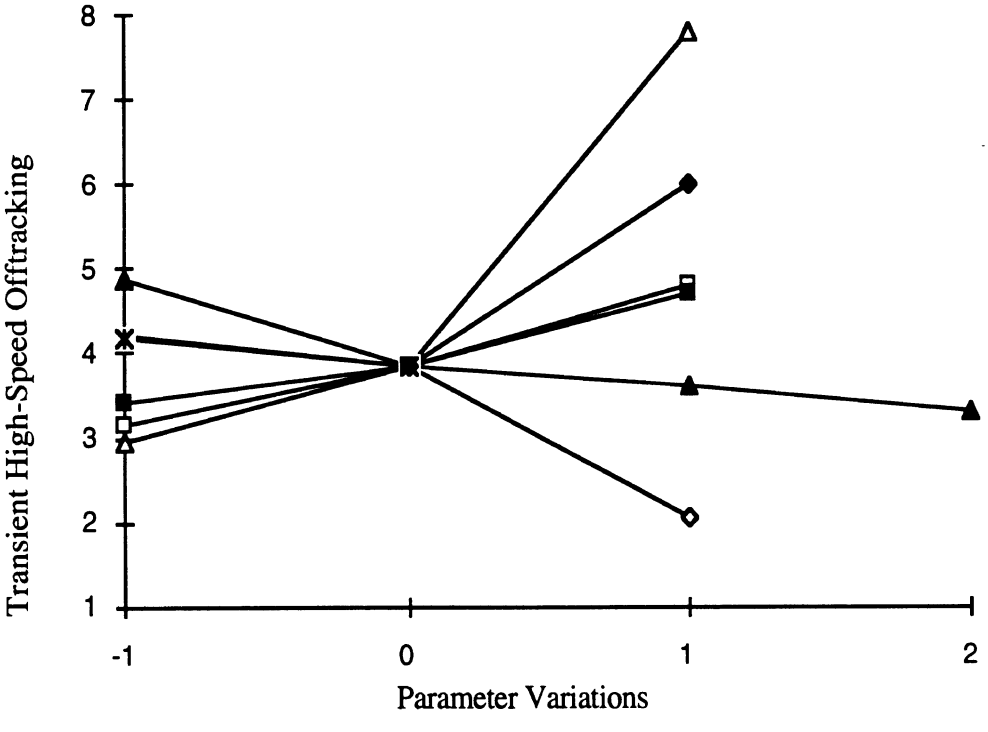


Figure C-127. Sensitivity of transient high-speed offtracking: 28'x28'x28' seven-axle 2C3-train triple

Sensitivity Plots of Damping Ratio in the RTAC-B Maneuver

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

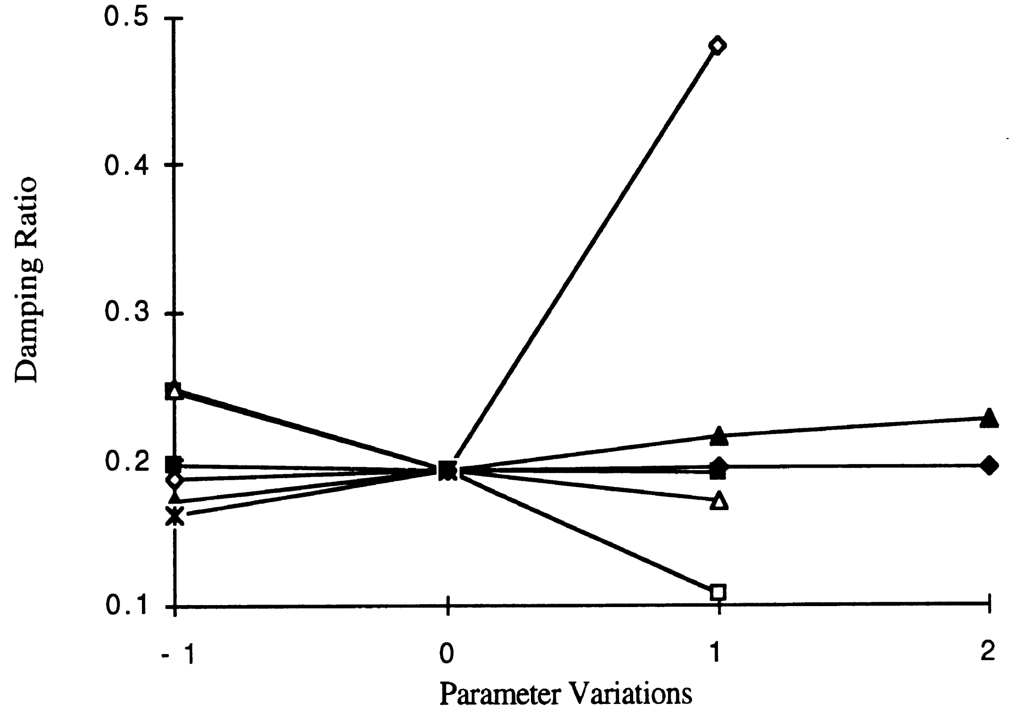


Figure C-128. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28' five-axle 2C3-train double

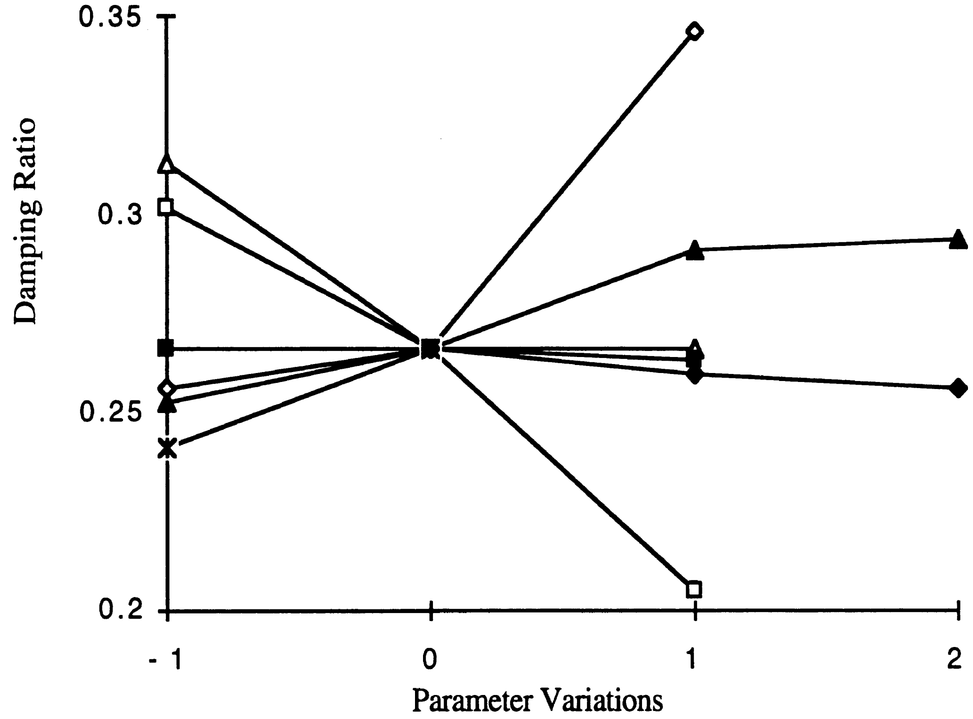


Figure C-129. Sensitivity of damping ratio in the RTAC-B maneuver: 32'x32' eight-axle 2C3-train double

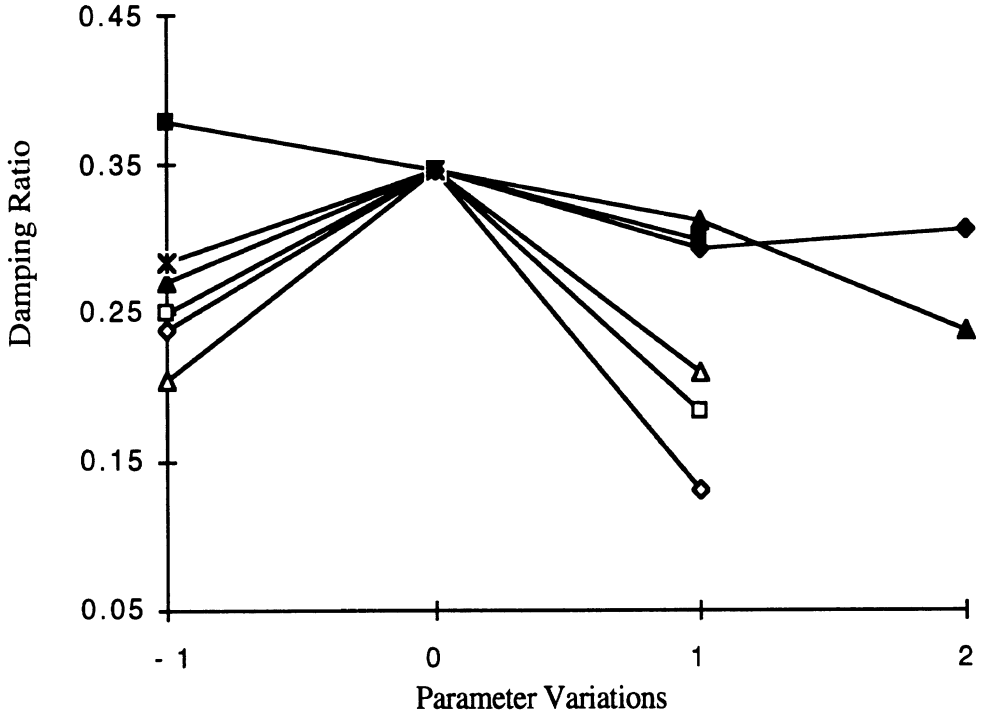


Figure C-130. Sensitivity of damping ratio in the RTAC-B maneuver: 38'x20' seven-axle 2C3-train double

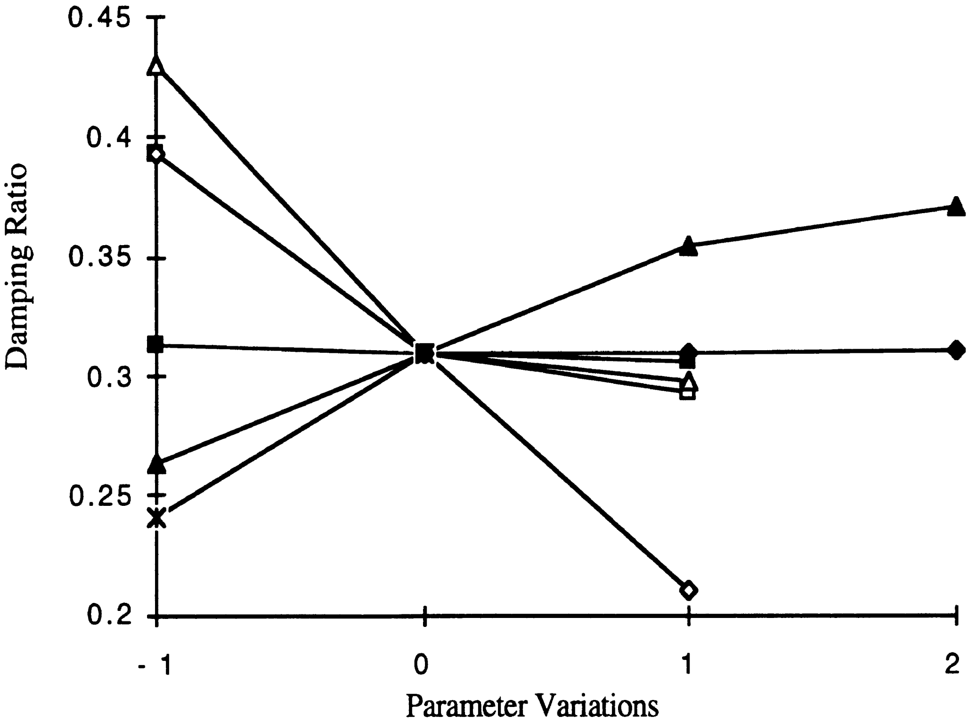


Figure C-131. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x28' seven-axle 2C3-train double

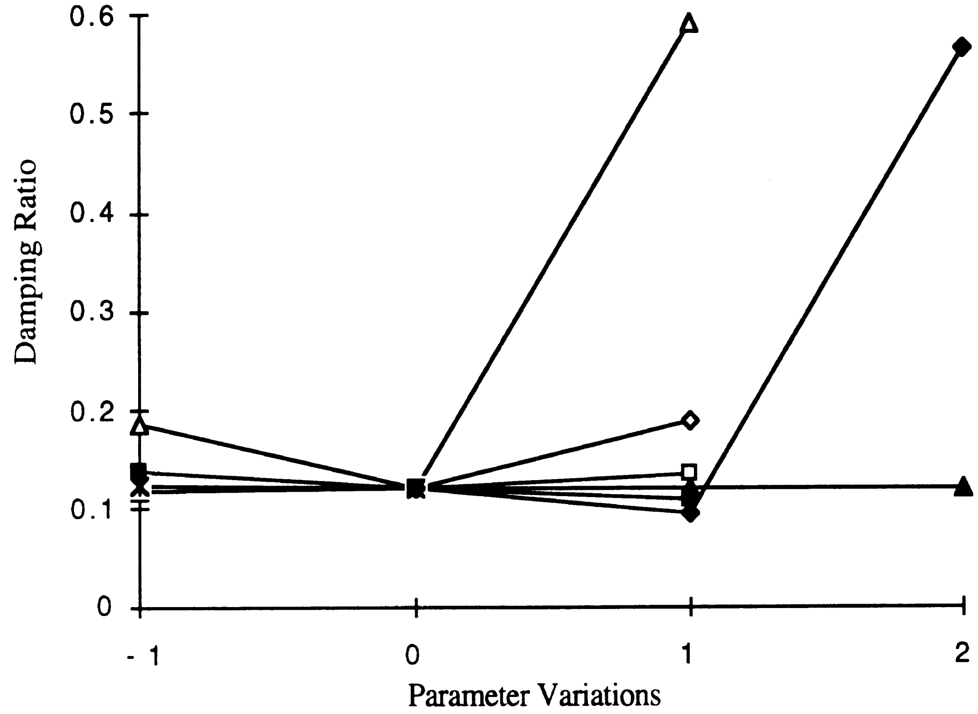


Figure C-132. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28'x28' seven-axle 2C3-train triple

SENSITIVITY STUDY RESULTS FOR THE 3C1-DOLLY

Table C-6. Performance measures obtained with the 3C1-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio
28x28bas3C1	0.428	-1.074	1.702	0.462	1.524	0.313
28x28do13C1	0.428	-1.102	1.702	0.455	1.545	0.305
28x28do23C1	0.428	-1.122	1.699	0.448	1.558	0.294
28x28pl13C1	0.369	-1.122	1.830	0.570	1.758	0.142
28x28pl23C1	0.523	-1.048	1.625	0.368	1.355	0.343
28x28pl33C1	0.430	-1.074	1.744	0.463	1.701	0.201
28x28pl43C1	0.426	-1.074	1.697	0.457	1.409	0.373
28x28se13C1	0.427	-1.092	1.703	0.457	1.537	0.311
28x28se23C1	0.430	-1.056	1.707	0.467	1.508	0.211
28x28sp23C1	0.420	-1.077	1.741	0.476	1.572	0.205
28x28sp33C1	0.433	-1.071	1.659	0.442	1.465	0.305
28x28ss23C1	0.463	-1.172	1.726	0.458	1.663	0.240
28x28su13C1	0.406	-1.096	1.772	0.520	1.641	0.209
28x28ti13C1	0.432	-0.767	1.634	0.434	0.974	0.135
28x28ti23C1	0.436	-1.640	1.865	0.458	2.541	0.361
32x32bas3C1	0.443	-1.143	1.602	0.405	1.410	0.296
32x32do13C1	0.442	-1.166	1.606	0.400	1.432	0.283
32x32do23C1	0.441	-1.191	1.605	0.394	1.447	0.264
32x32pl13C1	0.376	-1.173	1.700	0.498	1.548	0.207
32x32pl23C1	0.531	-1.121	1.527	0.324	1.297	0.358
32x32pl33C1	0.443	-1.143	1.602	0.405	1.410	0.296
32x32pl43C1	0.444	-1.144	1.561	0.398	1.265	0.329
32x32se13C1	0.443	-1.157	1.605	0.402	1.425	0.285
32x32se23C1	0.444	-1.121	1.603	0.408	1.393	0.303
32x32sp23C1	0.436	-1.145	1.626	0.416	1.439	0.281
32x32sp33C1	0.446	-1.136	1.561	0.387	1.362	0.338
32x32ss43C1	0.458	-1.224	1.592	0.392	1.483	0.305
32x32su13C1	0.413	-1.158	1.659	0.454	1.479	0.269
32x32ti13C1	0.450	-0.736	1.470	0.377	0.809	0.401
32x32ti23C1	0.453	-1.668	1.744	0.405	2.237	0.415
38x20bas3C1	0.438	-1.026	1.707	0.415	1.248	0.308
38x20do13C1	0.439	-1.056	1.715	0.410	1.269	0.295
38x20do23C1	0.438	-1.087	1.728	0.406	1.285	0.281
38x20pl13C1	0.367	-1.053	1.902	0.523	1.444	0.241
38x20pl23C1	0.553	-1.021	1.587	0.326	1.116	0.351
38x20pl33C1	0.439	-1.025	1.668	0.413	1.322	0.253
38x20pl43C1	0.438	-1.026	1.733	0.412	1.136	0.181
38x20se13C1	0.438	-1.043	1.707	0.411	1.261	0.297
38x20se23C1	0.438	-1.009	1.706	0.418	1.235	0.322
38x20sp23C1	0.427	-1.028	1.736	0.427	1.287	0.296
38x20sp33C1	0.442	-1.024	1.639	0.393	1.188	0.344
38x20ss43C1	0.454	-1.122	1.713	0.406	1.345	0.299
38x20su13C1	0.411	-1.034	1.792	0.465	1.332	0.290
38x20ti13C1	0.437	-0.663	1.605	0.387	0.715	0.125
38x20ti23C1	0.443	-1.574	1.842	0.418	2.041	0.221
45x28bas3C1	0.443	-1.064	1.435	0.343	1.010	0.299
45x28do13C1	0.444	-1.085	1.437	0.337	1.019	0.275
45x28do23C1	0.443	-1.105	1.437	0.332	1.027	0.259
45x28pl13C1	0.372	-1.101	1.539	0.425	1.183	0.286
45x28pl23C1	0.583	-1.043	1.358	0.272	0.919	0.214
45x28pl33C1	0.444	-1.064	1.431	0.334	1.173	0.253
45x28pl43C1	0.443	-1.061	1.413	0.344	0.915	0.124
45x28se13C1	0.443	-1.078	1.436	0.339	1.016	0.281
45x28se23C1	0.443	-1.048	1.433	0.346	1.009	0.324
45x28sp23C1	0.433	-1.069	1.457	0.352	1.044	0.315
45x28sp33C1	0.446	-1.061	1.397	0.327	0.968	0.274
45x28ss43C1	0.457	-1.182	1.452	0.335	1.100	0.169
45x28su13C1	0.412	-1.082	1.487	0.382	1.079	0.312
45x28ti13C1	0.444	-0.636	1.290	0.326	0.548	0.157
45x28ti23C1	0.447	-1.724	1.583	0.336	1.851	0.305
3X28BAS3C1	0.431	-1.625	2.080	0.371	2.729	0.359
3X28DO13C1	0.432	-1.681	2.066	0.363	3.052	0.358
3X28DO23C1	0.436	-1.742	2.037	0.354	3.139	0.358
3X28PL13C1	0.371	-1.693	2.157	0.439	3.557	0.309
3X28PL23C1	0.504	-1.585	1.966	0.303	2.175	0.392
3X28PL33C1	0.430	-1.623	2.109	0.369	3.209	0.306
3X28PL43C1	0.432	-1.625	2.065	0.370	2.448	0.362
3X28SE13C1	0.430	-1.656	2.058	0.365	2.917	0.361
3X28SE23C1	0.431	-1.596	2.093	0.380	2.514	0.304
3X28SP23C1	0.414	-1.644	2.201	0.387	3.073	0.328
3X28SP33C1	0.429	-1.620	2.037	0.353	2.372	0.368
3X28SS43C1	0.444	-1.456	2.000	0.383	2.737	0.321
3X28SU13C1	0.403	-1.658	2.121	0.414	3.070	0.324
3X28TI13C1	0.435	-1.210	1.995	0.366	1.335	0.311
3X28TI23C1	0.434	-2.375	2.237	0.379	3.545	0.279

Sensitivity Plots of Static Rollover Threshold

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

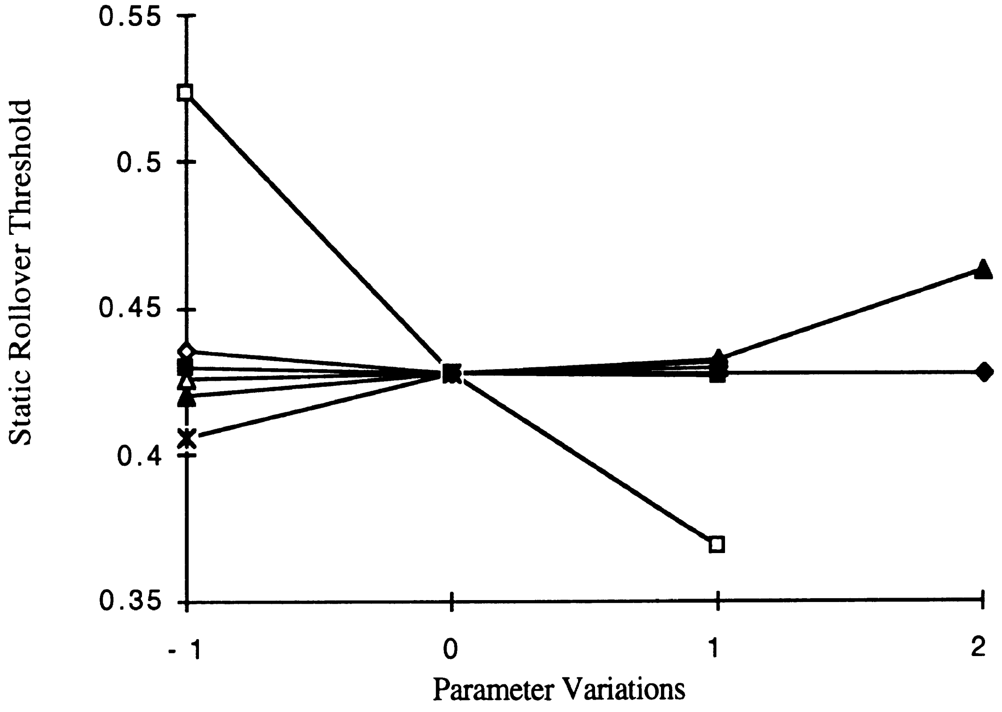


Figure C-133. Sensitivity of static rollover threshold: 28'x28' five-axle 3C1-train double

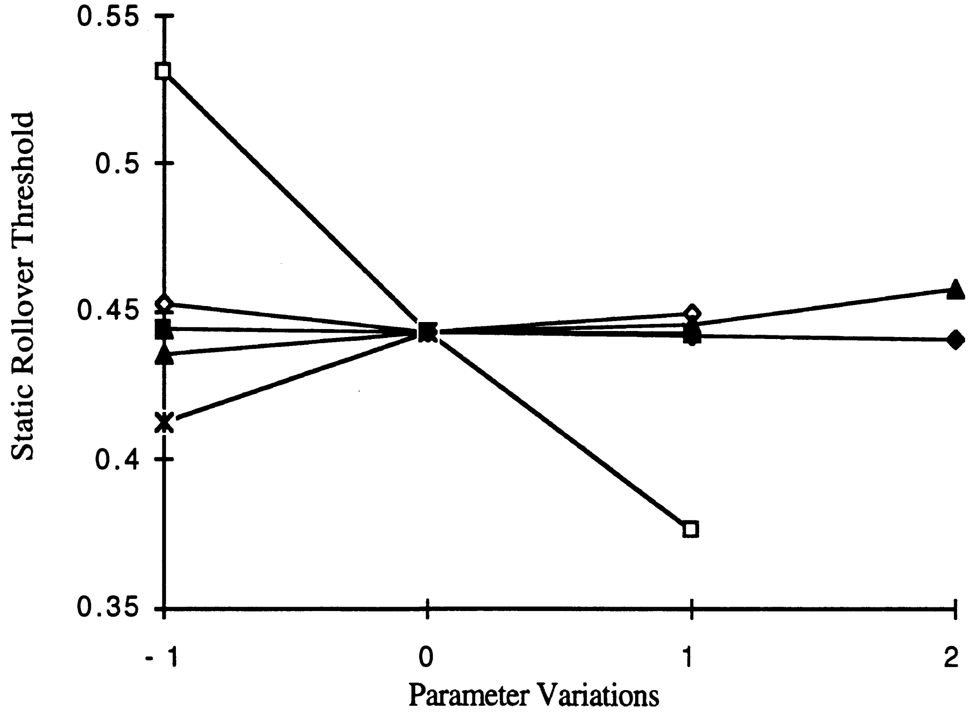


Figure C-134. Sensitivity of static rollover threshold: 32'x32' eight-axle 3C1-train double

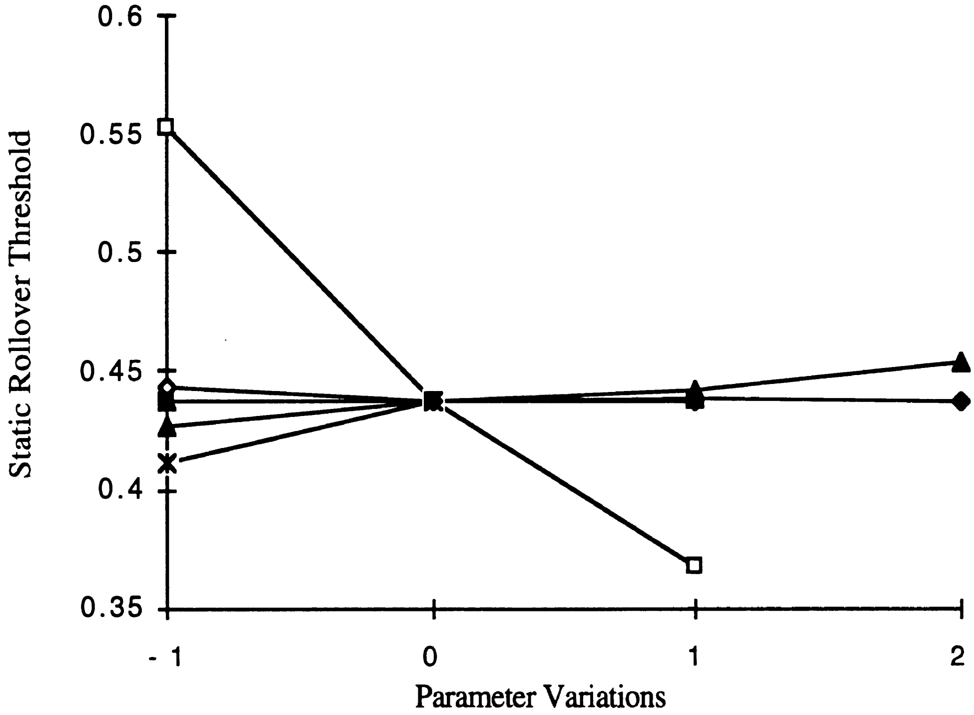


Figure C-135. Sensitivity of static rollover threshold: 38'x20' seven-axle 3C1-train double

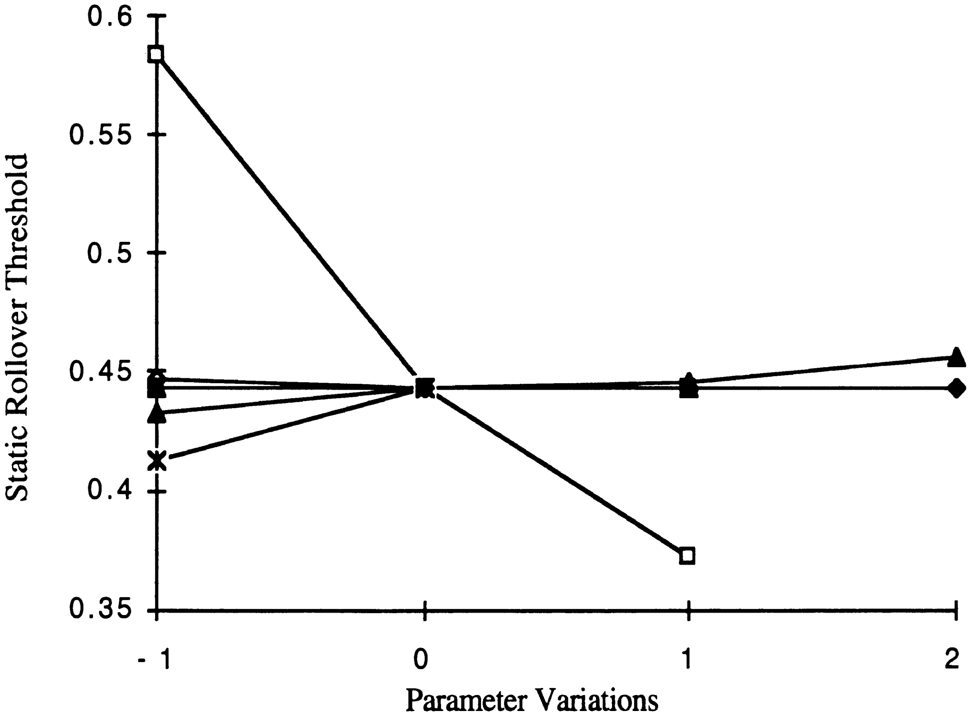


Figure C-136. Sensitivity of static rollover threshold: 45'x28' seven-axle 3C1-train double

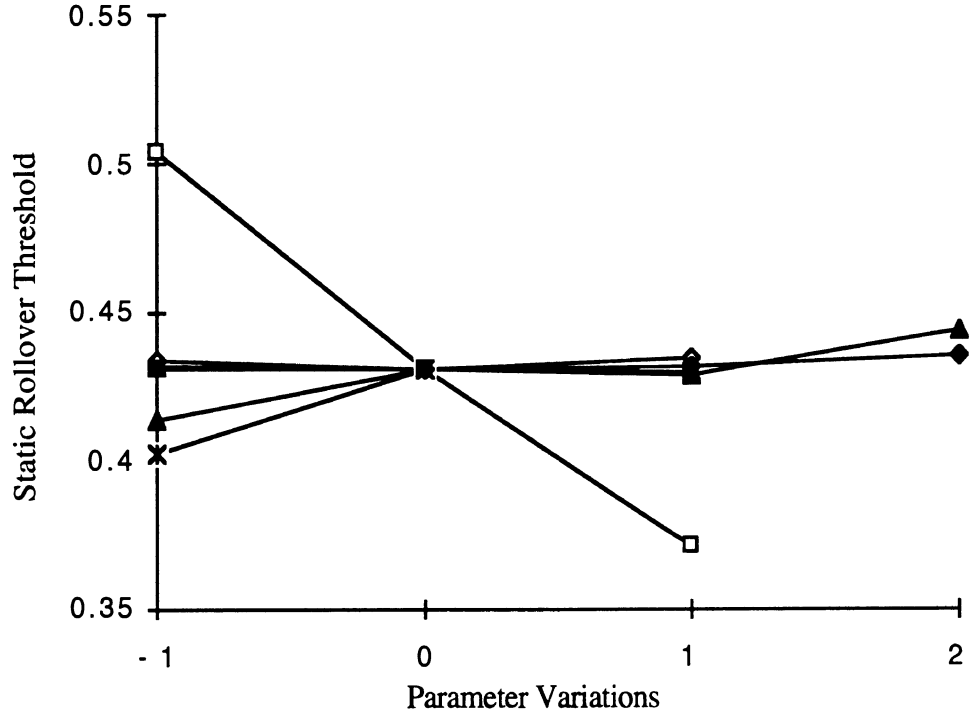


Figure C-137. Sensitivity of static rollover threshold: 28'x28'x28' seven-axle 3C1-train triple

Sensitivity Plots of High-Speed Steady-State Offtracking

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
─□─	Payload cg height, inches	70	85	100	None
─△─	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
─◇─	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
─▲─	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
─✱─	Overall axle width, inches	96	102	None	None
─■─	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
─◆─	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

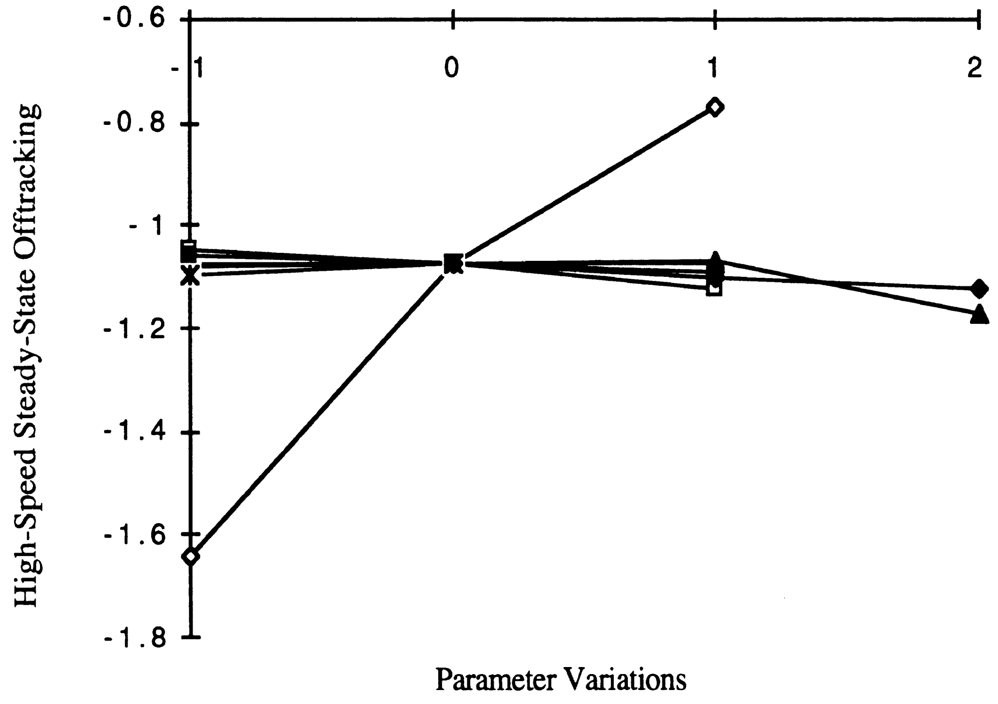


Figure C-138. Sensitivity of high-speed steady-state offtracking: 28'x28' five-axle 3C1-train double

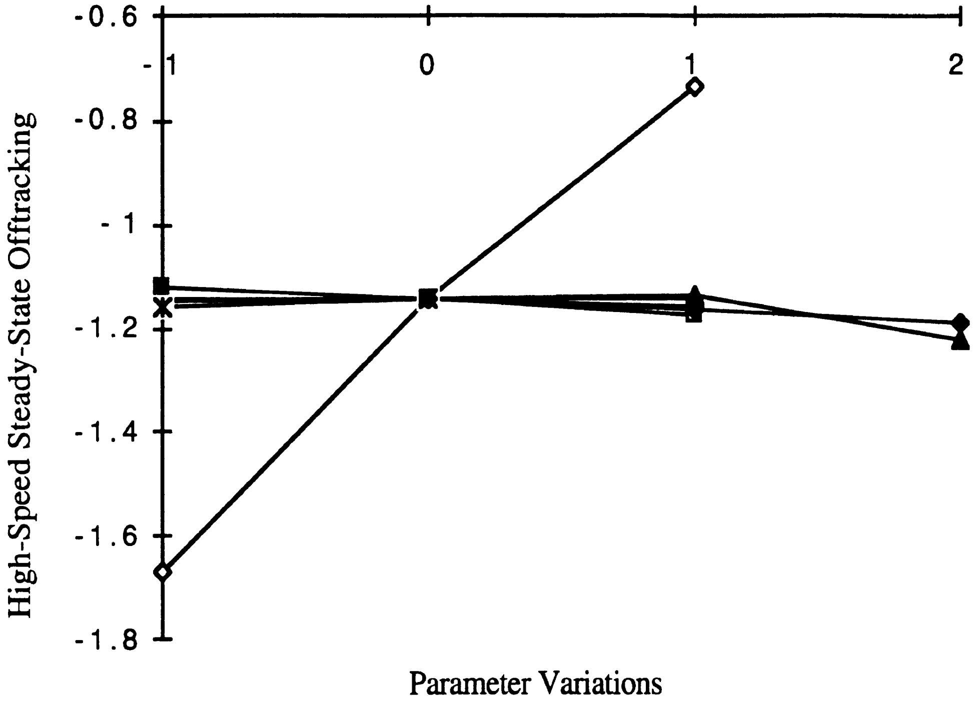


Figure C-139. Sensitivity of high-speed steady-state offtracking: 32'x32' eight-axle 3C1-train double

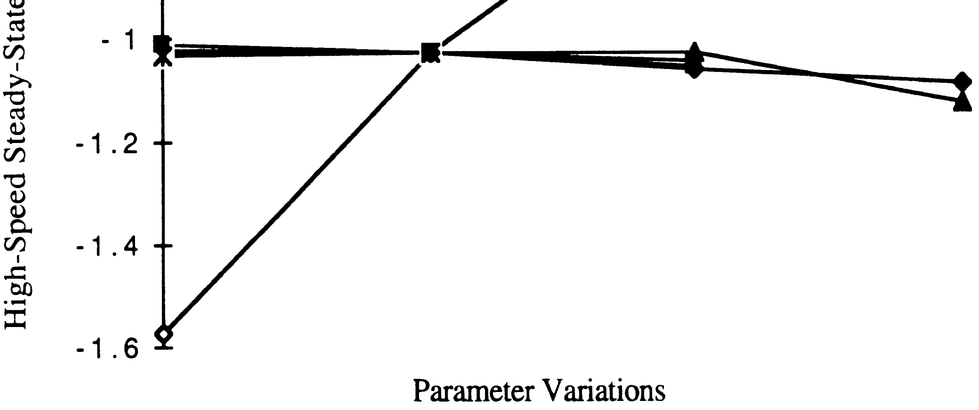


Figure C-140. Sensitivity of high-speed steady-state offtracking: 38'x20' seven-axle 3C1-train double

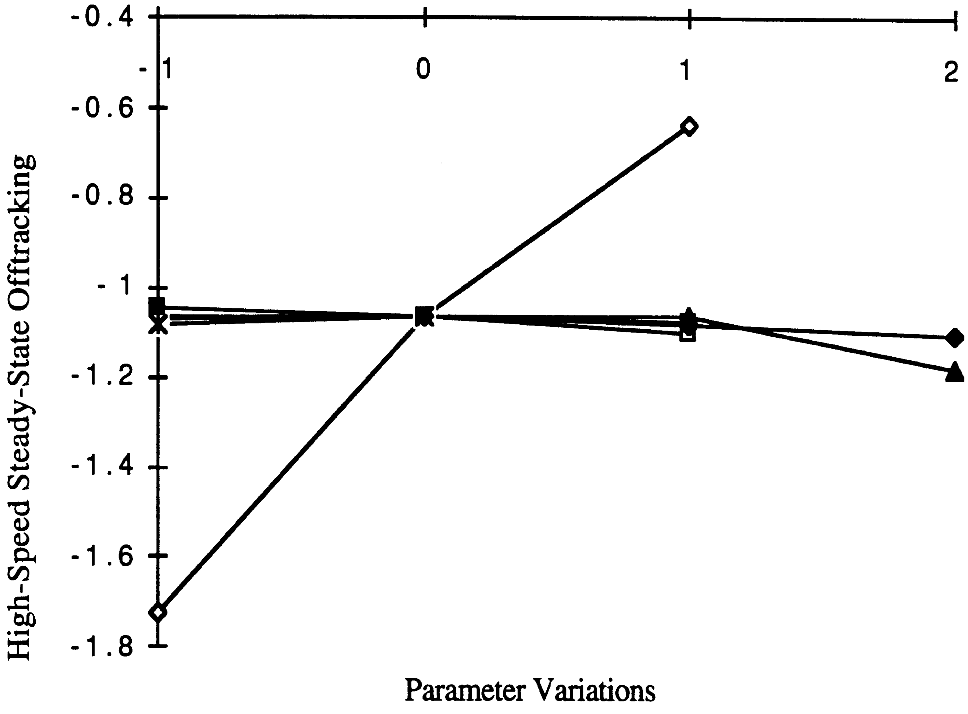


Figure C-141. **Sensitivity of high-speed steady-state offtracking: 45'x28' seven-axle 3C1-train double**

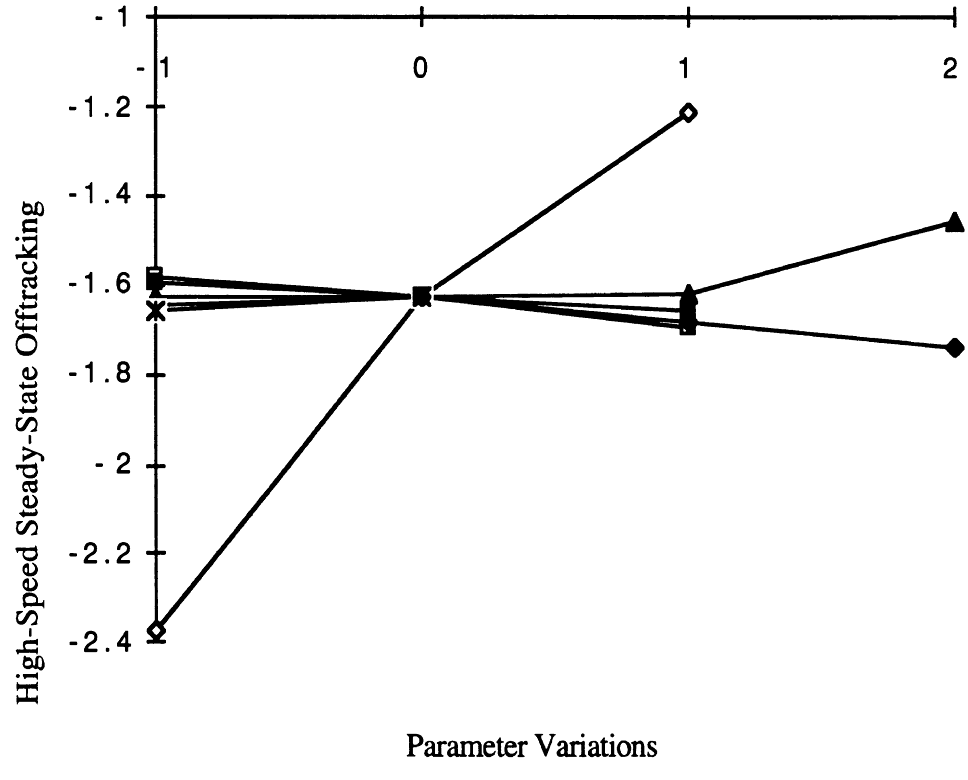


Figure C-142. **Sensitivity of high-speed steady-state offtracking: 28'x28'x28' seven-axle 3C1-train triple**

Sensitivity Plots of Rearward Amplification

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

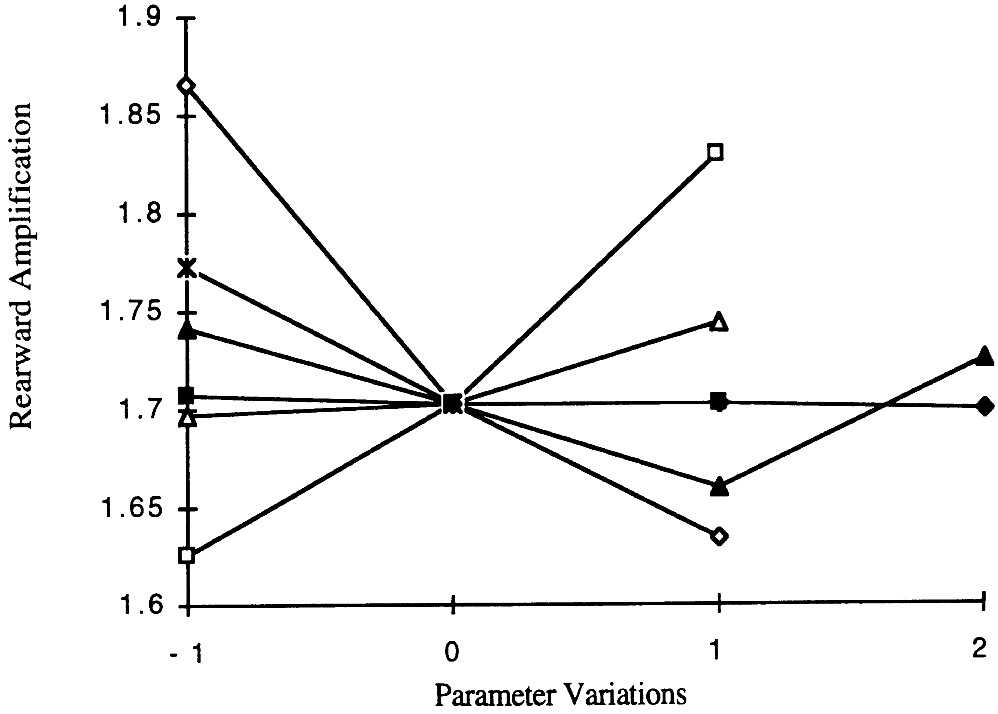


Figure C-143. Sensitivity of rearward amplification: 28'x28' five-axle 3C1-train double

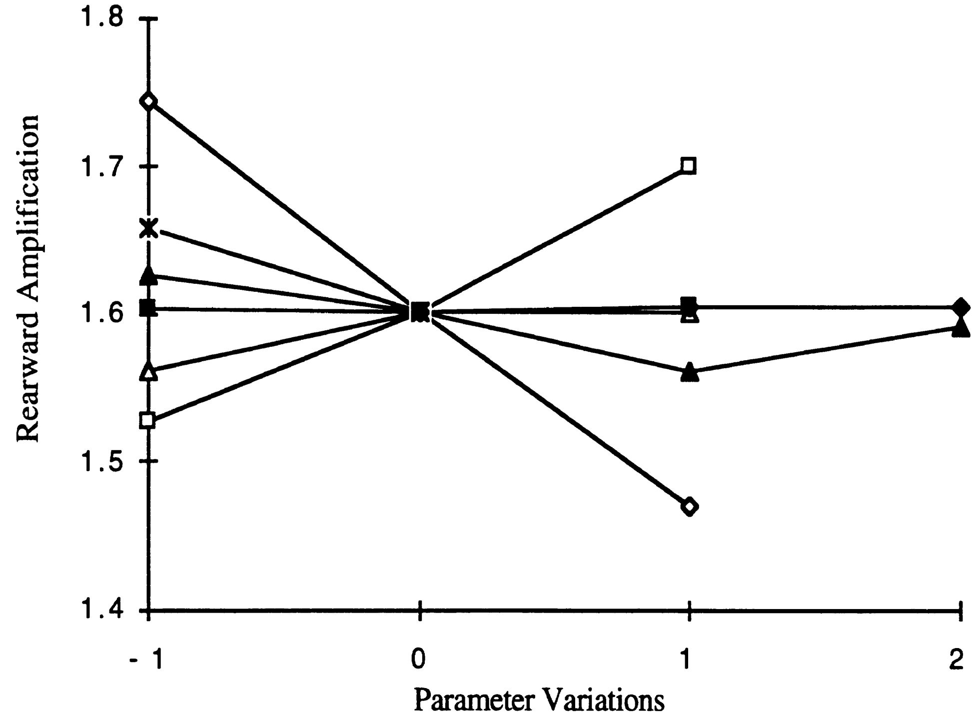


Figure C-144. Sensitivity of rearward amplification: 32'x32' eight-axle 3C1-train double

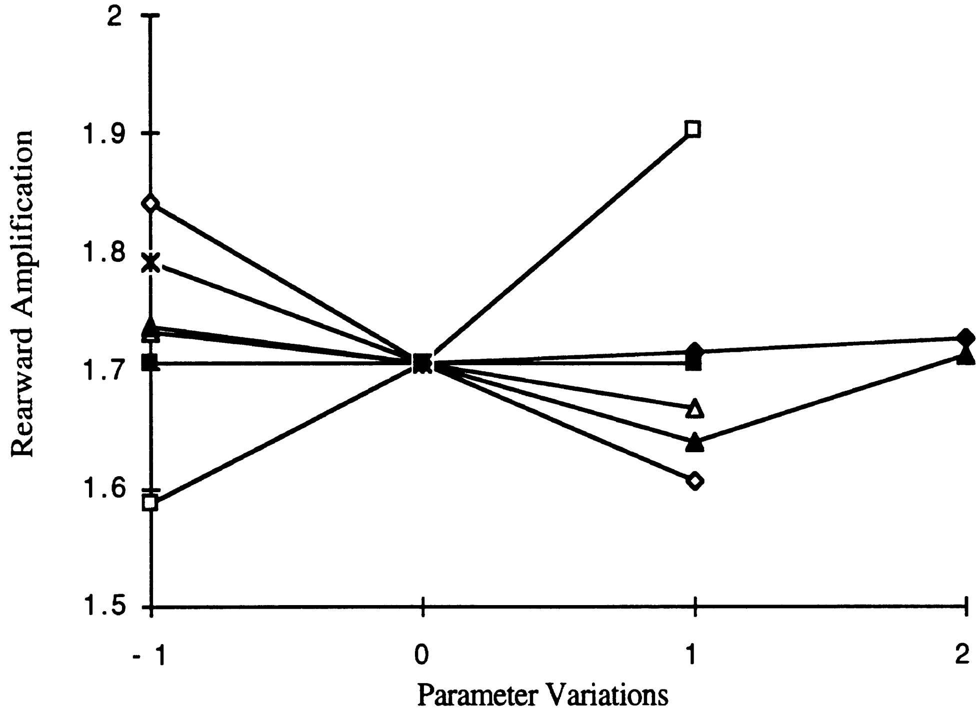


Figure C-145. Sensitivity of rearward amplification: 38'x20' seven-axle 3C1-train double

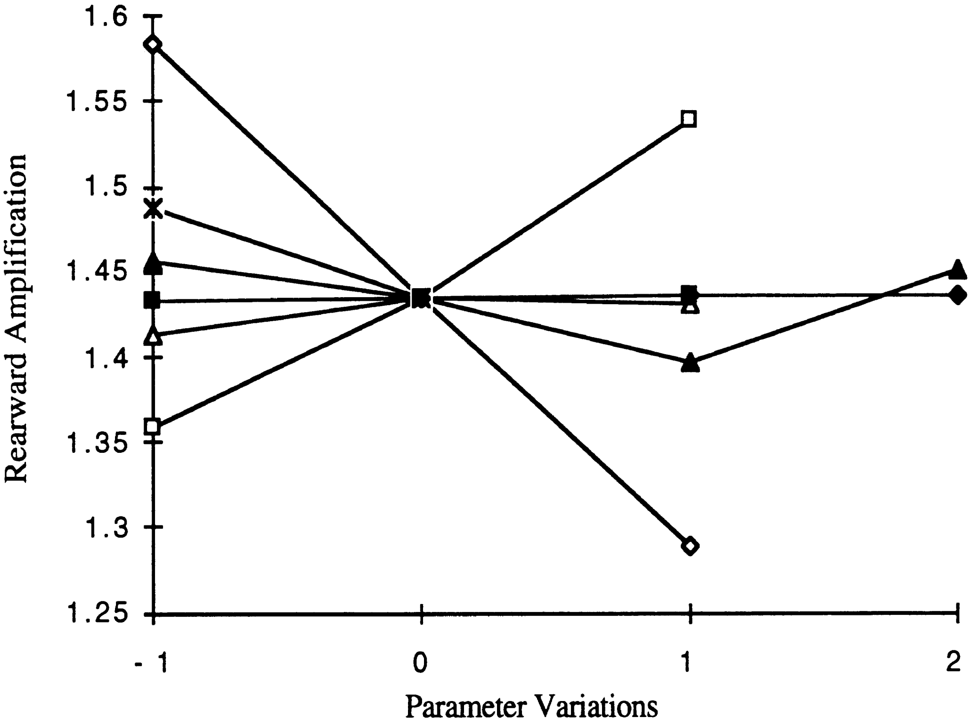


Figure C-146. Sensitivity of rearward amplification: 45'x28' seven-axle 3C1-train double

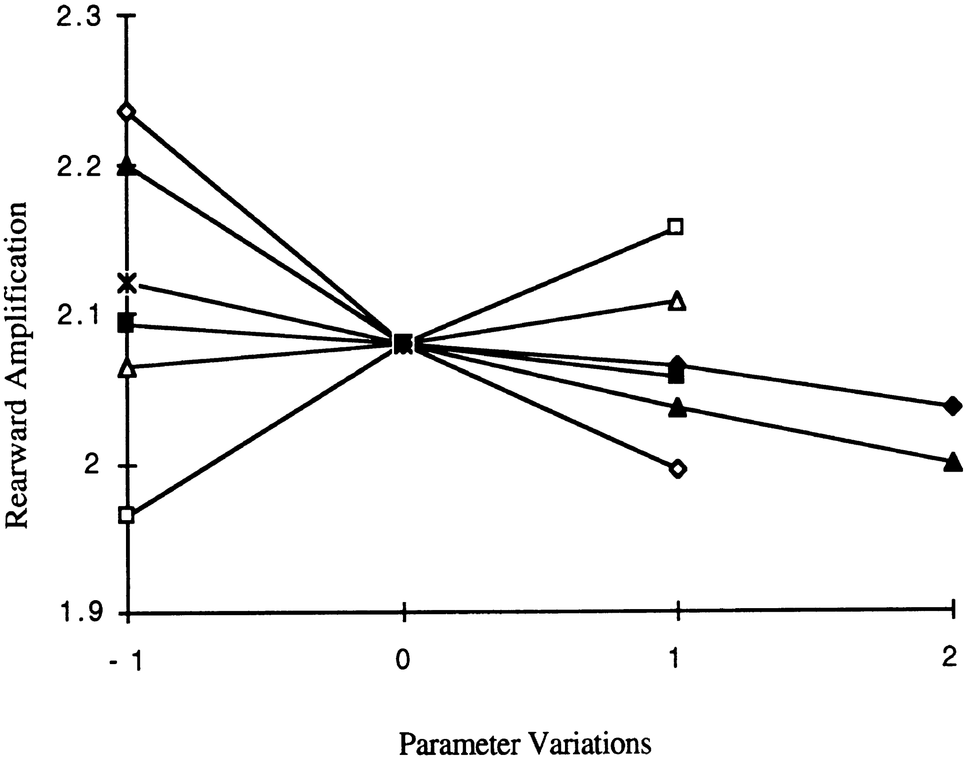


Figure C-147. Sensitivity of rearward amplification: 28'x28'x28' seven-axle 3C1-train triple

Sensitivity Plots of Dynamic-Load-Transfer Ratio

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations* -1	0	1	2
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✳	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

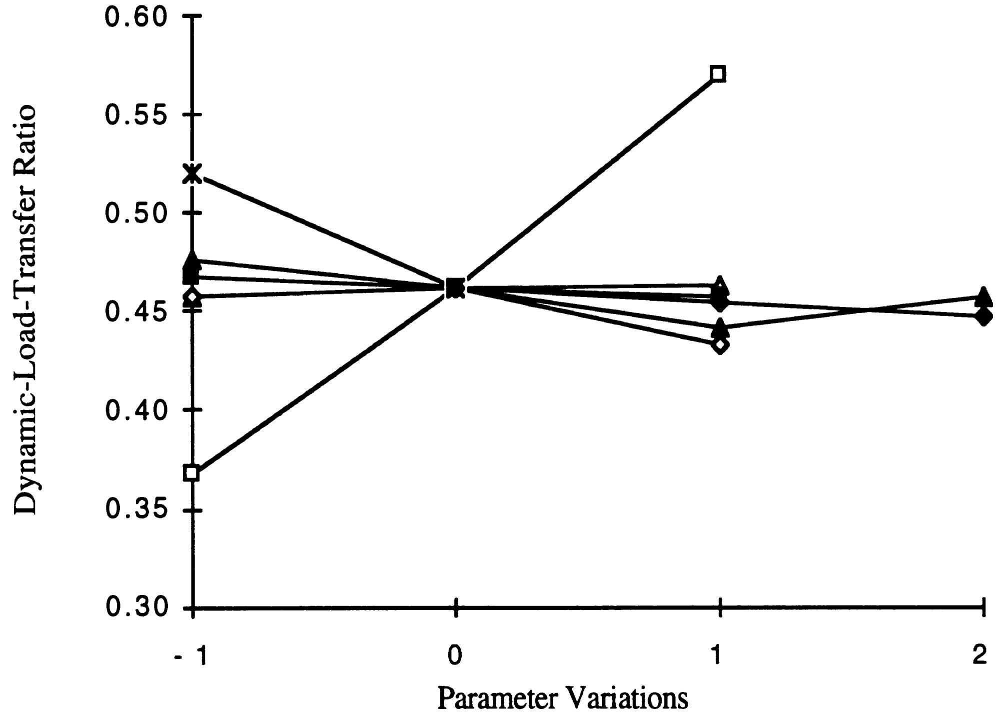


Figure C-148. Sensitivity of dynamic-load-transfer ratio: 28'x28' five-axle 3C1-train double

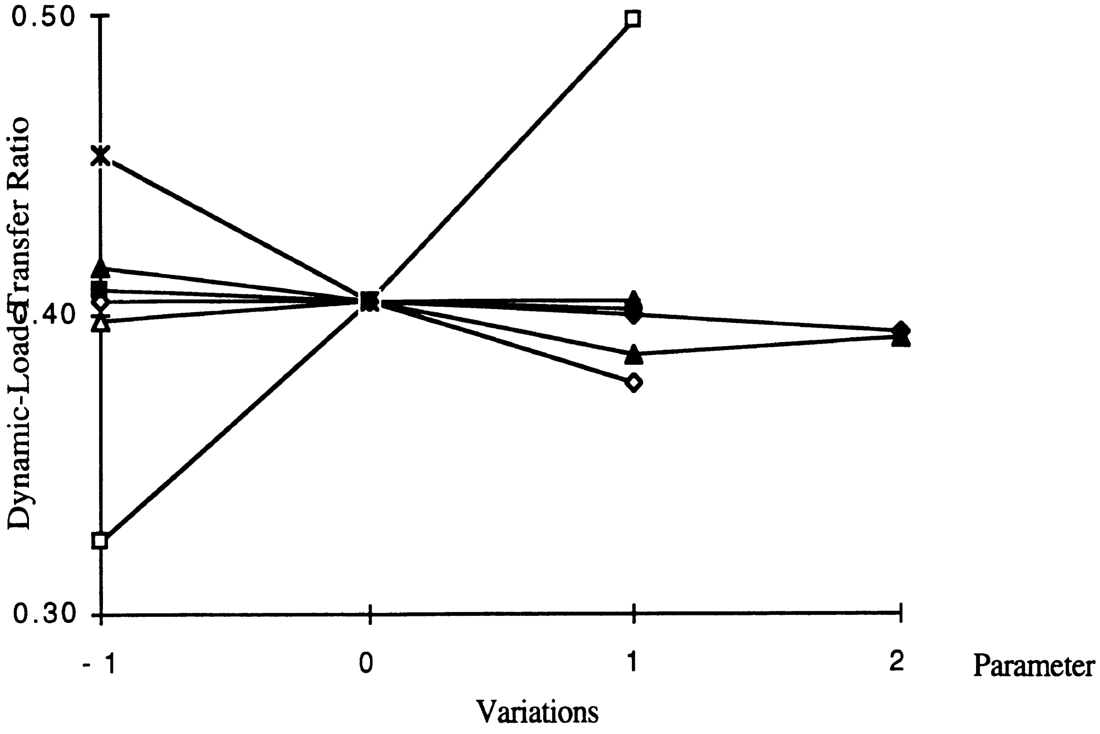


Figure C-149. Sensitivity of dynamic-load-transfer ratio: 32'x32' eight-axle 3C1-train double

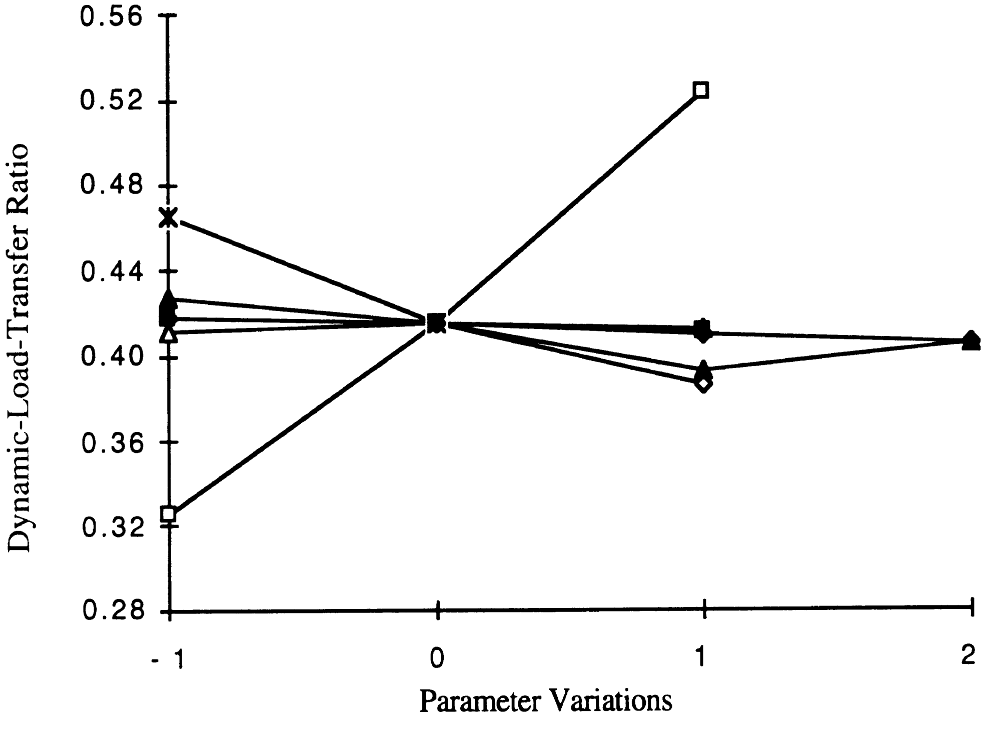


Figure C-150. Sensitivity of dynamic-load-transfer ratio: 38'x20' seven-axle 3C1-train double

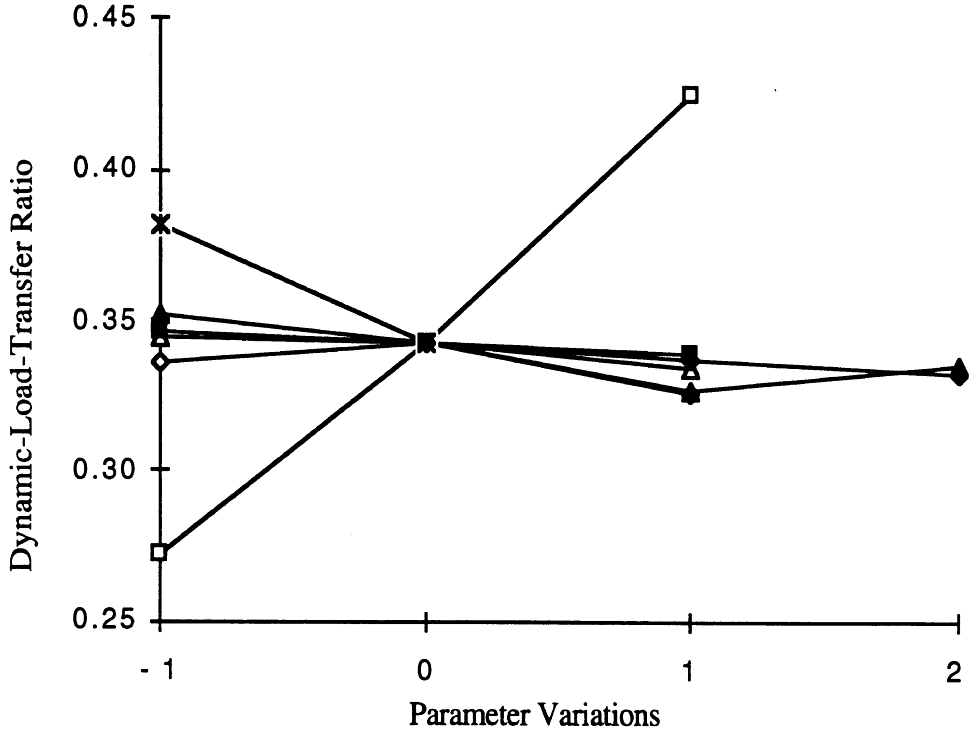


Figure C-151. Sensitivity of dynamic-load-transfer ratio: 45'x28' seven-axle 3C1-train double

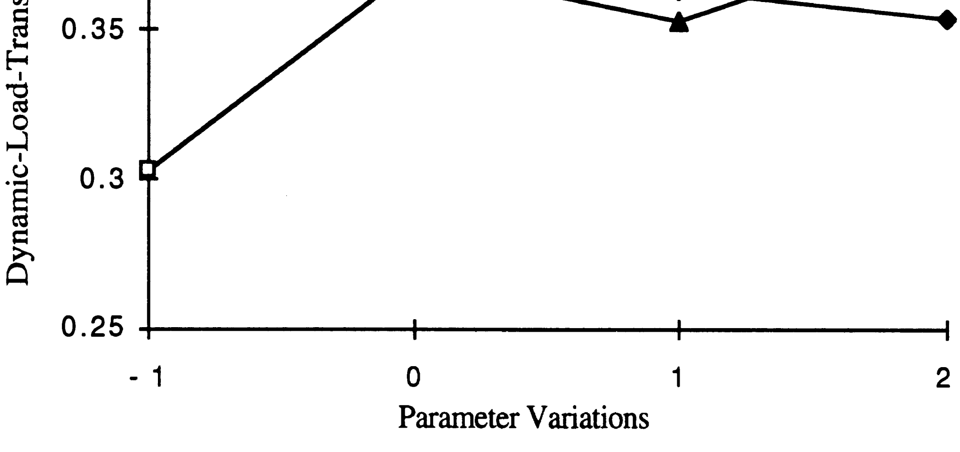


Figure C-152. Sensitivity of dynamic-load-transfer ratio: 28'x28'x28' seven-axle 3C1-train triple

Sensitivity Plots of Transient High-Speed Offtracking

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✳	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

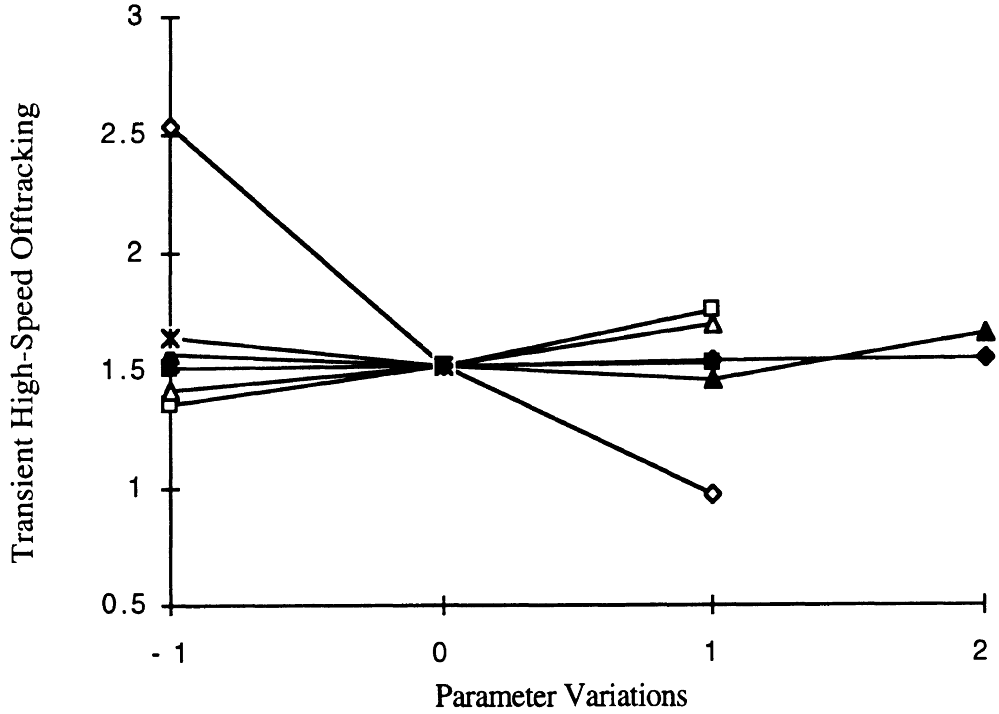


Figure C-153. Sensitivity of transient high-speed offtracking: 28'x28' five-axle 3C1-train double

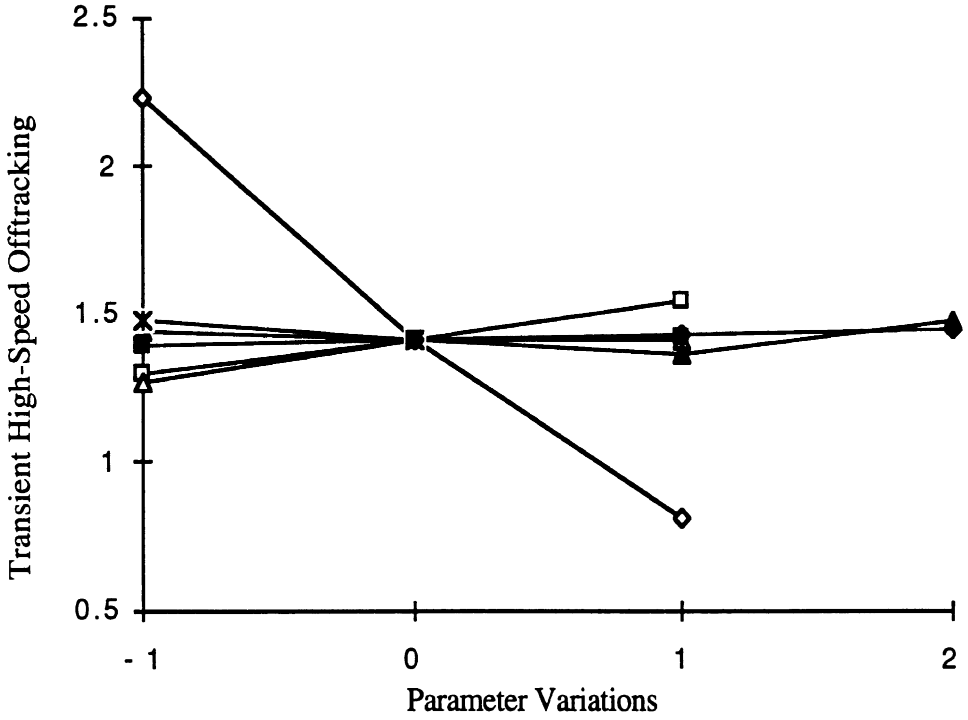


Figure C-154. Sensitivity of transient high-speed offtracking: 32'x32' eight-axle 3C1-train double

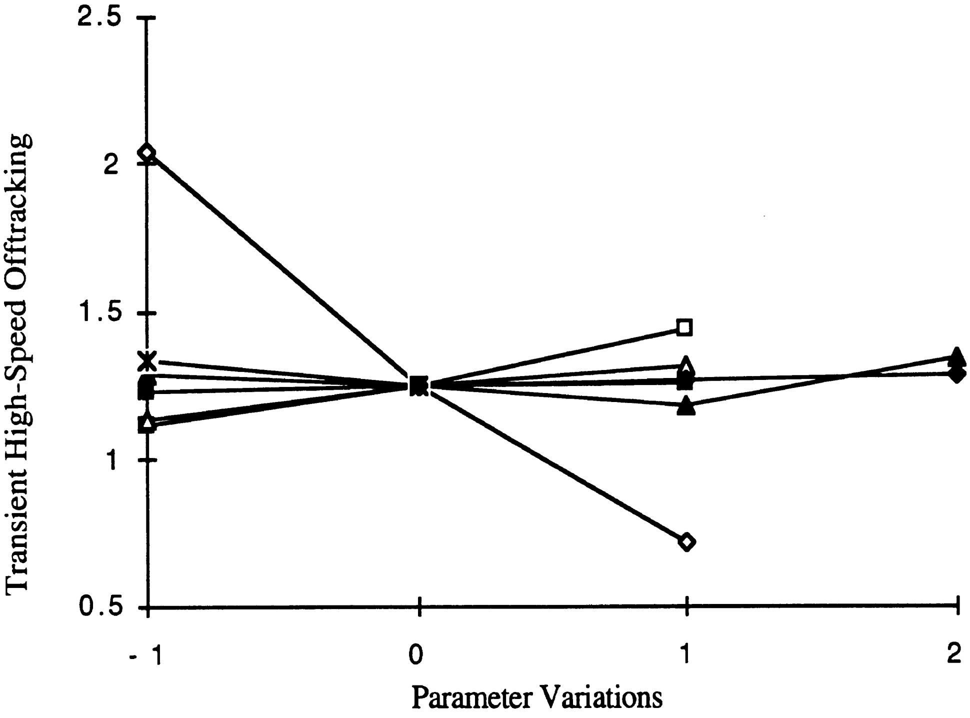


Figure C-155. Sensitivity of transient high-speed offtracking: 38'x20' seven-axle 3C1-train double

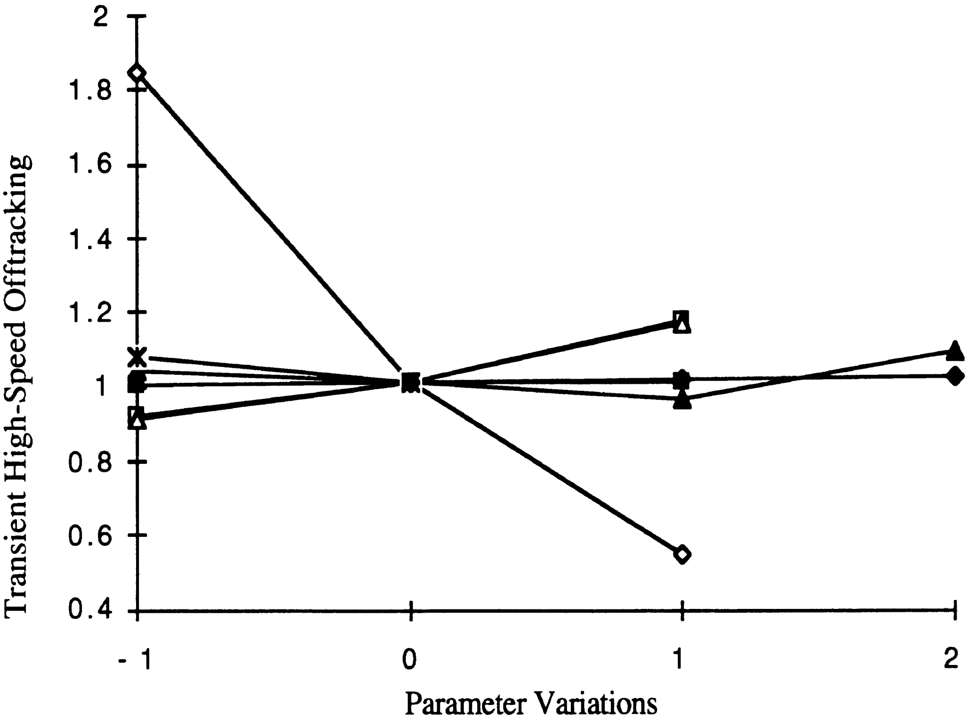


Figure C-156. Sensitivity of transient high-speed offtracking: 45'x28' seven-axle 3C1-train double

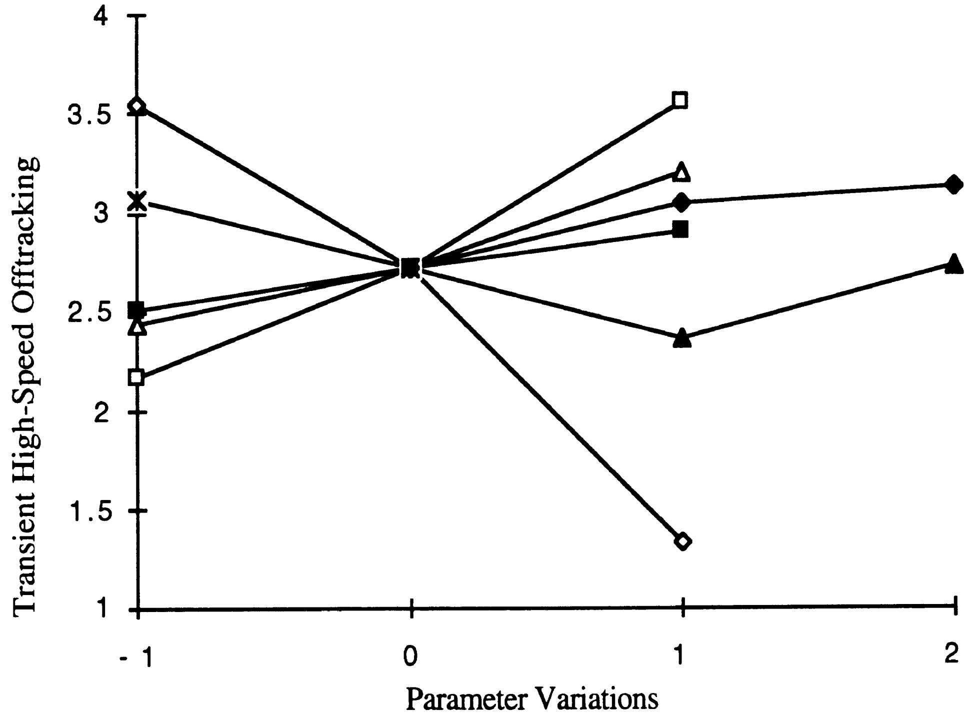


Figure C-157. Sensitivity of transient high-speed offtracking: 28'x28'x28' seven-axle 3C1-train triple

Sensitivity Plots of Damping Ratio in the RTAC-B Maneuver

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✱	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

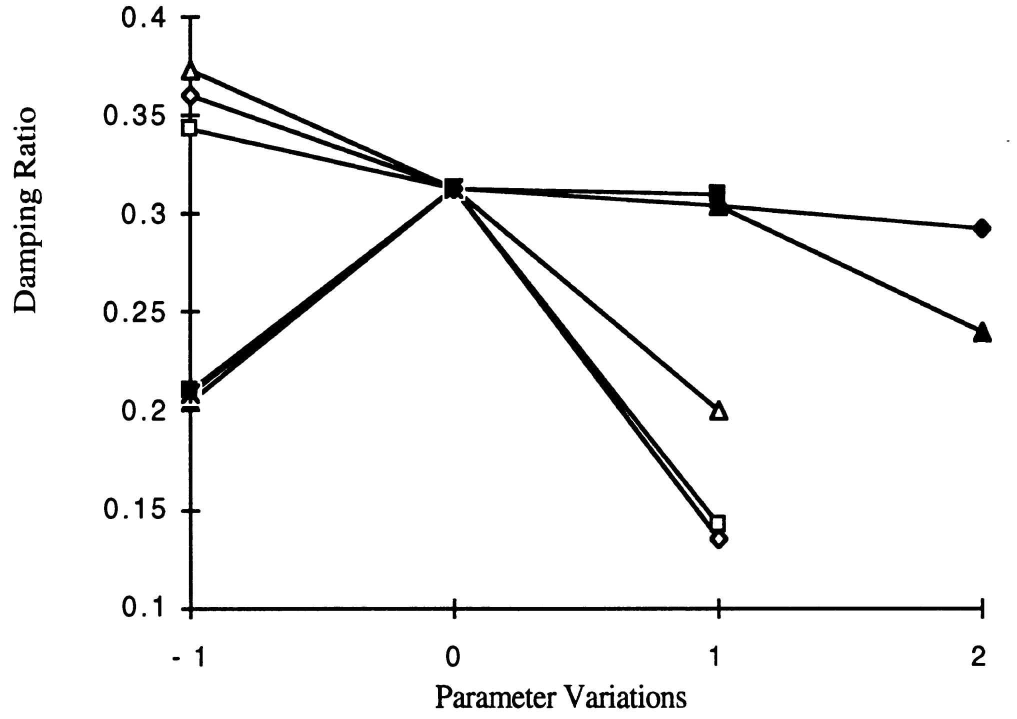


Figure C-158. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28' five-axle 3C1-train double

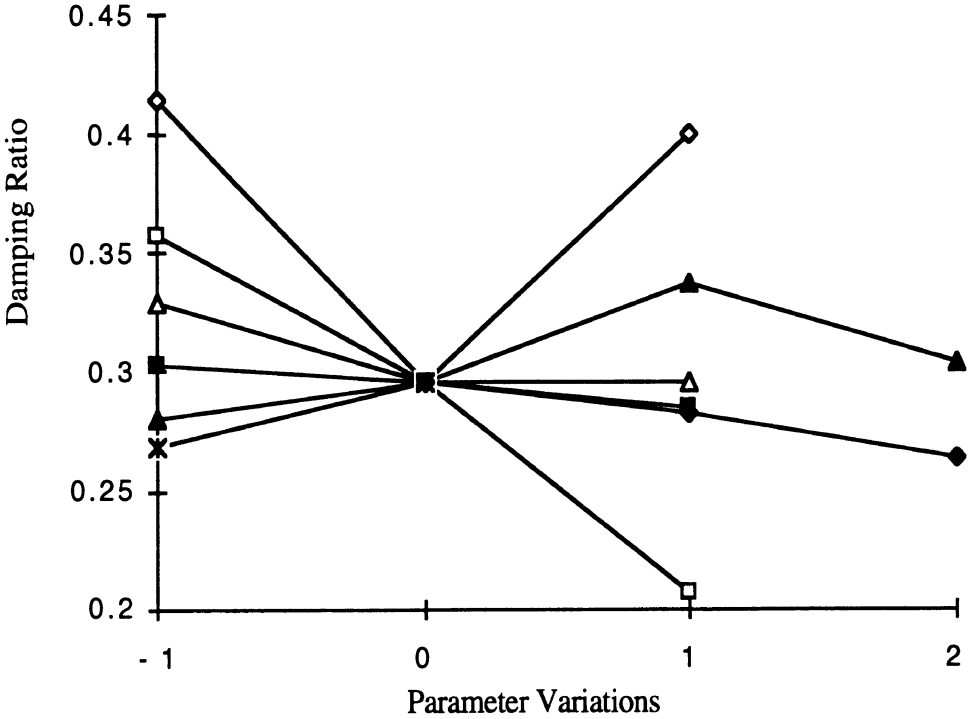


Figure C-159. Sensitivity of damping ratio in the RTAC-B maneuver: 32'x32' eight-axle 3C1-train double

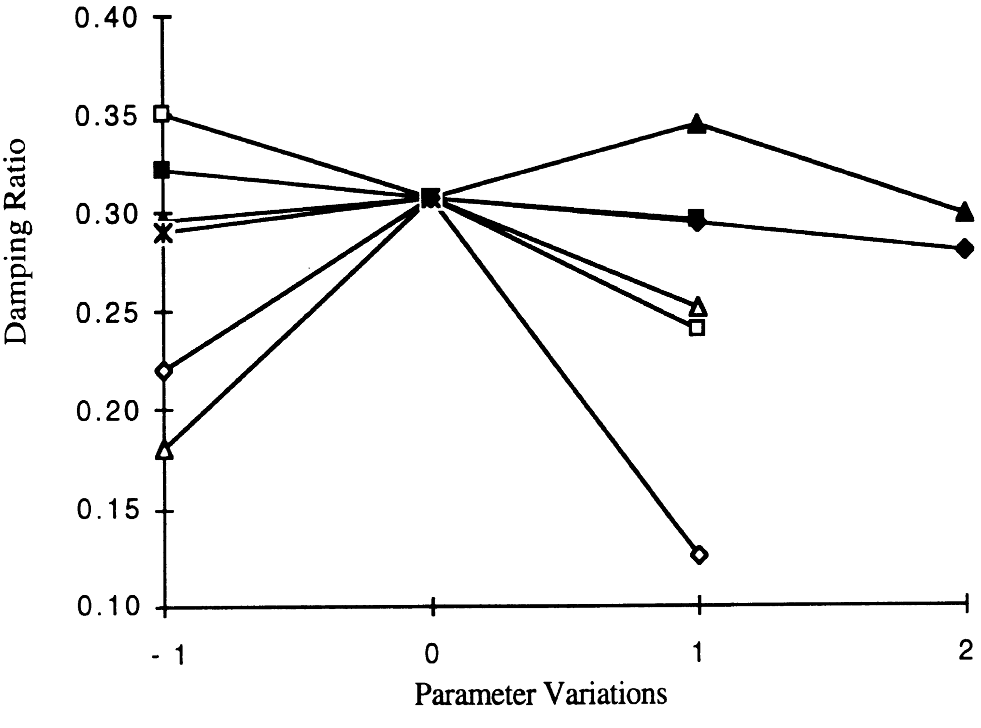


Figure C-160. Sensitivity of damping ratio in the RTAC-B maneuver: 38'x20' seven-axle 3C1-train double

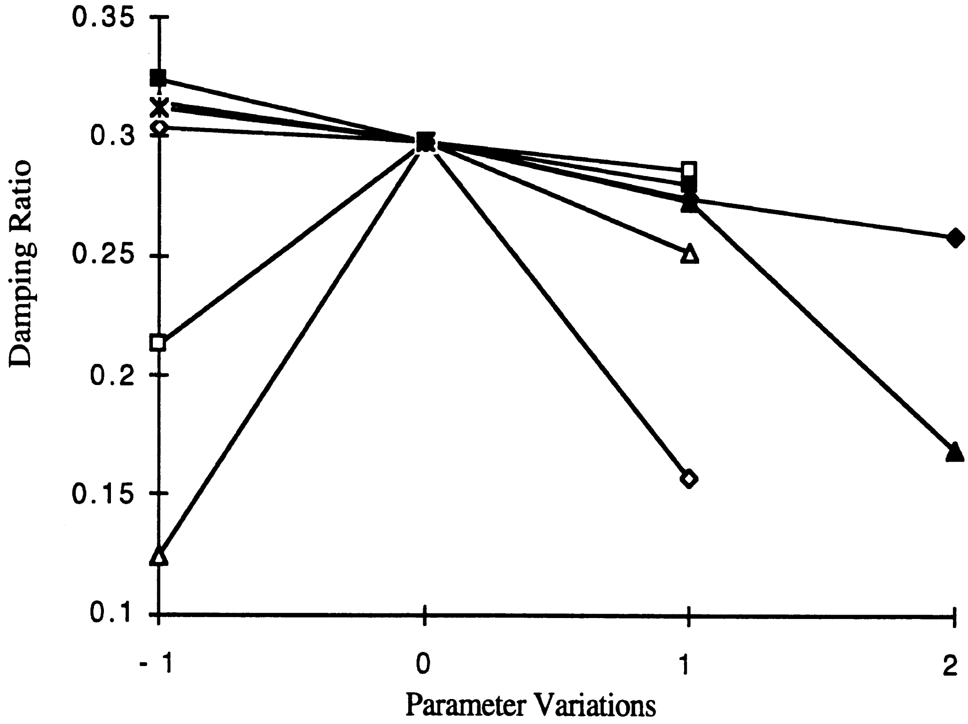


Figure C-161. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x28' seven-axle 3C1-train double

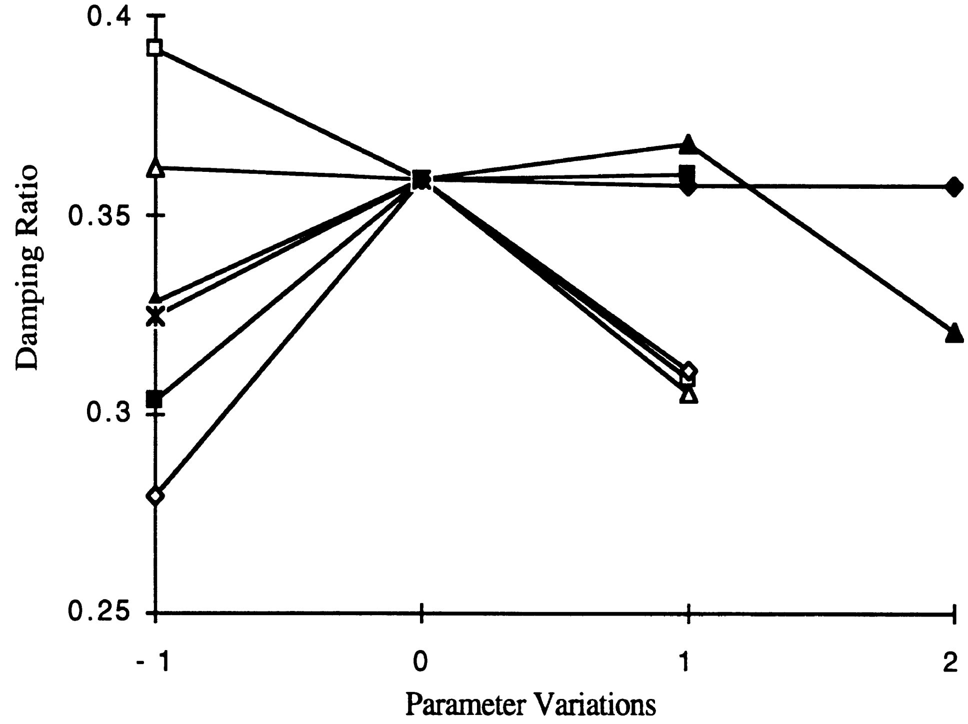


Figure C-162. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28'x28' seven-axle 3C1-train triple

SENSITIVITY STUDY RESULTS FOR THE 3C2-DOLLY

Table C-7. Performance measures obtained with the 3C2-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio
28x28bas3C2	0.438	-1.115	1.717	0.457	1.56	0.218
28x28do13C2	0.436	-1.148	1.716	0.449	1.582	0.320
28x28do23C2	0.434	-1.173	1.71	0.441	1.596	0.310
28x28pl13C2	0.365	-1.163	1.827	0.562	1.785	0.155
28x28pl23C2	0.523	-1.088	1.634	0.363	1.384	0.355
28x28pl33C2	0.436	-1.116	1.766	0.453	1.753	0.218
28x28pl43C2	0.436	-1.115	1.701	0.452	1.43	0.370
28x28se13C2	0.437	-1.137	1.717	0.451	1.574	0.324
28x28se23C2	0.438	-1.095	1.714	0.461	1.543	0.223
28x28sp23C2	0.423	-1.118	1.753	0.47	1.606	0.218
28x28sp33C2	0.437	-1.112	1.673	0.437	1.502	0.314
28x28ss23C2	0.454	-1.213	1.742	0.451	1.699	0.252
28x28su13C2	0.396	-1.136	1.784	0.513	1.672	0.221
28x28tl13C2	0.429	-0.794	1.635	0.431	0.995	0.108
28x28tl23C2	0.426	-1.733	1.88	0.442	2.632	0.333
32x32bas3C2	0.446	-1.176	1.615	0.401	1.436	0.297
32x32do13C2	0.448	-1.204	1.619	0.396	1.459	0.284
32x32do23C2	0.445	-1.233	1.617	0.39	1.476	0.264
32x32pl13C2	0.374	-1.207	1.71	0.493	1.569	0.212
32x32pl23C2	0.662	-1.155	1.534	0.322	1.325	0.358
32x32pl33C2	0.446	-1.176	1.615	0.401	1.436	0.297
32x32pl43C2	0.446	-1.177	1.565	0.395	1.285	0.333
32x32se13C2	0.446	-1.193	1.618	0.398	1.451	0.287
32x32se23C2	0.444	-1.153	1.61	0.405	1.418	0.303
32x32sp23C2	0.432	-1.179	1.638	0.413	1.463	0.284
32x32sp33C2	0.454	-1.17	1.573	0.384	1.389	0.336
32x32ss43C2	0.466	-1.258	1.608	0.389	1.51	0.308
32x32su13C2	0.408	-1.191	1.67	0.45	1.502	0.271
32x32tl13C2	0.444	-0.756	1.469	0.375	0.82	0.401
32x32tl23C2	0.442	-1.749	1.769	0.397	2.302	0.405
38x20bas3C2	0.432	-1.068	1.701	0.411	1.27	0.306
38x20do13C2	0.432	-1.103	1.718	0.406	1.292	0.293
38x20do23C2	0.432	-1.14	1.73	0.402	1.311	0.279
38x20pl13C2	0.364	-1.095	1.899	0.518	1.462	0.240
38x20pl23C2	0.535	-1.063	1.588	0.323	1.14	0.348
38x20pl33C2	0.433	-1.068	1.661	0.409	1.344	0.254
38x20pl43C2	0.432	-1.068	1.73	0.408	1.157	0.174
38x20se13C2	0.432	-1.088	1.71	0.408	1.283	0.295
38x20se23C2	0.432	-1.049	1.701	0.414	1.255	0.320
38x20sp23C2	0.422	-1.071	1.737	0.423	1.308	0.293
38x20sp33C2	0.437	-1.067	1.637	0.389	1.21	0.340
38x20ss43C2	0.449	-1.164	1.71	0.402	1.366	0.293
38x20su13C2	0.406	-1.074	1.791	0.461	1.351	0.287
38x20ti13C2	0.433	-0.685	1.603	0.385	0.722	0.126
38x20ti23C2	0.438	-1.719	1.855	0.409	2.105	0.315
45x28bas3C2	0.437	-1.114	1.435	0.34	1.022	0.298
45x28do13C2	0.438	-1.141	1.437	0.335	1.033	0.272
45x28do23C2	0.438	-1.166	1.439	0.329	1.042	0.256
45x28pl13C2	0.369	-1.151	1.537	0.422	1.194	0.291
45x28pl23C2	0.537	-1.094	1.361	0.27	0.932	0.206
45x28pl33C2	0.438	-1.114	1.439	0.33	1.19	0.260
45x28pl43C2	0.437	-1.11	1.412	0.342	0.924	0.113
45x28se13C2	0.437	-1.132	1.436	0.336	1.029	0.278
45x28se23C2	0.438	-1.094	1.433	0.343	1.018	0.324
45x28sp23C2	0.429	-1.119	1.457	0.349	1.056	0.314
45x28sp33C2	0.442	-1.111	1.398	0.324	0.978	0.271
45x28ss43C2	0.454	-1.232	1.452	0.332	1.118	0.160
45x28su13C2	0.41	-1.13	1.485	0.379	1.09	0.312
45x28tl13C2	0.441	-0.662	1.289	0.325	0.55	0.155
45x28tl23C2	0.443	-1.858	1.595	0.331	1.891	0.289
3X28BAS3C2	0.426	-1.702	2.124	0.372	3.088	0.361
3X28DO13C2	0.429	-1.767	2.111	0.361	3.09	0.361
3X28DO23C2	0.431	-1.839	2.087	0.356	2.881	0.356
3X28PL13C2	0.364	-1.772	2.151	0.44	4.007	0.304
3X28PL23C2	0.475	-1.661	2.027	0.301	2.691	0.392
3X28PL33C2	0.426	-1.701	2.137	0.366	3.721	0.297
3X28PL43C2	0.425	-1.704	2.098	0.369	3.064	0.365
3X28SE13C2	0.427	-1.739	2.094	0.365	3.174	0.358
3X28SE23C2	0.425	-1.669	2.118	0.376	2.99	0.309
3X28SP23C2	0.41	-1.723	2.22	0.386	3.587	0.328
3X28SP33C2	0.422	-1.698	2.094	0.351	2.827	0.370
3X28SS43C2	0.438	-1.534	2.058	0.38	3.098	0.319
3X28SU13C2	0.391	-1.736	2.127	0.412	3.583	0.325
3X28TI13C2	0.424	-1.26	2.014	0.367	1.619	0.314
3X28TI23C2	0.428	-2.579	2.268	0.372	4.661	0.281

Sensitivity Plots of Static Rollover Threshold

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

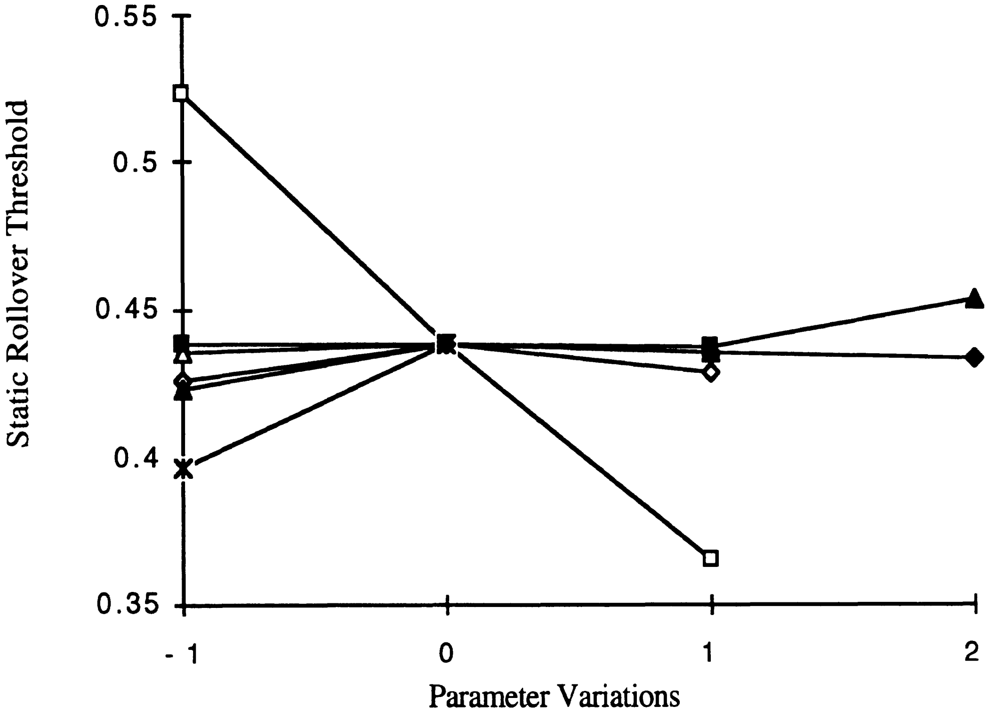


Figure C-163. Sensitivity of static rollover threshold: 28'x28' five-axle 3C2-train double

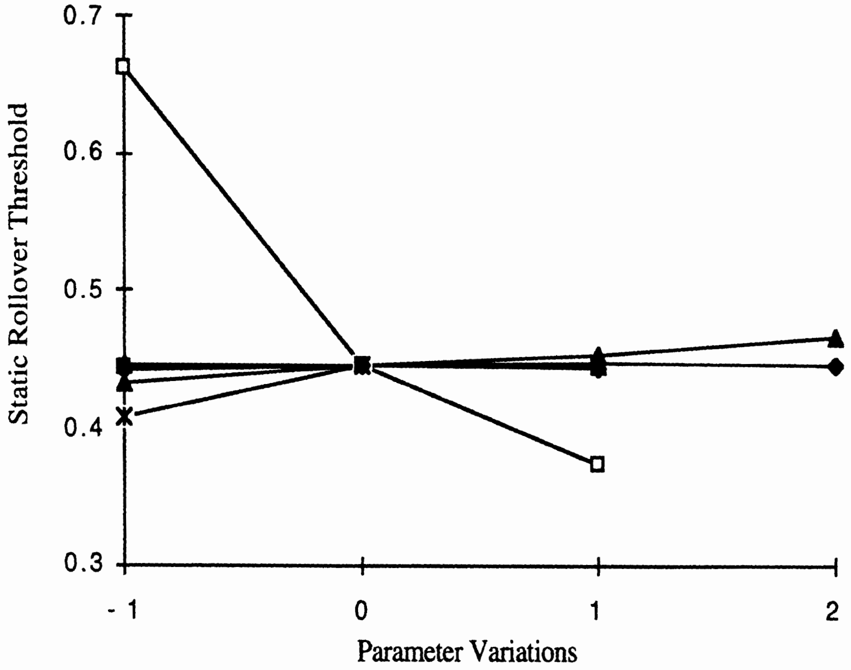


Figure C-164. Sensitivity of static rollover threshold: 32'x32' eight-axle 3C2-train double

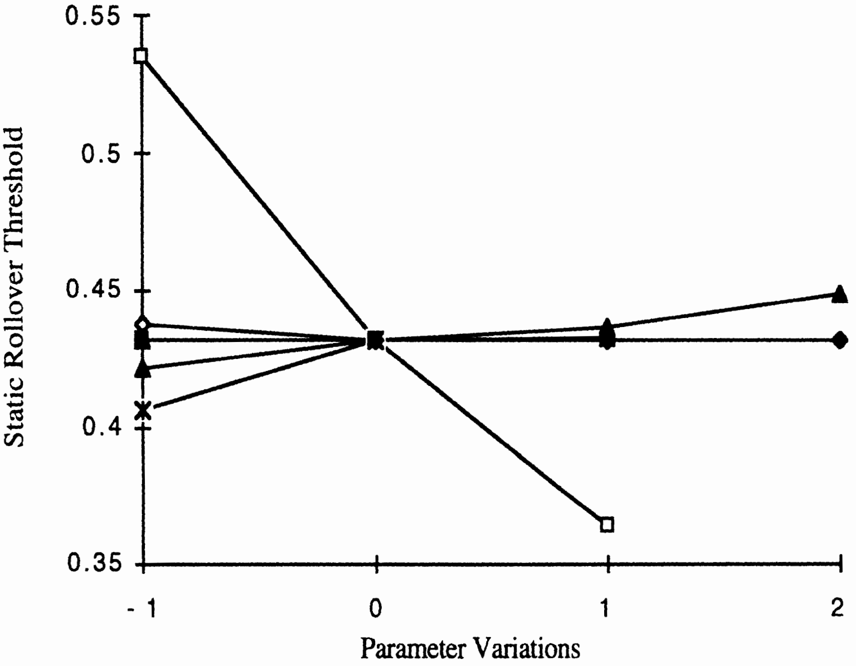


Figure C-165. Sensitivity of static rollover threshold: 38'x20' seven-axle 3C2-train double

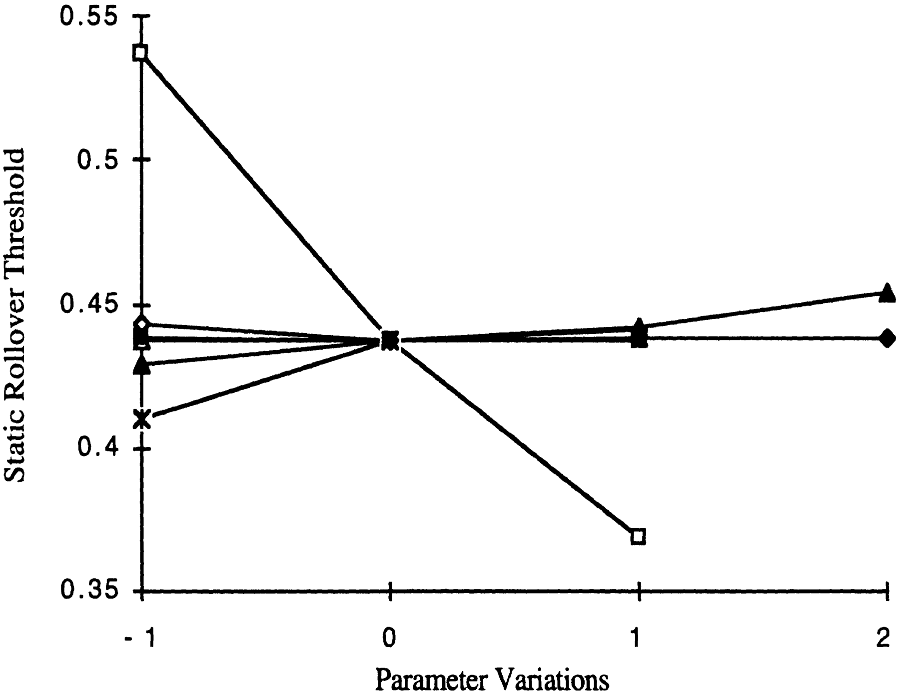


Figure C-166. Sensitivity of static rollover threshold: 45'x28' seven-axle 3C2-train double

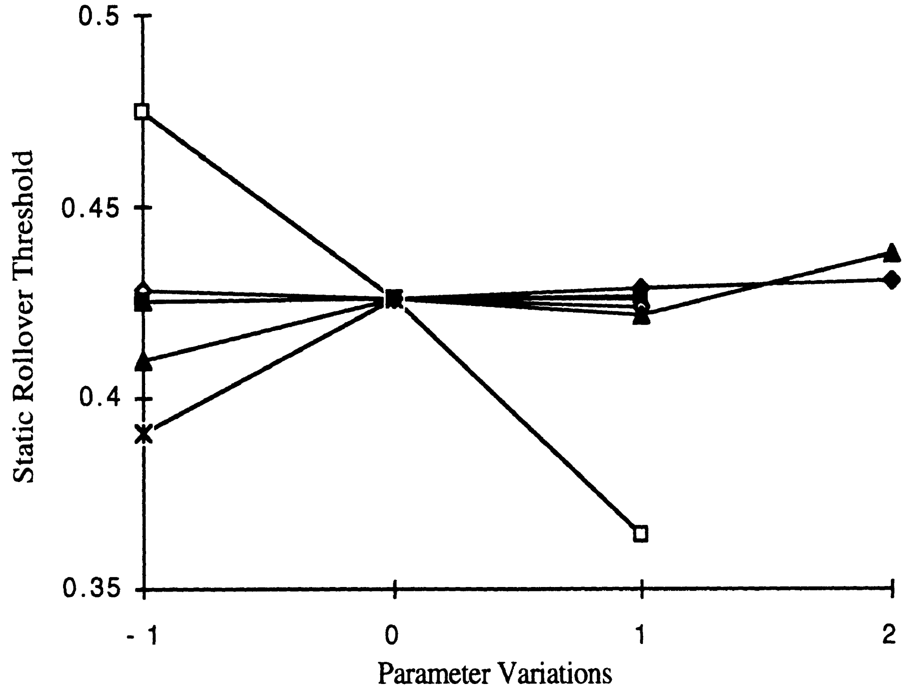


Figure C-167. Sensitivity of static rollover threshold: 28'x28'x28' seven-axle 3C2-train triple

Sensitivity Plots of High-Speed Steady-State Offtracking

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations* -1	0	1	2
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

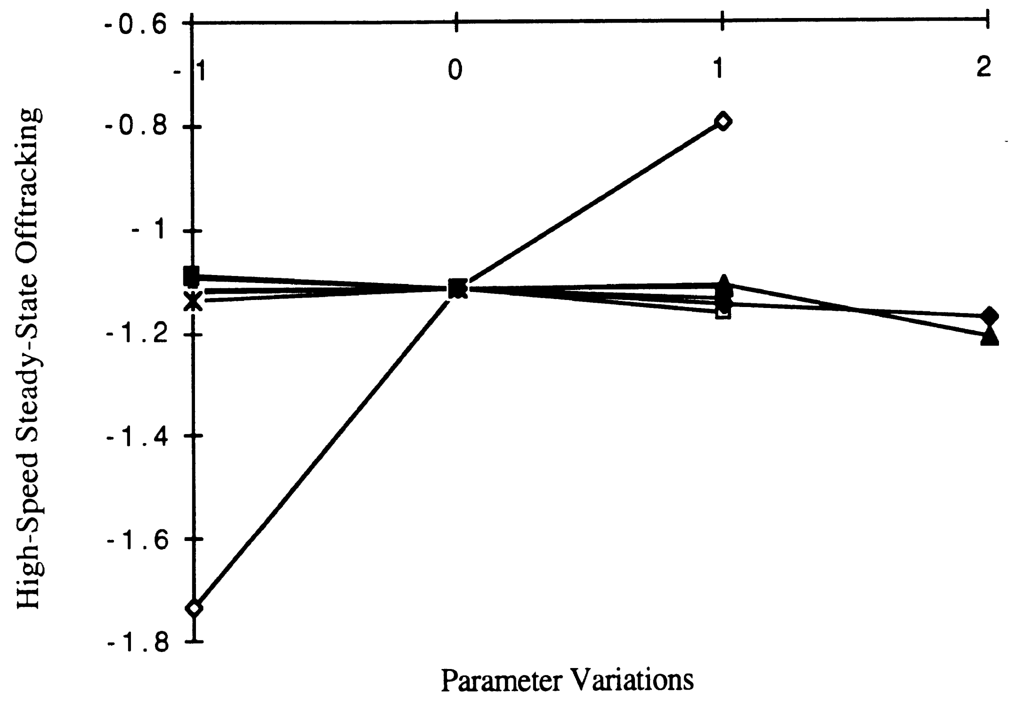


Figure C-168. Sensitivity of high-speed steady-state offtracking: 28'x28' five-axle 3C2-train double

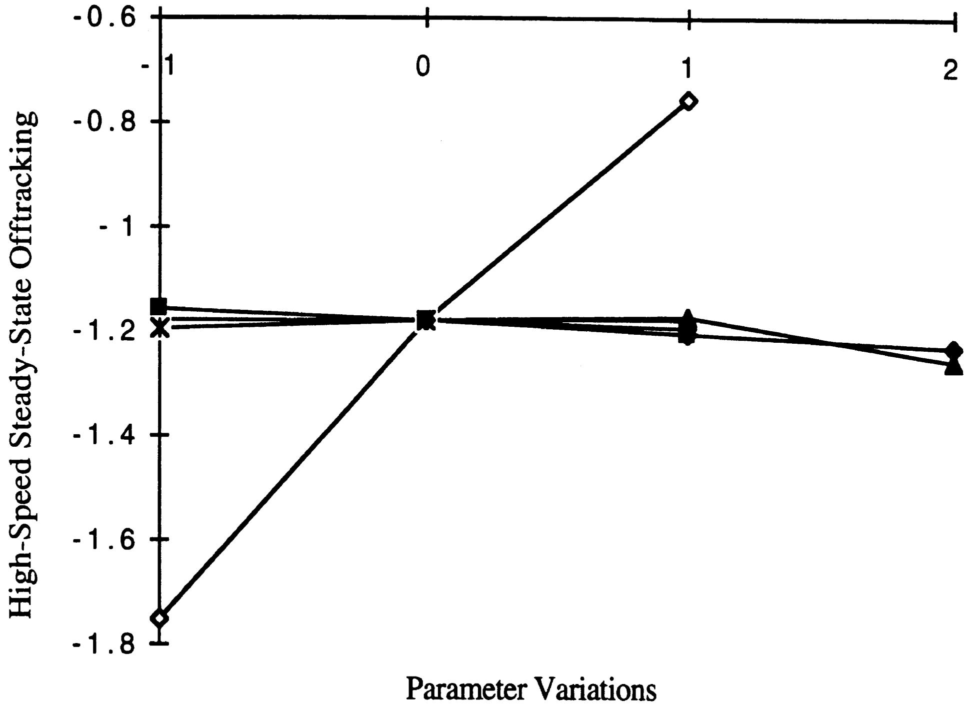


Figure C-169. Sensitivity of high-speed steady-state offtracking: 32'x32' eight-axle 3C2-train double

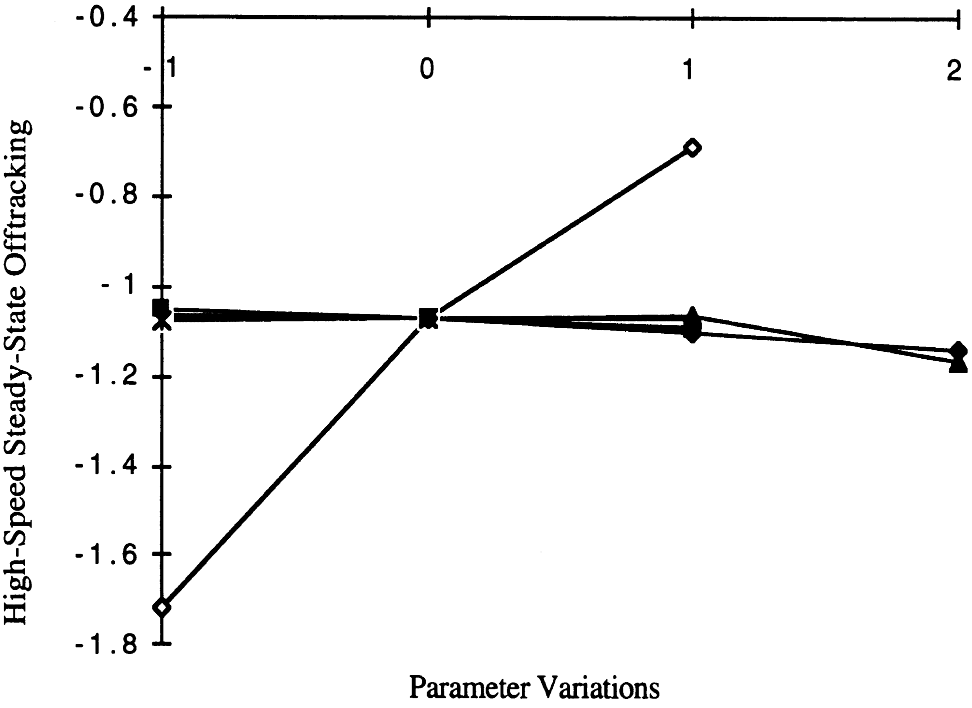


Figure C-170. Sensitivity of high-speed steady-state offtracking: 38'x20' seven-axle 3C2-train double

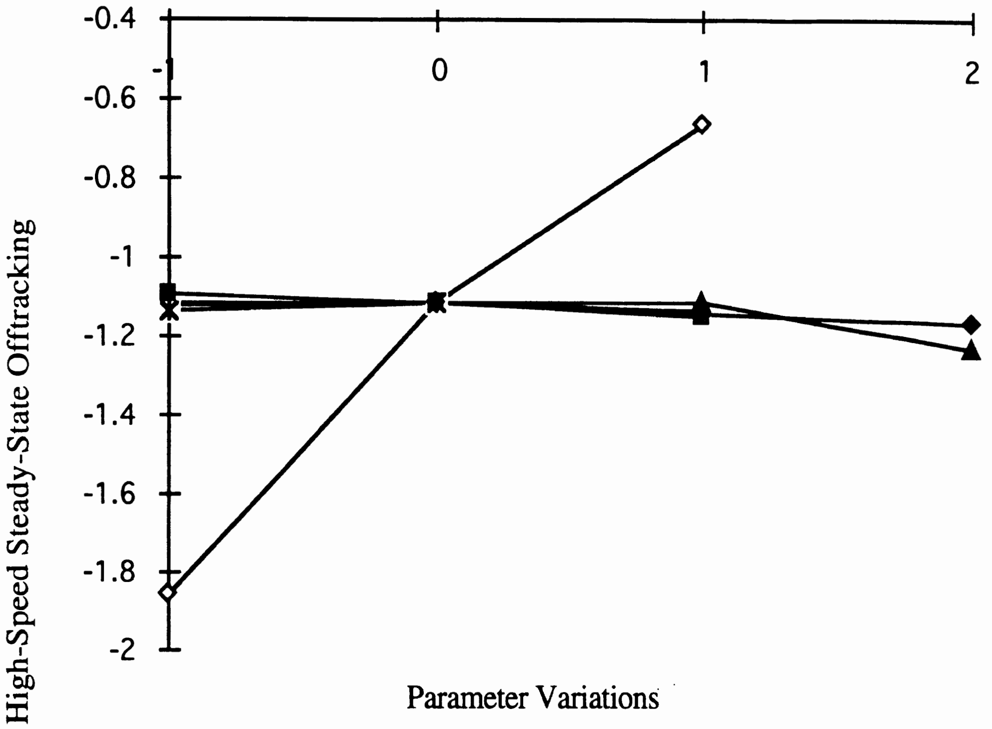


Figure C-171. Sensitivity of high-speed steady-state offtracking: 45'x28' seven-axle 3C2-train double

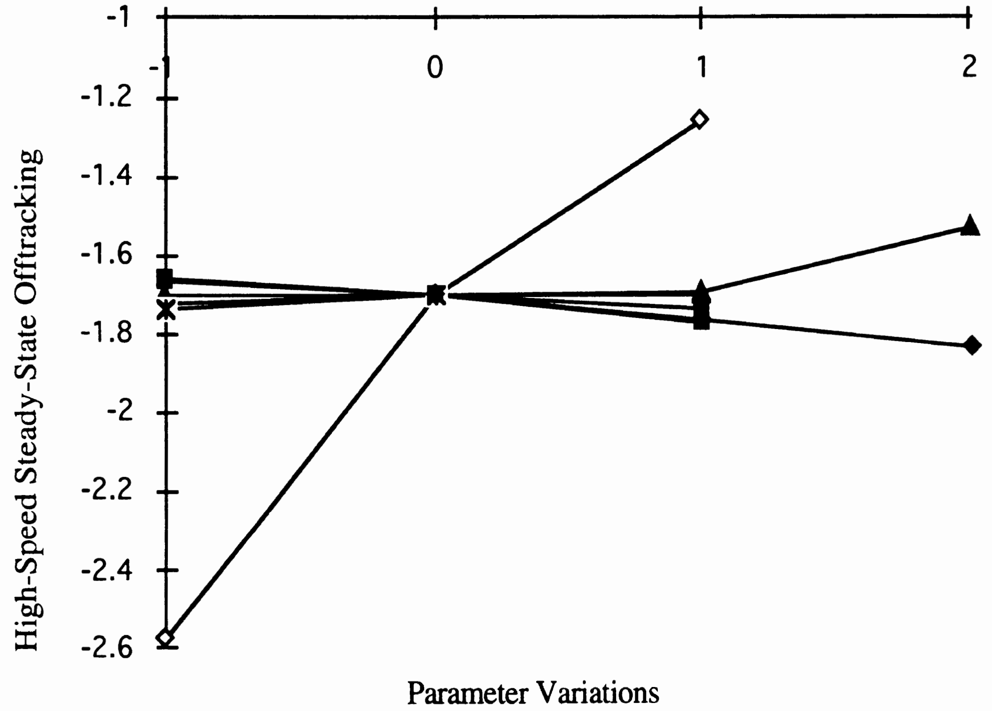


Figure C-172. Sensitivity of high-speed steady-state offtracking: 28'x28'x28' seven-axle 3C2-train triple

Sensitivity Plots of Rearward Amplification

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

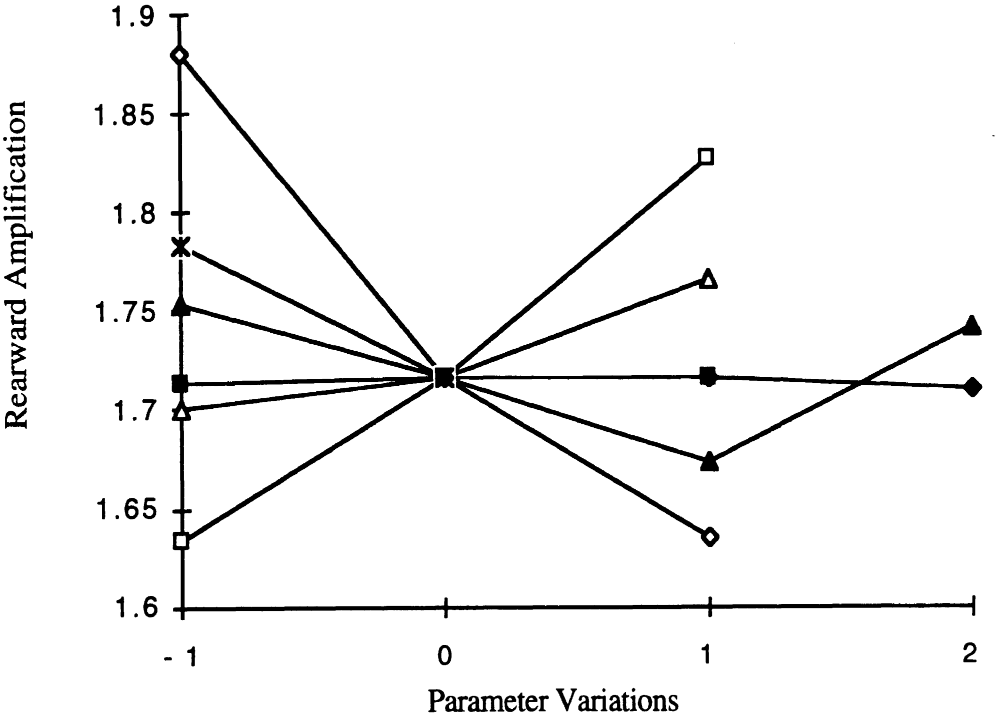


Figure C-173. Sensitivity of rearward amplification: 28'x28' five-axle 3C2-train double

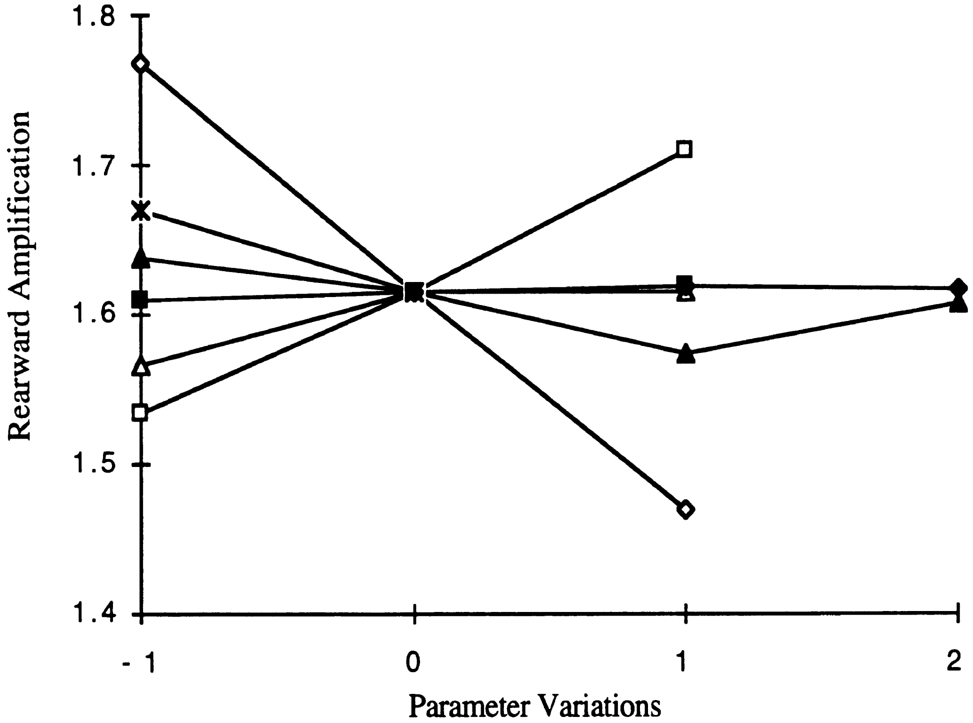


Figure C-174. Sensitivity of rearward amplification: 32'x32' eight-axle 3C2-train double

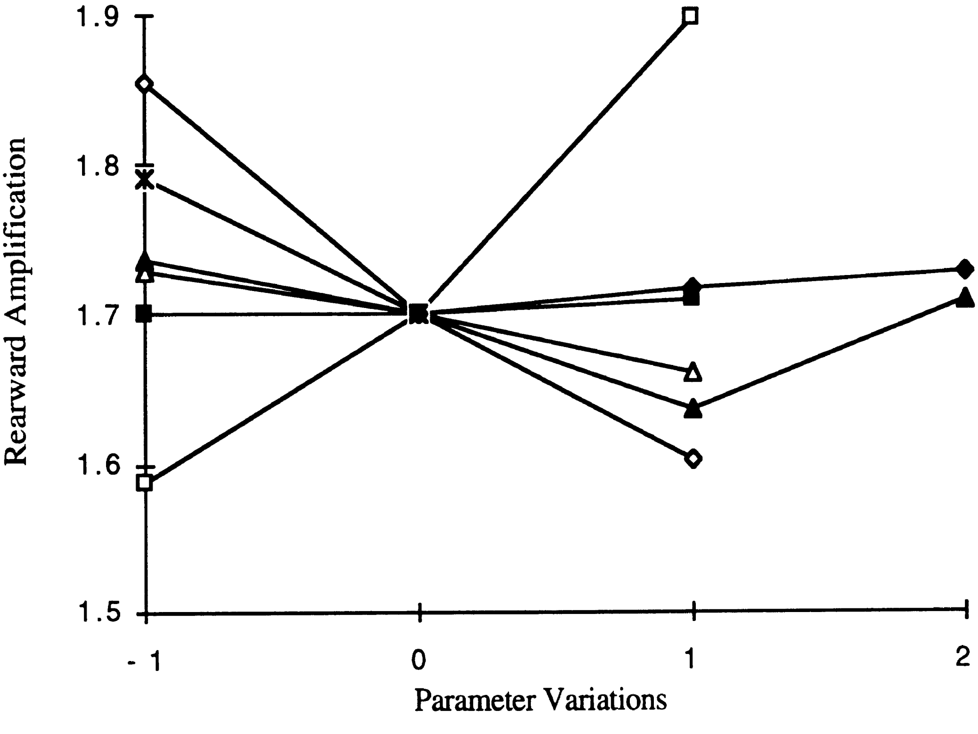


Figure C-175. Sensitivity of rearward amplification: 38'x20' seven-axle 3C2-train double

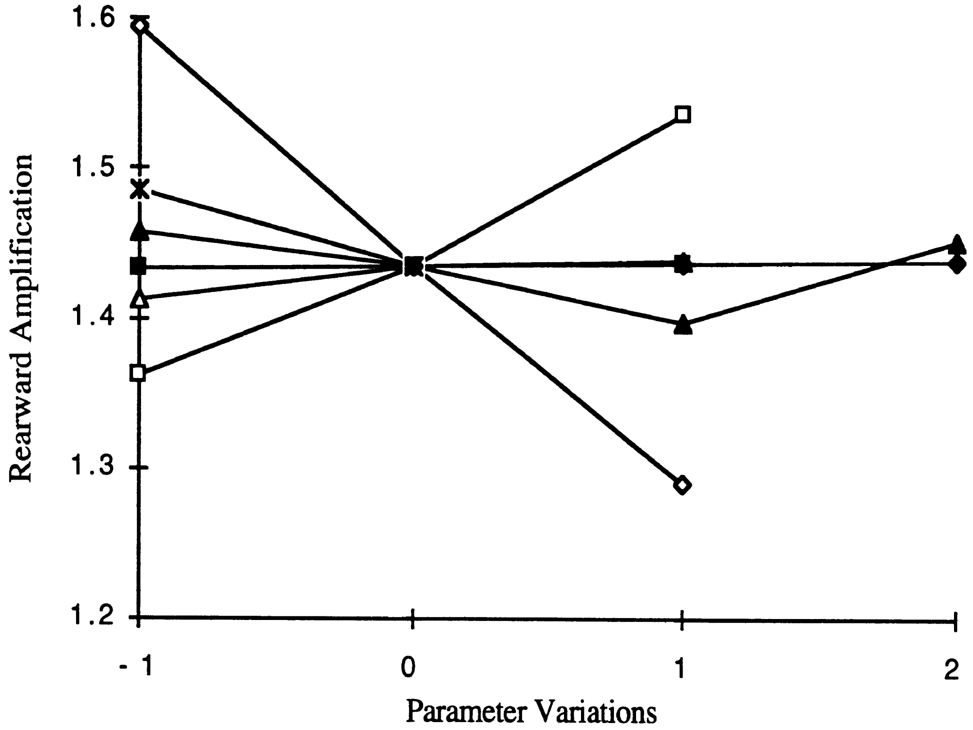


Figure C-176. Sensitivity of rearward amplification: 45'x28' seven-axle 3C2-train double

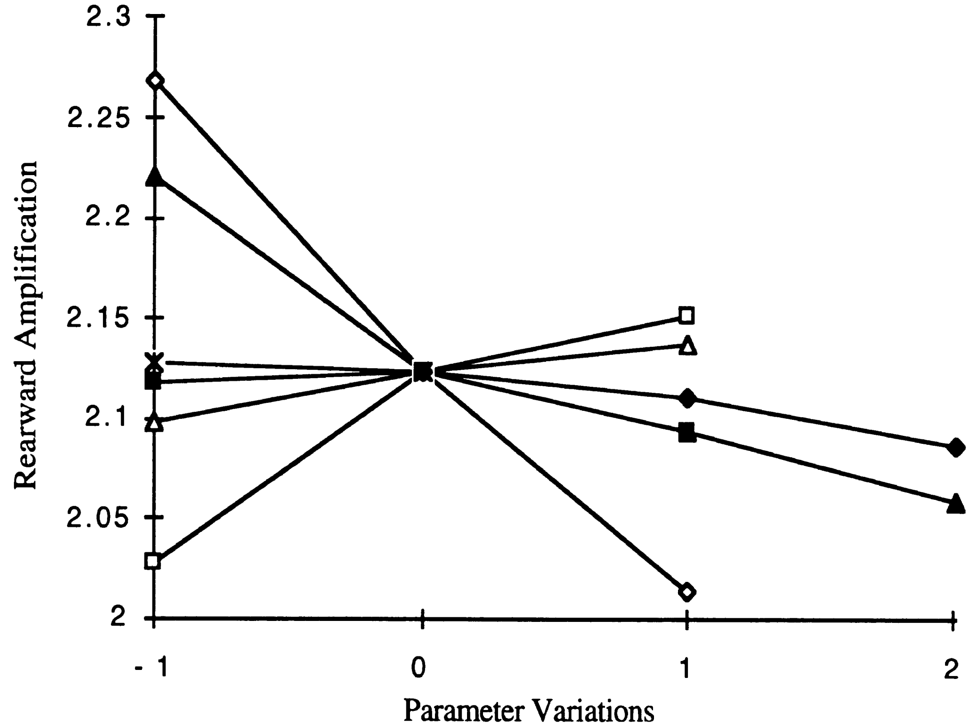


Figure C-177. Sensitivity of rearward amplification: 28'x28'x28' seven-axle 3C2-train triple

Sensitivity Plots of Dynamic-Load-Transfer Ratio

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

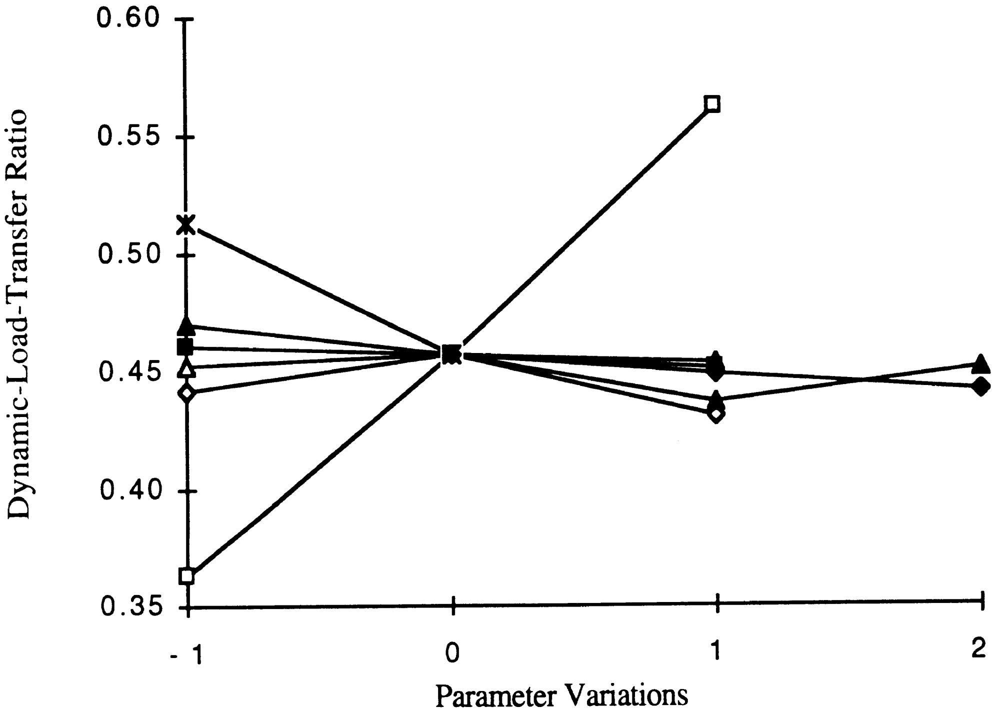


Figure C-178. Sensitivity of dynamic-load-transfer ratio: 28'x28' five-axle 3C2-train double

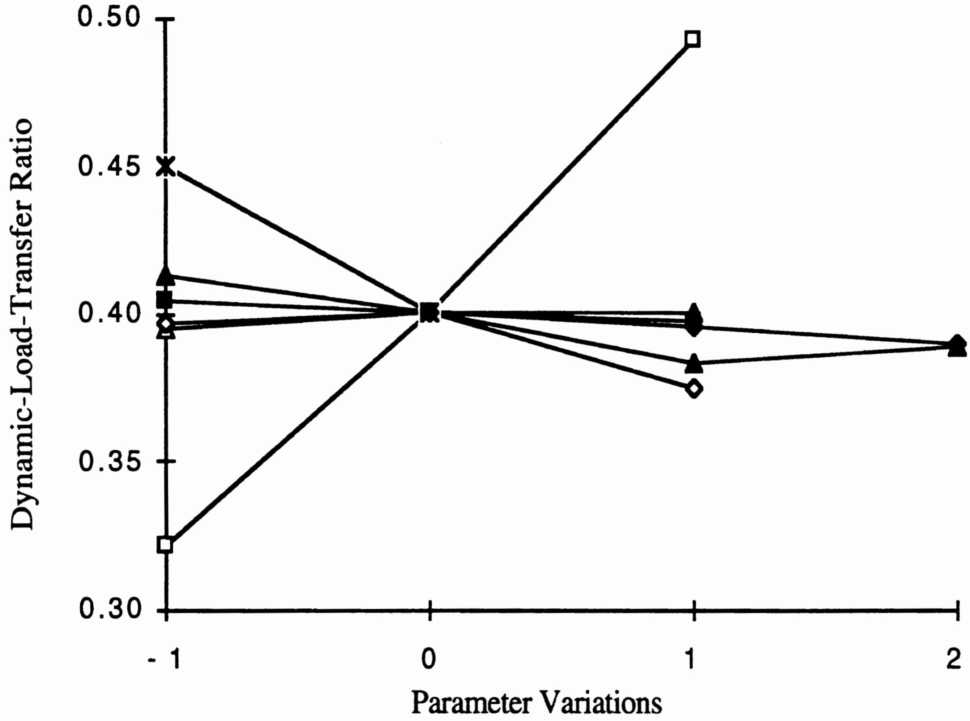


Figure C-179. Sensitivity of dynamic-load-transfer ratio: 32'x32' eight-axle 3C2-train double

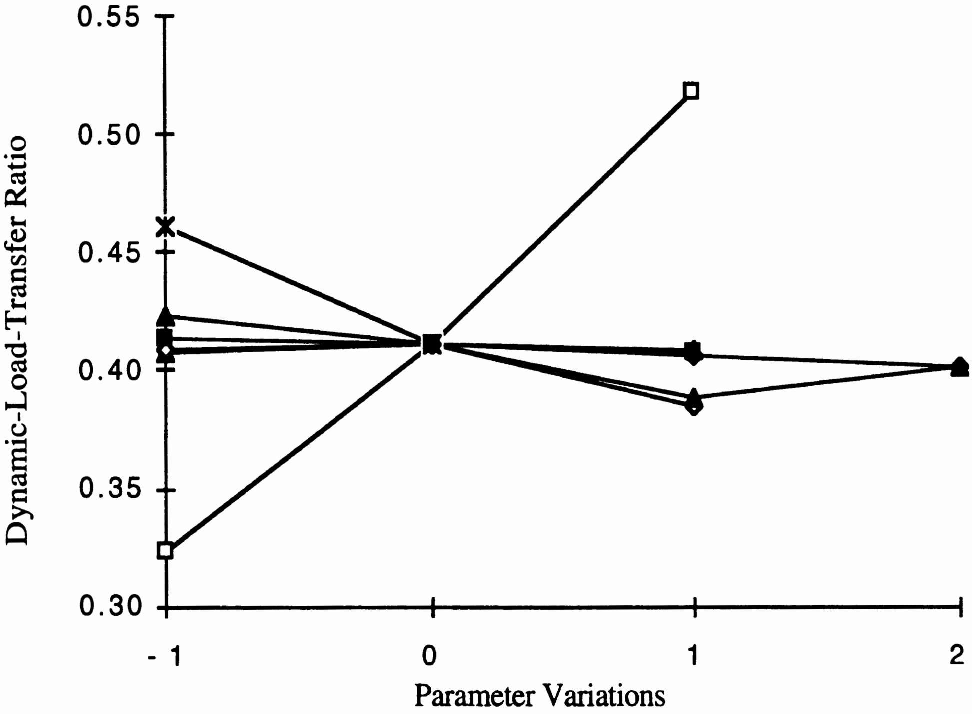


Figure C-180. Sensitivity of dynamic-load-transfer ratio: 38'x20' seven-axle 3C2-train double

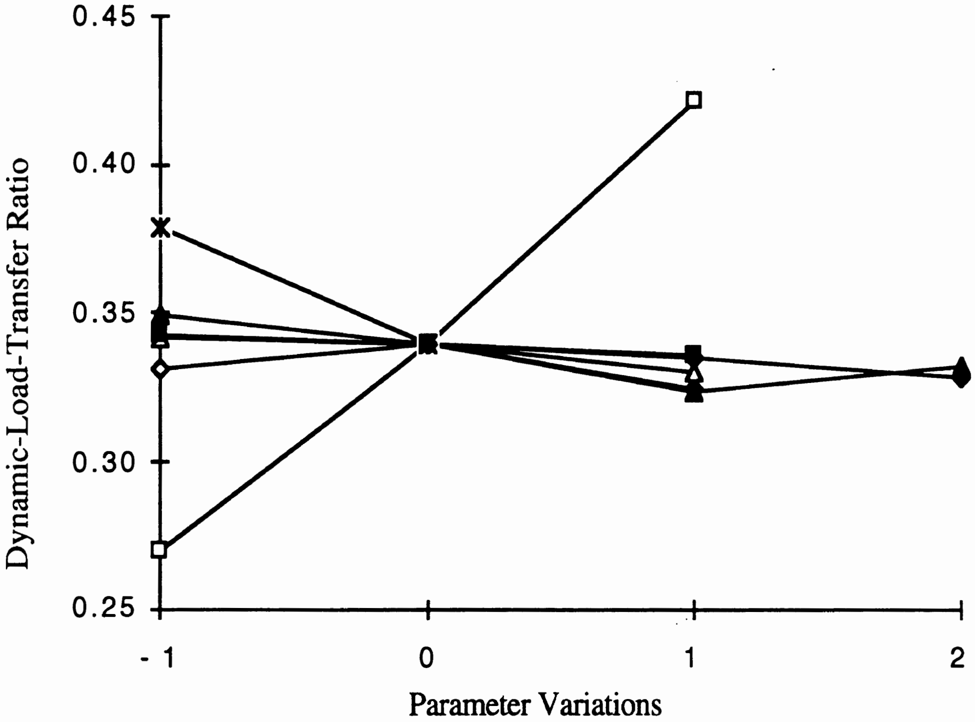


Figure C-181. Sensitivity of dynamic-load-transfer ratio: 45'x28' seven-axle 3C2-train double

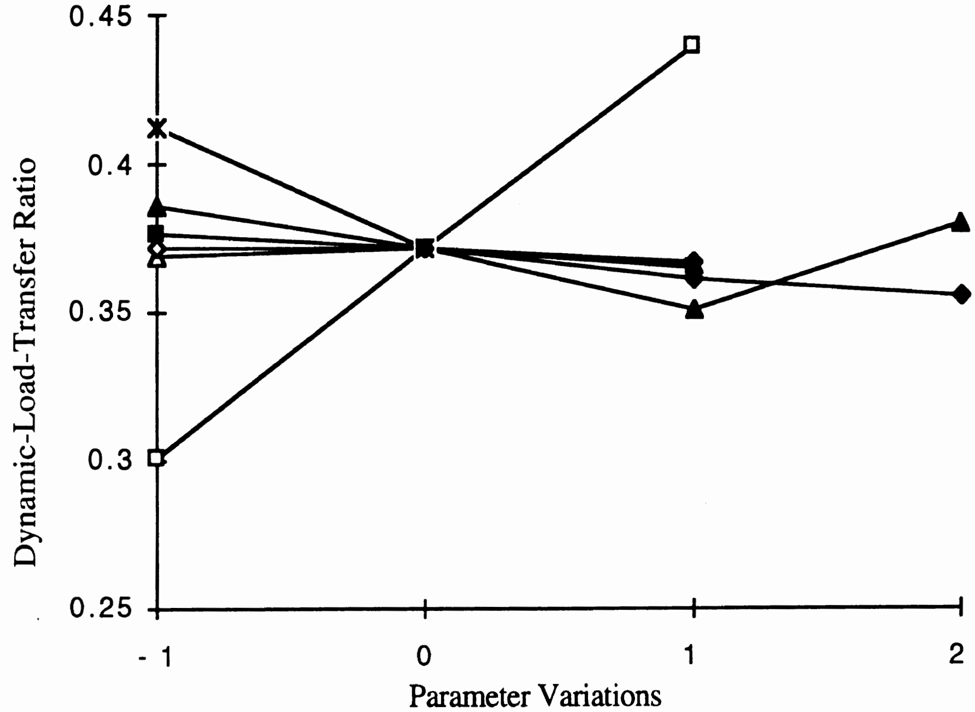


Figure C-182. Sensitivity of dynamic-load-transfer ratio: 28'x28'x28' seven-axle 3C2-train triple

Sensitivity Plots of Transient High-Speed Offtracking

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

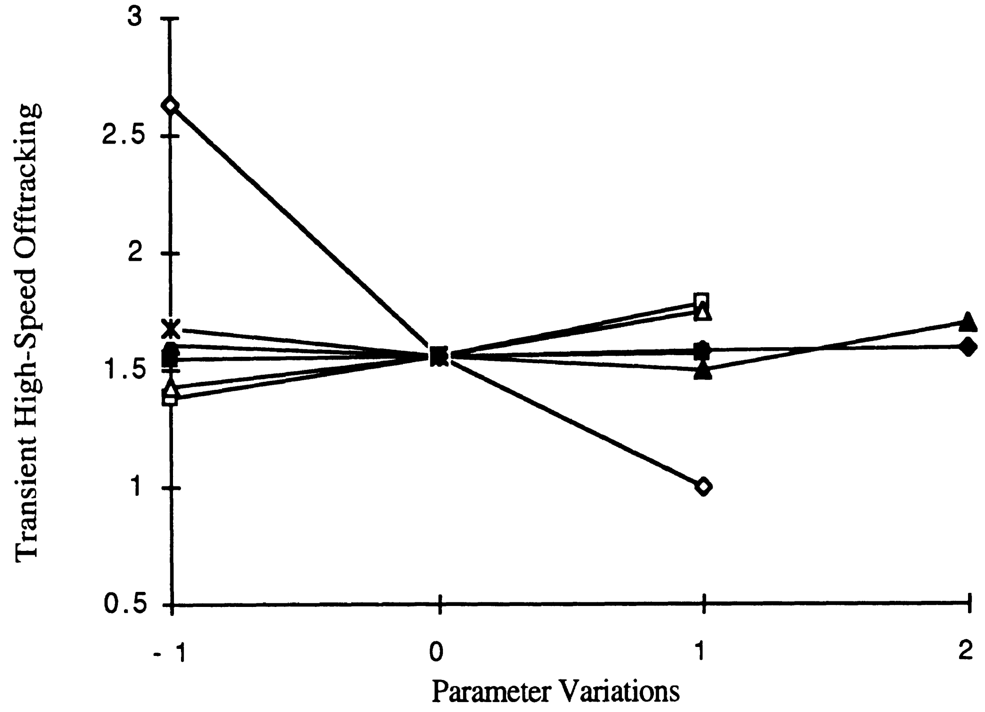


Figure C-183. Sensitivity of transient high-speed offtracking: 28'x28' five-axle 3C2-train double

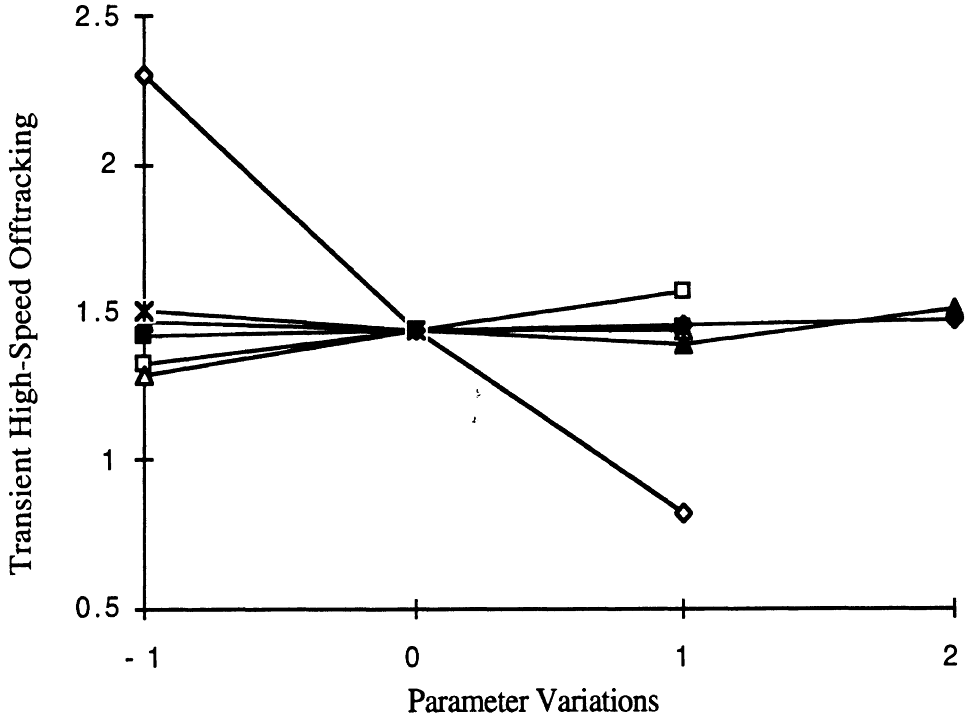


Figure C-184. Sensitivity of transient high-speed offtracking: 32'x32' eight-axle 3C2-train double

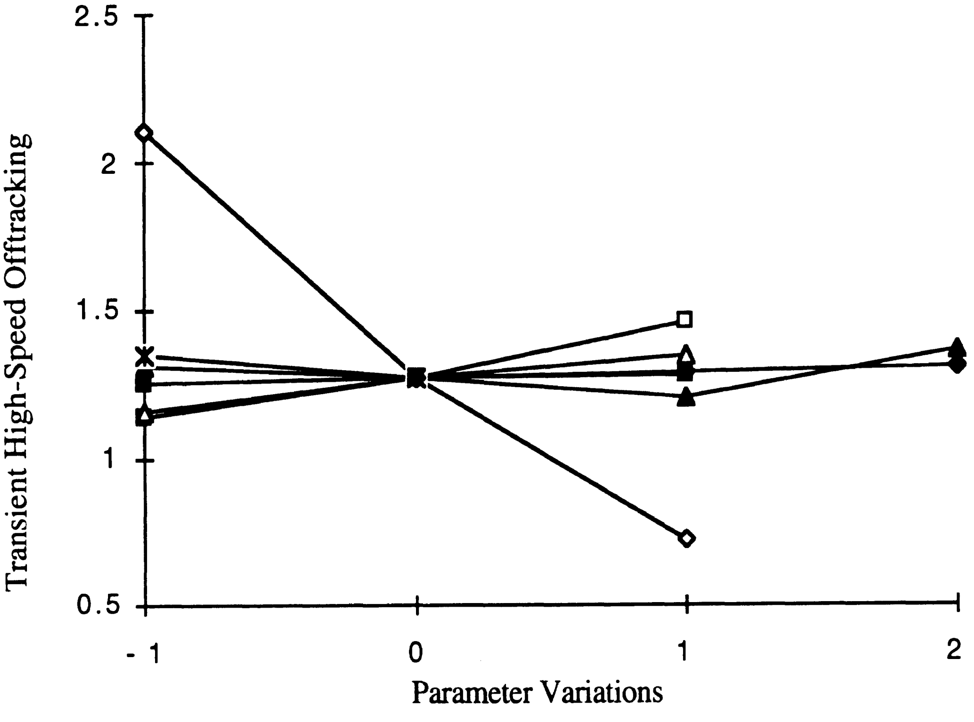


Figure C-185. Sensitivity of transient high-speed offtracking: 38'x20' seven-axle 3C2-train double

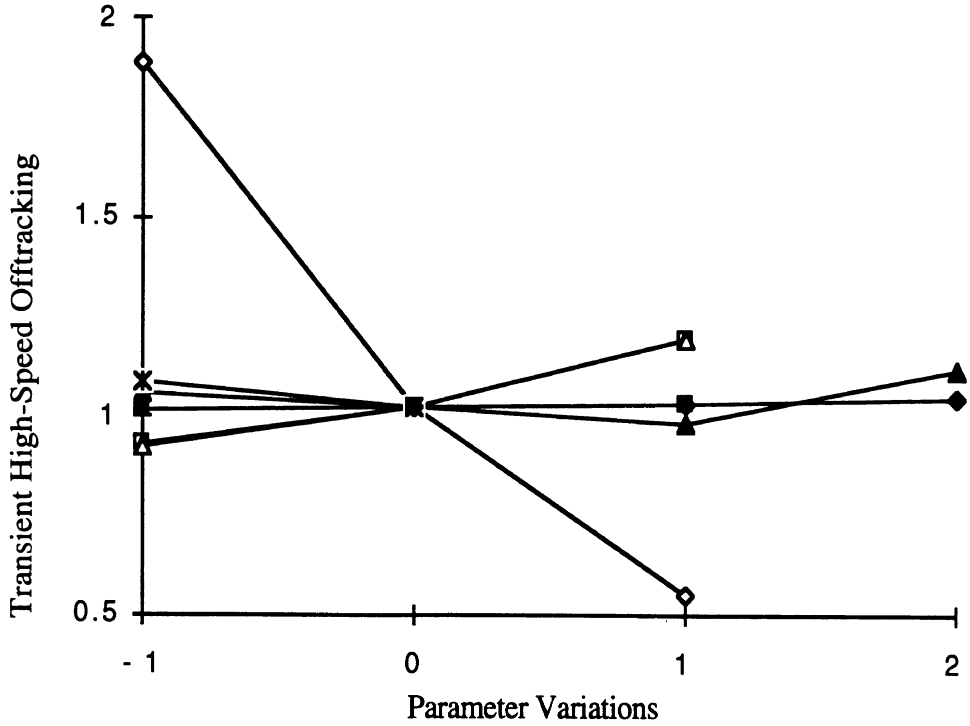


Figure C-186. Sensitivity of transient high-speed offtracking: 45'x28' seven-axle 3C2-train double

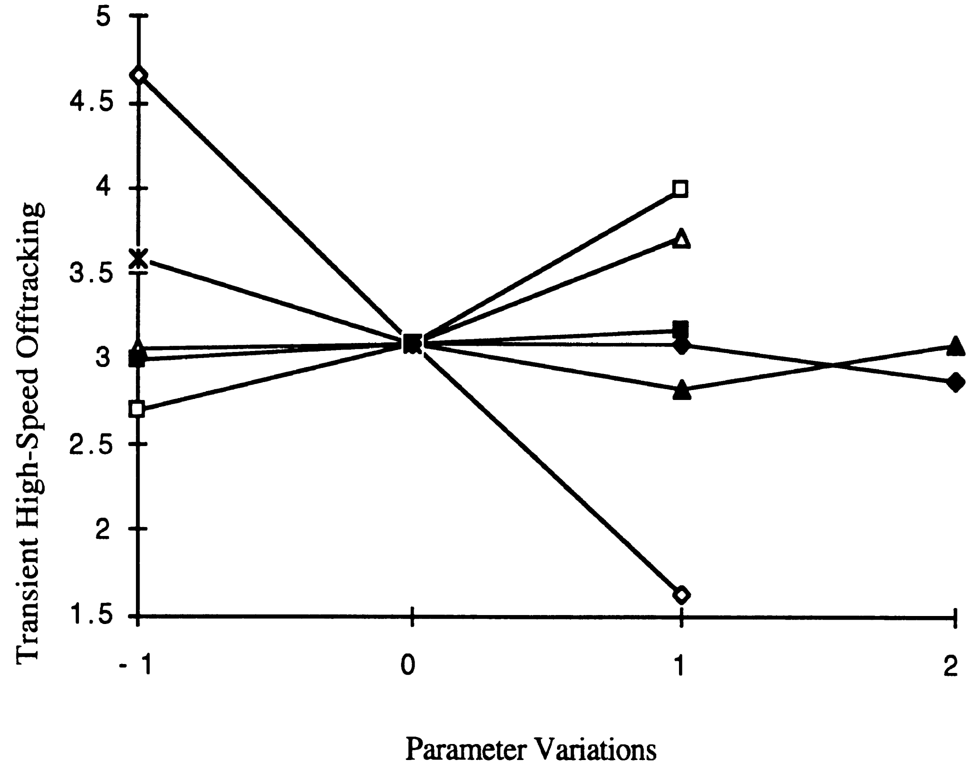


Figure C-187. Sensitivity of transient high-speed offtracking: 28'x28'x28' seven-axle 3C2-train triple

Sensitivity Plots of Damping Ratio in the RTAC-B Maneuver

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

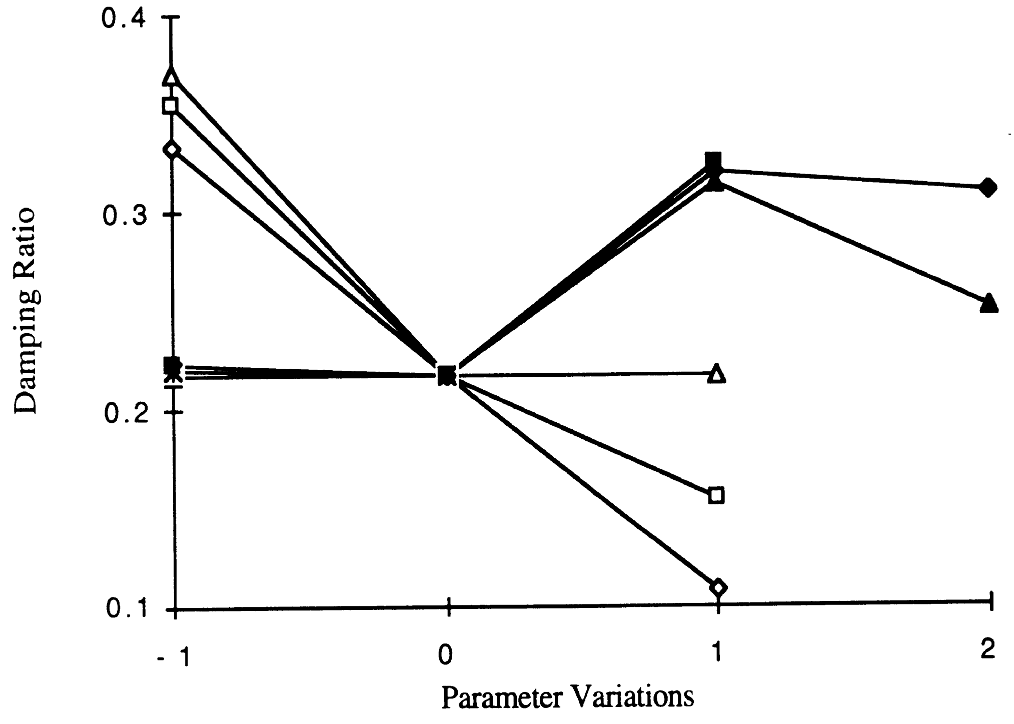


Figure C-188. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28' five-axle 3C2-train double

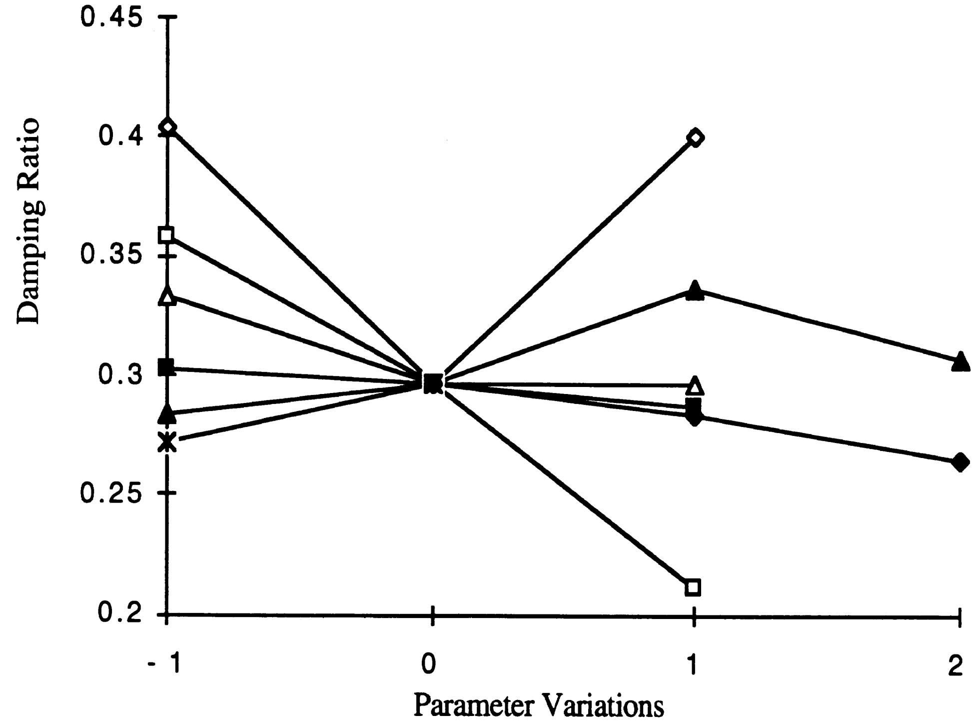


Figure C-189. Sensitivity of damping ratio in the RTAC-B maneuver: 32'x32' eight-axle 3C2-train double

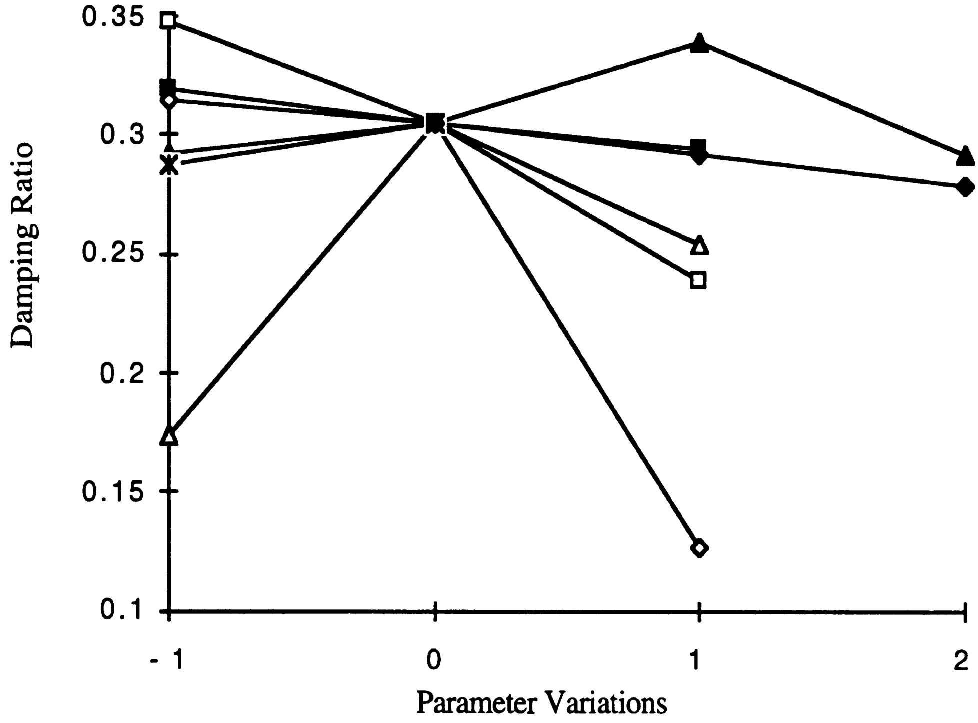


Figure C-190. Sensitivity of damping ratio in the RTAC-B maneuver: 38'x20' seven-axle 3C2-train double

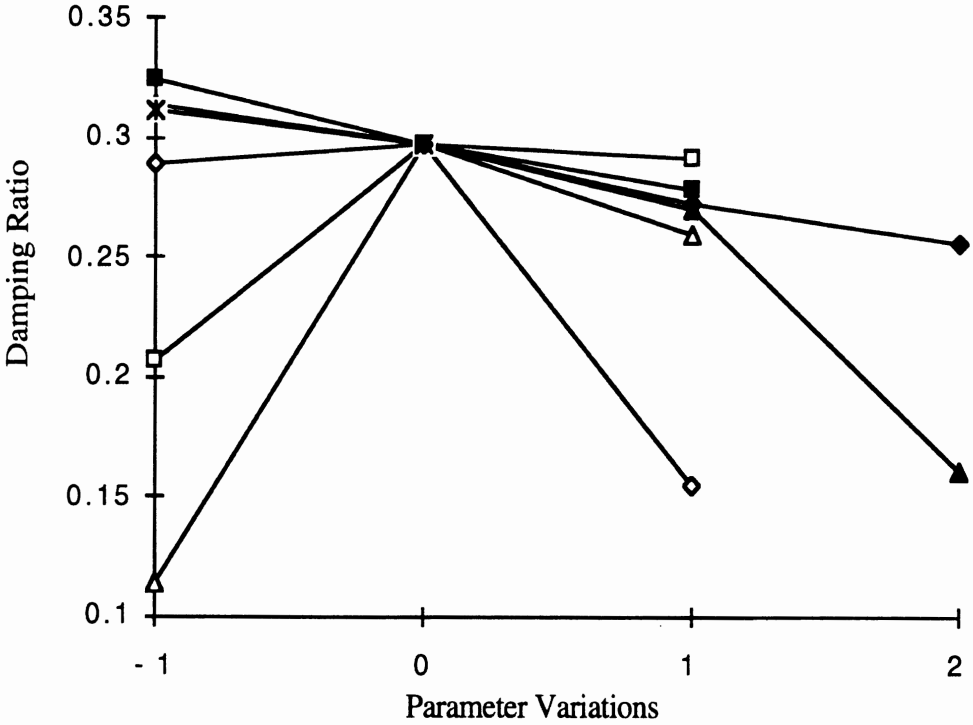


Figure C-191. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x28' seven-axle 3C2-train double

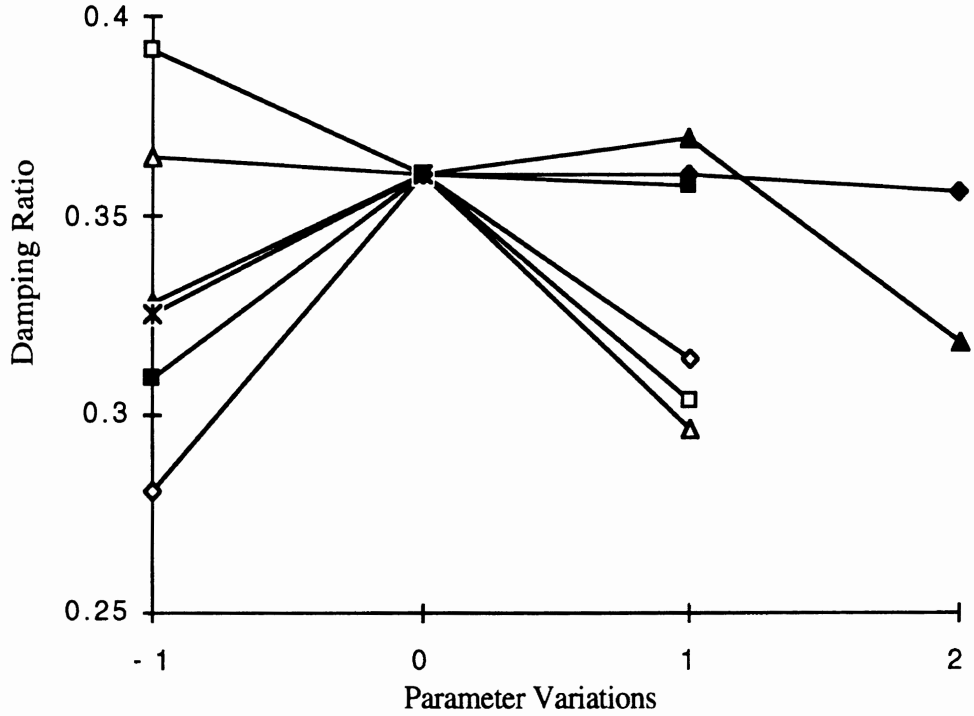


Figure C-192. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28'x28' seven-axle 3C2-train triple

SENSITIVITY STUDY RESULTS FOR THE 3C3-DOLLY

Table C-8. Performance measures obtained with the 3C3-dolly

Filename	Rollover Threshold (g's)	High Speed Steady State Offtracking (feet)	Rearward Amplification	Dynamic Load Transfer Coefficient	Transient High Speed Offtracking (feet)	Damping Ratio
28x28bas3C3	0.446	-1.192	1.949	0.494	1.937	0.225
28x28do13C3	0.447	-1.254	1.981	0.491	2.046	0.225
28x28do23C3	0.447	-1.307	2.019	0.483	2.154	0.225
28x28pl13C3	0.366	-1.239	2.018	0.600	2.165	0.165
28x28pl23C3	0.553	-1.165	1.861	0.395	1.743	0.257
28x28pl33C3	0.447	-1.200	1.968	0.490	2.152	0.173
28x28pl43C3	0.446	-1.192	1.878	0.485	1.750	0.301
28x28se13C3	0.447	-1.218	1.947	0.490	1.959	0.227
28x28se23C3	0.446	-1.168	1.947	0.498	1.912	0.225
28x28sp23C3	0.438	-1.196	1.976	0.509	1.984	0.215
28x28sp33C3	0.455	-1.189	1.897	0.471	1.881	0.236
28x28ss23C3	0.460	-1.289	1.975	0.491	2.093	0.246
28x28su13C3	0.406	-1.214	2.006	0.556	2.053	0.209
28x28tl13C3	0.440	-0.770	1.747	0.456	1.102	0.373
28x28tl23C3	0.443	-1.978	2.212	0.522	3.595	0.174
32x32bas3C3	0.455	-1.283	1.810	0.427	1.772	0.270
32x32do13C3	0.455	-1.342	1.845	0.425	1.879	0.264
32x32do23C3	0.455	-1.396	1.860	0.420	1.990	0.276
32x32pl13C3	0.379	-1.310	1.860	0.524	1.931	0.226
32x32pl23C3	0.623	-1.263	1.726	0.342	1.661	0.302
32x32pl33C3	0.455	-1.283	1.810	0.427	1.772	0.270
32x32pl43C3	0.455	-1.285	1.741	0.418	1.569	0.325
32x32se13C3	0.455	-1.305	1.813	0.424	1.795	0.270
32x32se23C3	0.455	-1.254	1.805	0.430	1.745	0.271
32x32sp23C3	0.448	-1.286	1.826	0.438	1.797	0.262
32x32sp33C3	0.458	-1.276	1.766	0.407	1.727	0.292
32x32ss43C3	0.474	-1.362	1.792	0.414	1.856	0.295
32x32su13C3	0.417	-1.295	1.855	0.482	1.837	0.253
32x32tl13C3	0.456	-0.779	1.540	0.389	0.932	0.355
32x32tl23C3	0.456	-2.050	2.058	0.456	3.206	0.252
38x20bas3C3	0.448	-1.151	1.938	0.451	1.634	0.419
38x20do13C3	0.448	-1.206	1.993	0.451	1.727	0.556
38x20do23C3	0.448	-1.267	2.048	0.451	1.824	0.462
38x20pl13C3	0.368	-1.179	2.115	0.559	1.835	0.247
38x20pl23C3	0.584	-1.145	1.822	0.354	1.476	0.282
38x20pl33C3	0.448	-1.151	1.865	0.442	1.702	0.260
38x20pl43C3	0.447	-1.151	1.952	0.446	1.462	0.358
38x20se13C3	0.448	-1.175	1.955	0.449	1.664	0.392
38x20se23C3	0.447	-1.126	1.921	0.453	1.603	0.477
38x20sp23C3	0.433	-1.154	1.970	0.464	1.676	0.419
38x20sp33C3	0.452	-1.149	1.870	0.425	1.565	0.262
38x20ss43C3	0.468	-1.245	1.962	0.443	1.752	0.279
38x20su13C3	0.411	-1.157	2.015	0.506	1.735	0.445
38x20tl13C3	0.446	-0.681	1.746	0.411	0.846	0.086
38x20tl23C3	0.447	-1.925	2.237	0.465	2.943	0.204
45x28bas3C3	0.450	-1.213	1.594	0.358	1.310	0.348
45x28do13C3	0.450	-1.265	1.627	0.355	1.372	0.348
45x28do23C3	0.450	-1.319	1.658	0.351	1.443	0.347
45x28pl13C3	0.373	-1.247	1.704	0.442	1.507	0.226
45x28pl23C3	0.582	-1.197	1.519	0.284	1.201	0.405
45x28pl33C3	0.450	-1.212	1.584	0.340	1.541	0.296
45x28pl43C3	0.450	-1.214	1.574	0.360	1.167	0.477
45x28se13C3	0.450	-1.236	1.602	0.355	1.325	0.348
45x28se23C3	0.450	-1.189	1.589	0.361	1.296	0.348
45x28sp23C3	0.437	-1.218	1.620	0.368	1.350	0.320
45x28sp33C3	0.453	-1.210	1.560	0.341	1.259	0.373
45x28ss43C3	0.470	-1.329	1.616	0.351	1.431	0.385
45x28su13C3	0.415	-1.228	1.647	0.401	1.393	0.310
45x28tl13C3	0.449	-0.654	1.371	0.339	0.642	0.471
45x28tl23C3	0.452	-2.154	1.830	0.352	2.609	0.325
3X28BAS3C3	0.456	-1.824	2.603	0.427	3.787	0.123
3X28DO13C3	0.456	-1.973	4.795	0.462	7.768	0.034
3X28DO23C3	0.456	-2.065	2.702	0.832	NA	-0.050
3X28PL13C3	0.378	-1.902	2.826	0.502	4.968	0.134
3X28PL23C3	0.564	-1.798	2.522	0.358	3.126	0.123
3X28PL33C3	0.453	-1.841	3.448	0.431	10.754	0.009
3X28PL43C3	0.455	-1.844	2.557	0.422	2.898	0.186
3X28SE13C3	0.456	-1.857	2.662	0.422	4.514	0.108
3X28SE23C3	0.455	-1.793	2.583	0.433	3.387	0.138
3X28SP23C3	0.436	-1.841	2.722	0.454	4.707	0.117
3X28SP33C3	0.458	-1.820	2.563	0.410	3.747	0.119
3X28SS43C3	0.471	-1.657	2.689	0.439	3.196	0.121
3X28SU13C3	0.416	-1.853	2.598	0.477	4.837	0.124
3X28TI13C3	0.453	-1.212	2.259	0.399	1.787	0.193
3X28TI23C3	0.455	-3.058	4.450	0.473	11.993	0.014

Sensitivity Plots of Static Rollover Threshold

Key for the sensitivity plots:

		Parameter Variations			
Symbol	*Parameter*	*-1*	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

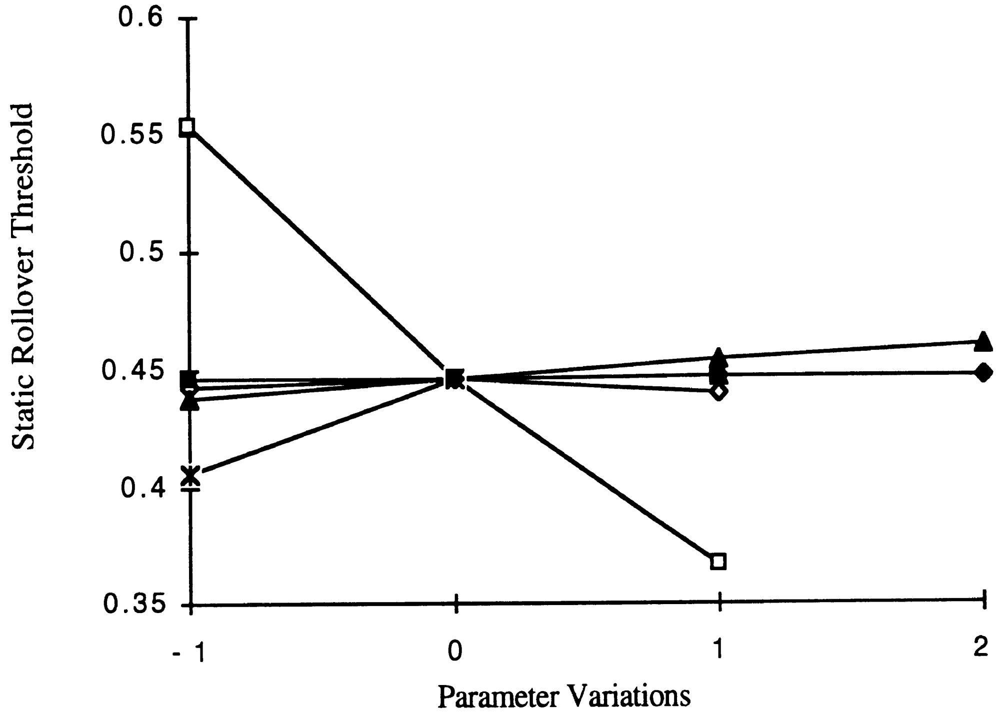


Figure C-193. Sensitivity of static rollover threshold: 28'x28' five-axle 3C3-train double

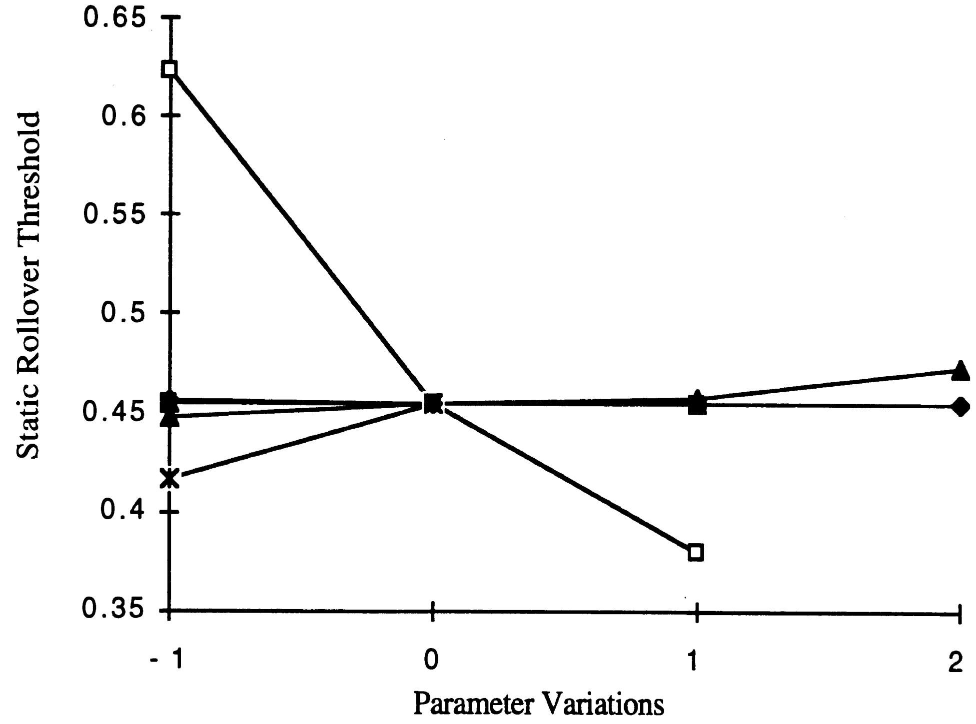


Figure C-194. Sensitivity of static rollover threshold: 32'x32' eight-axle 3C3-train double

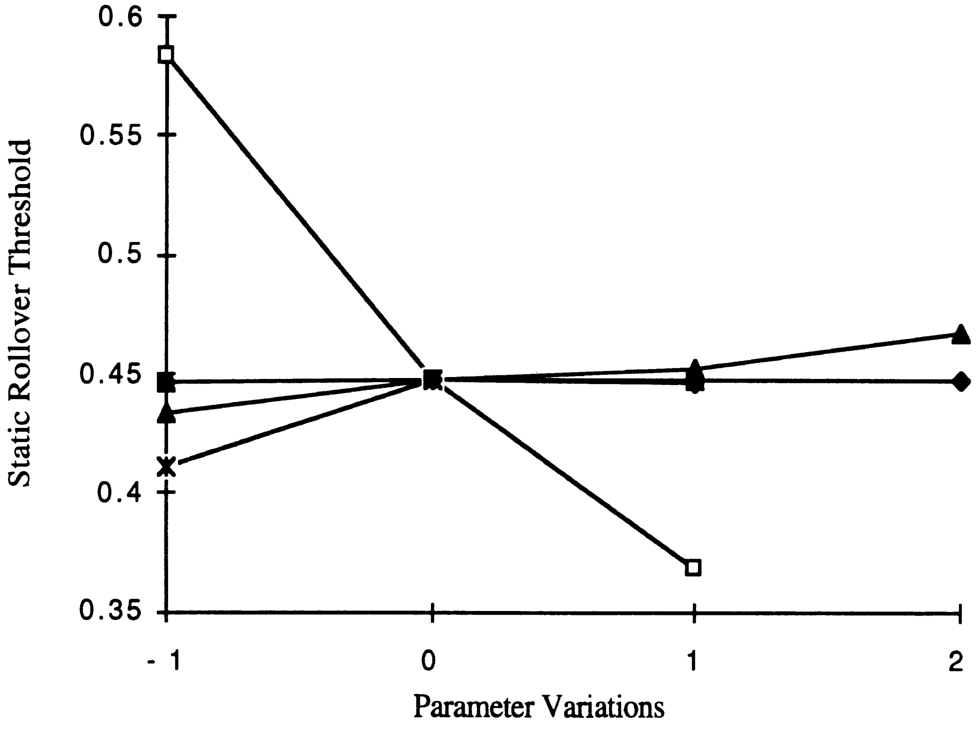


Figure C-195. Sensitivity of static rollover threshold: 38'x20' seven-axle 3C3-train double

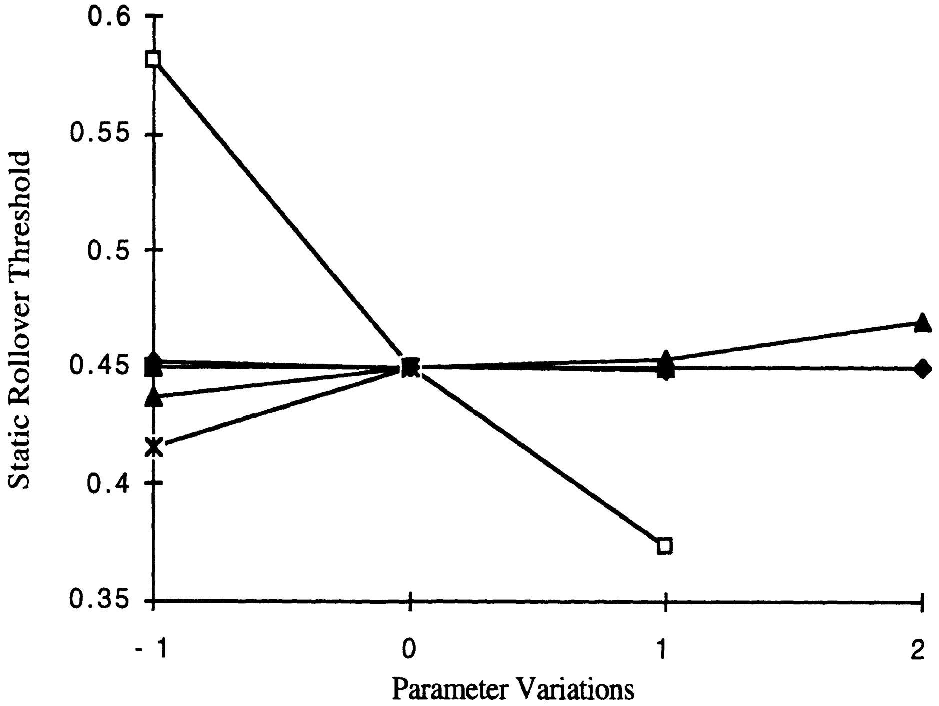


Figure C-196. Sensitivity of static rollover threshold: 45'x28' seven-axle 3C3-train double

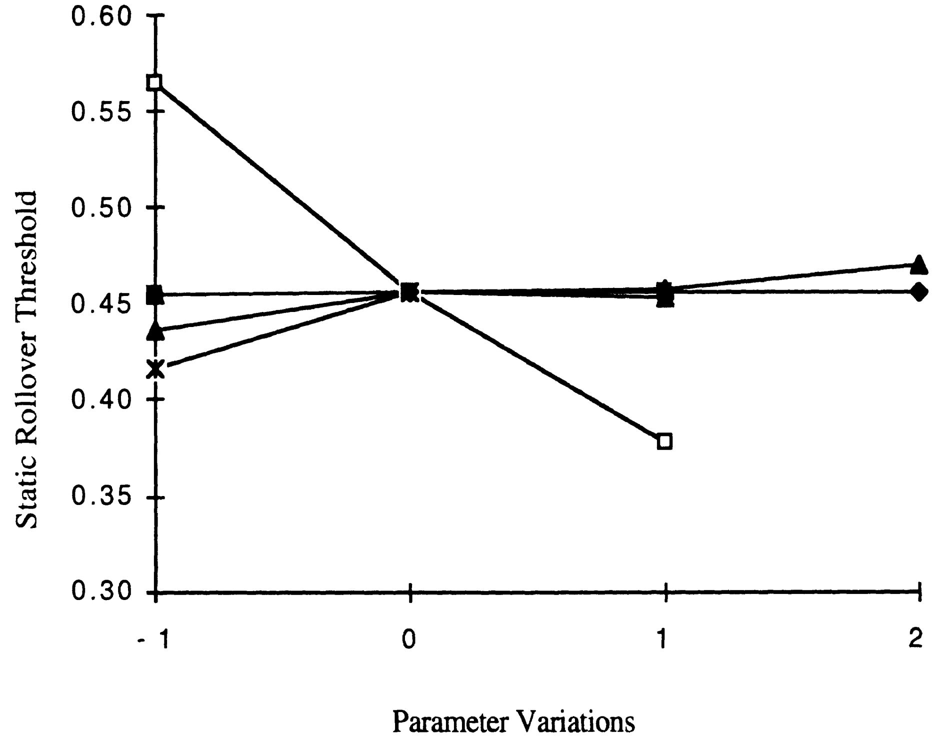


Figure C-197. Sensitivity of static rollover threshold: 28'x28'x28' seven-axle 3C3-train triple

Sensitivity Plots of High-Speed Steady-State Offtracking

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

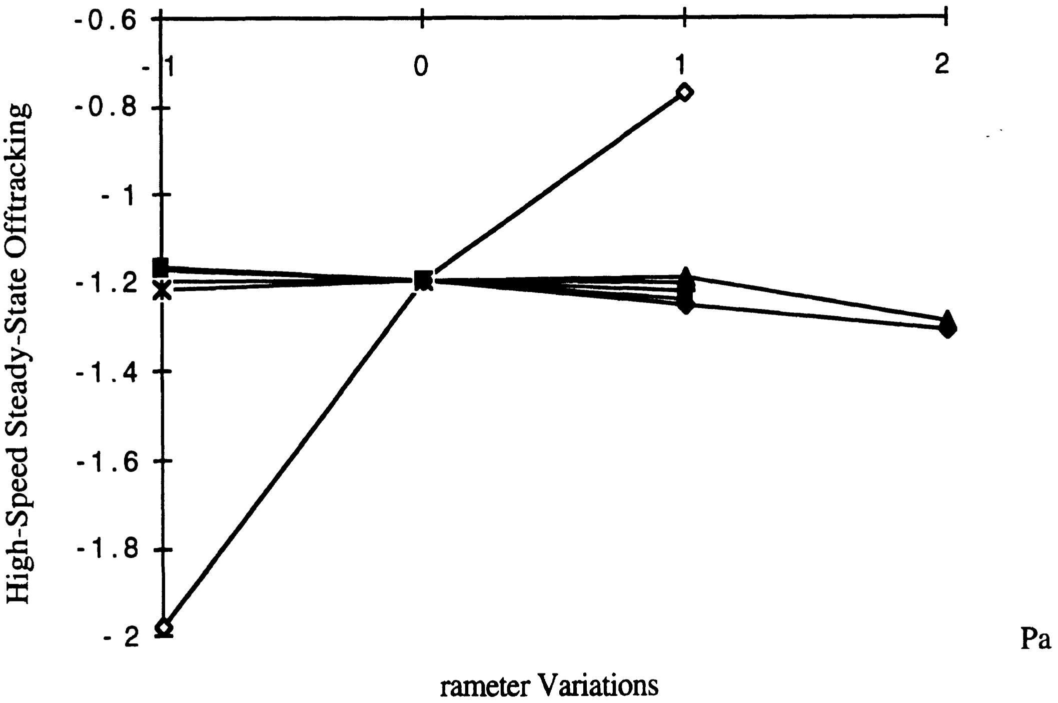


Figure C-198. Sensitivity of high-speed steady-state offtracking: 28'x28' five-axle 3C3-train double

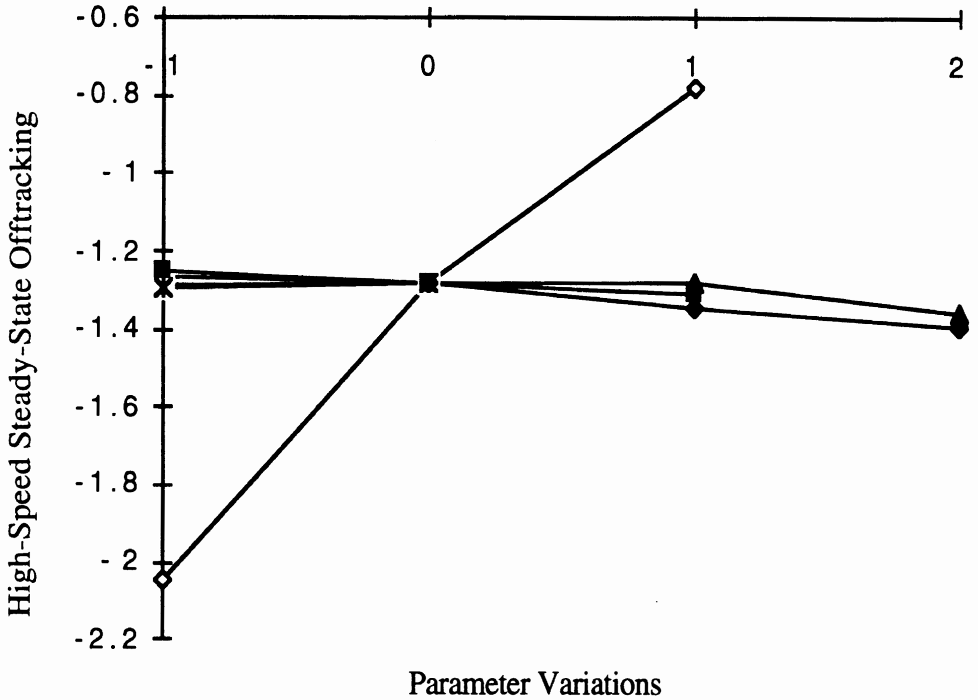


Figure C-199. Sensitivity of high-speed steady-state offtracking: 32'x32' eight-axle 3C3-train double

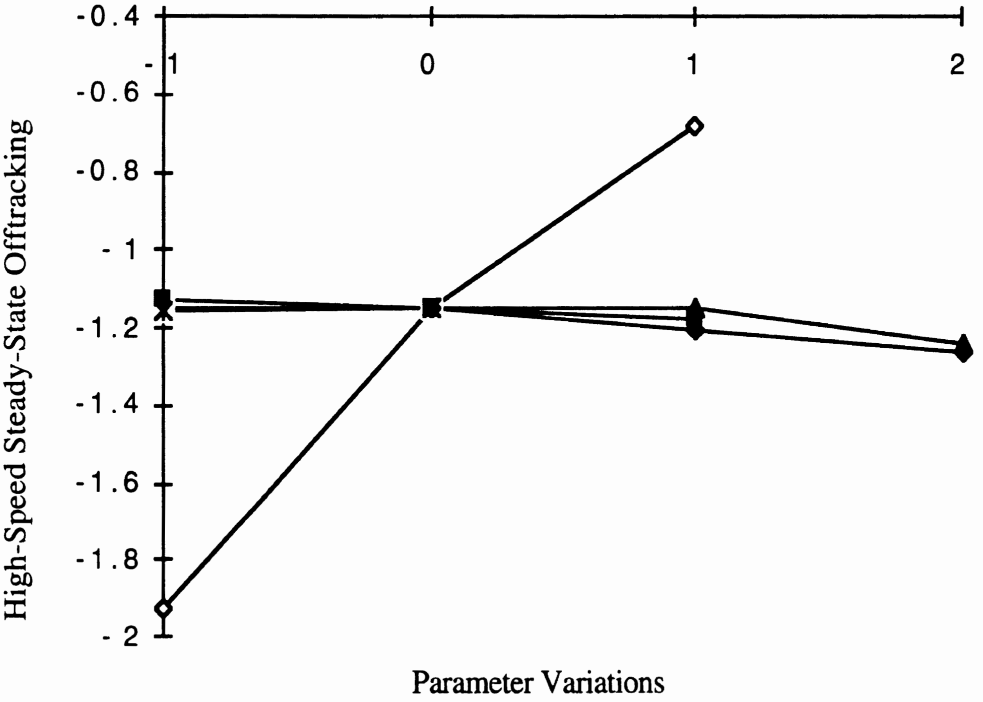


Figure C-200. Sensitivity of high-speed steady-state offtracking: 38'x20' seven-axle 3C3-train double

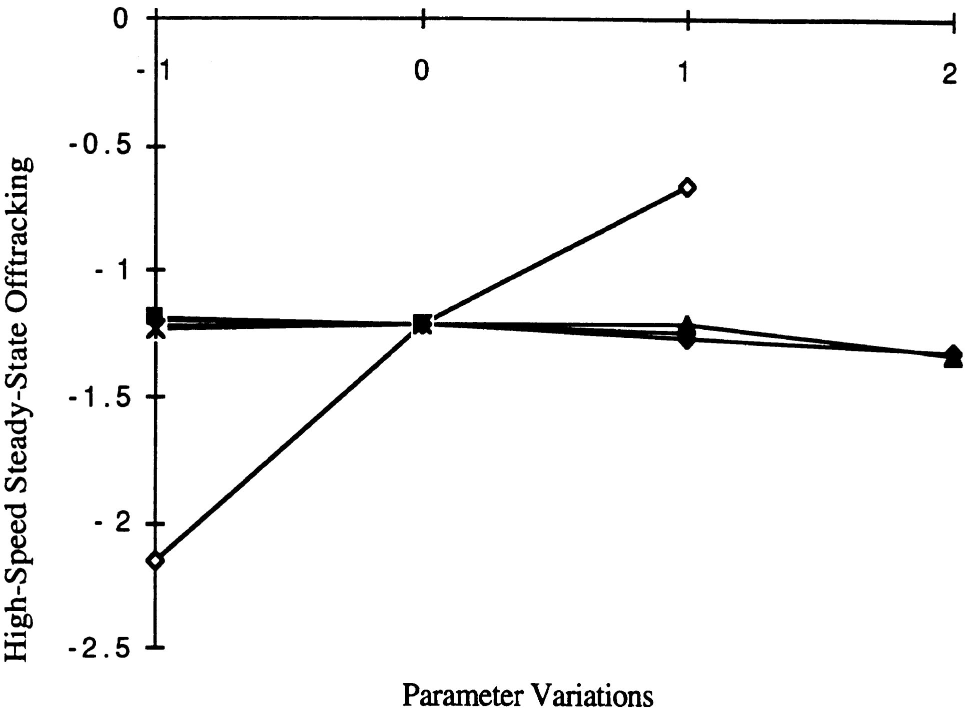


Figure C-201. Sensitivity of high-speed steady-state offtracking: 45'x28' seven-axle 3C3-train double

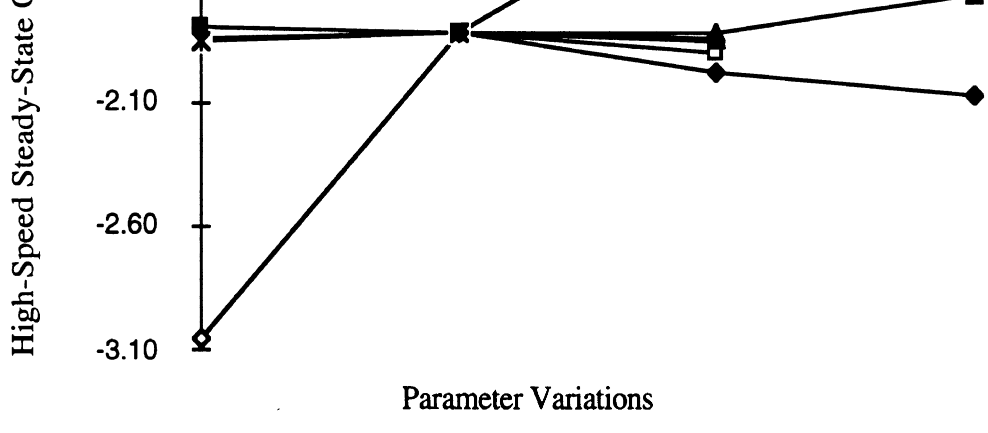


Figure C-202. Sensitivity of high-speed steady-state offtracking: 28'x28'x28' seven-axle 3C3-train triple

Sensitivity Plots of Rearward Amplification

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	2
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✱—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

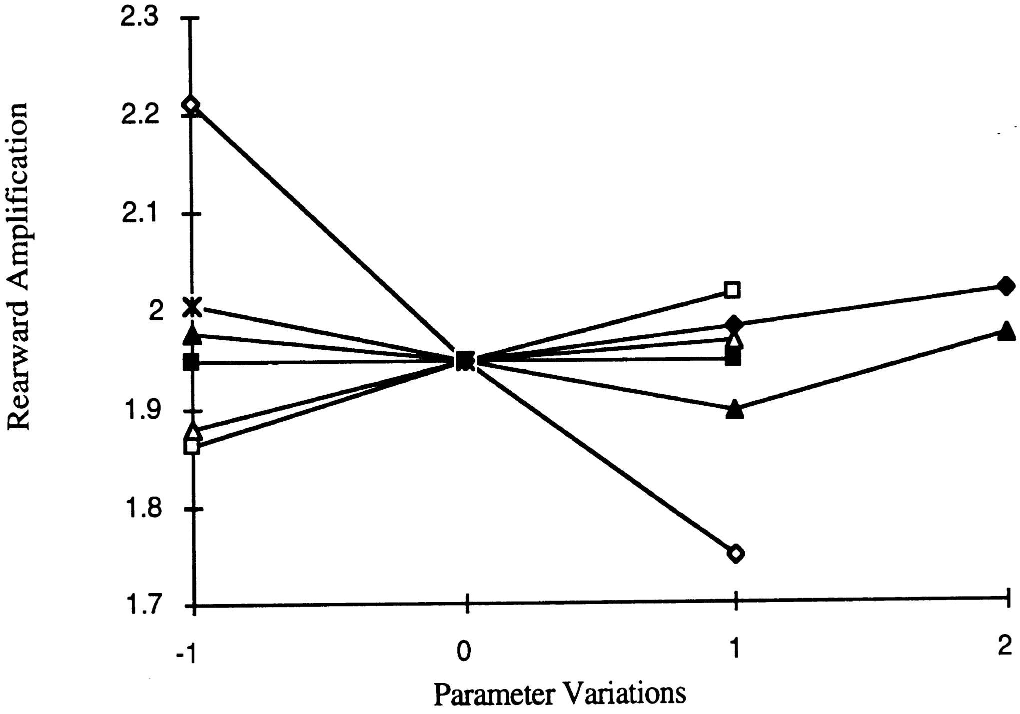


Figure C-203. Sensitivity of rearward amplification: 28'x28' five-axle 3C3-train double

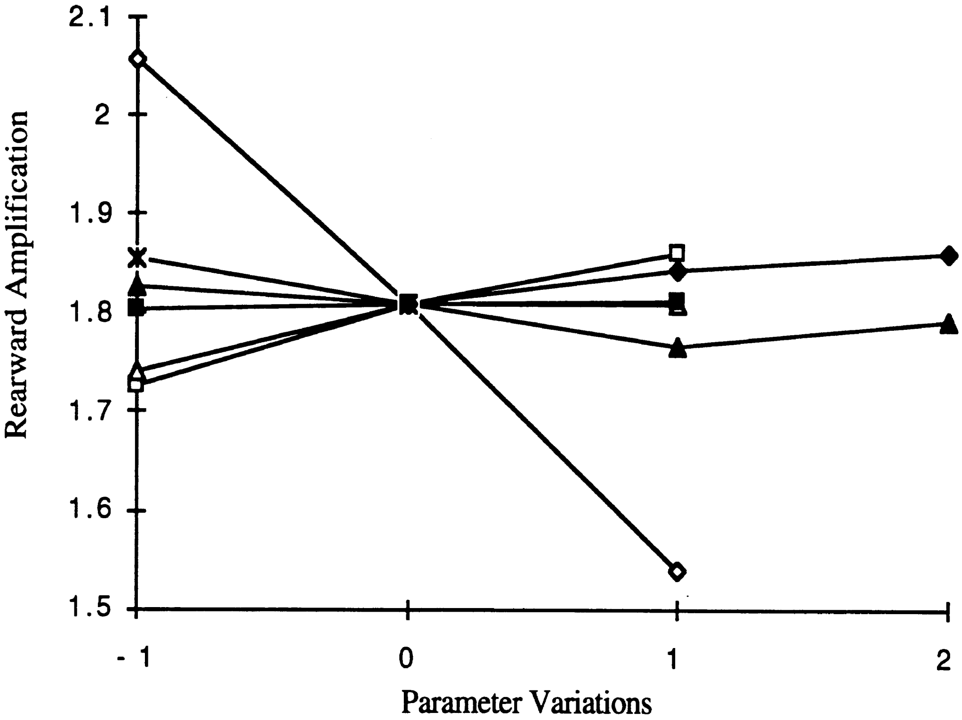


Figure C-204. Sensitivity of rearward amplification: 32'x32' eight-axle 3C3-train double

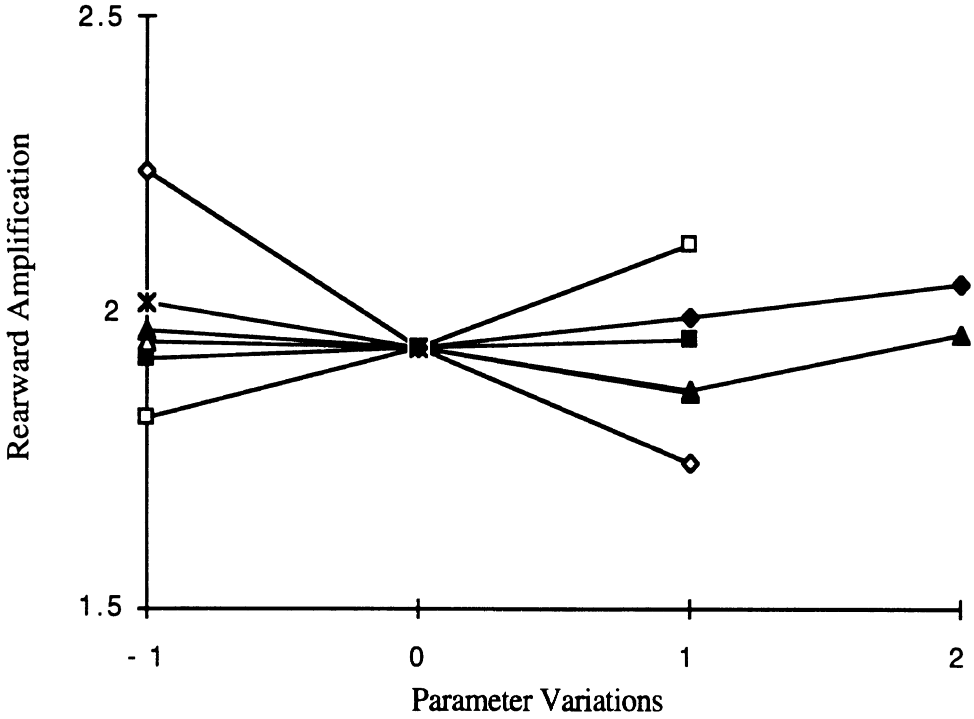


Figure C-205. Sensitivity of rearward amplification: 38'x20' seven-axle 3C3-train double

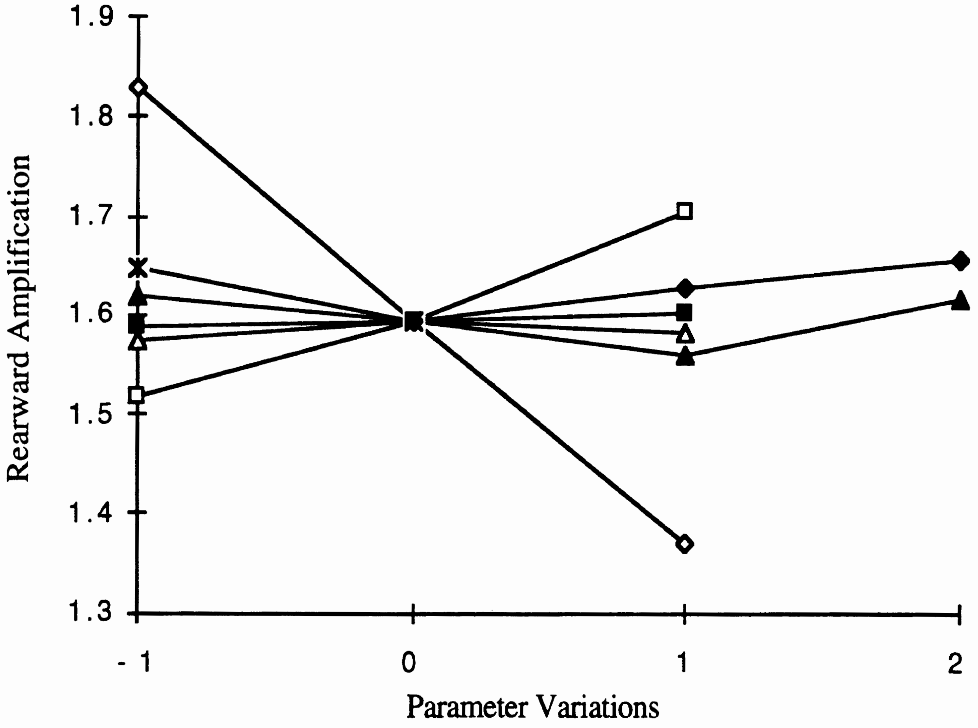


Figure C-206. Sensitivity of rearward amplification: 45'x28' seven-axle 3C3-train double

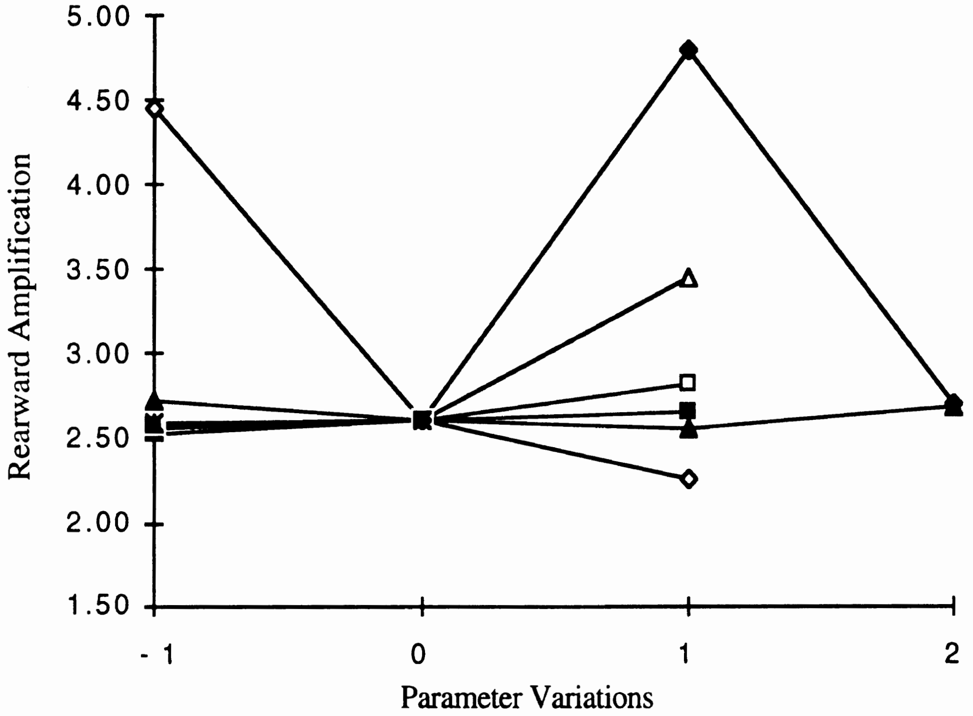


Figure C-207. Sensitivity of rearward amplification: 28'x28'x28' seven-axle 3C3-train triple

Sensitivity Plots of Dynamic-Load-Transfer Ratio

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✳	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

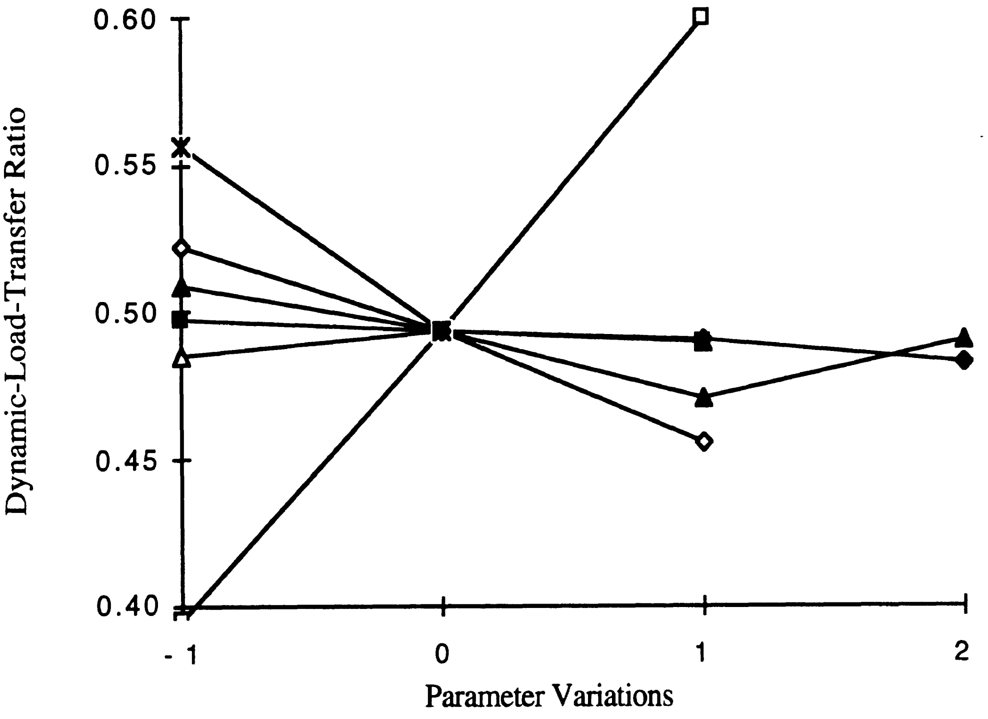


Figure C-208. Sensitivity of dynamic-load-transfer ratio: 28'x28' five-axle 3C3-train double

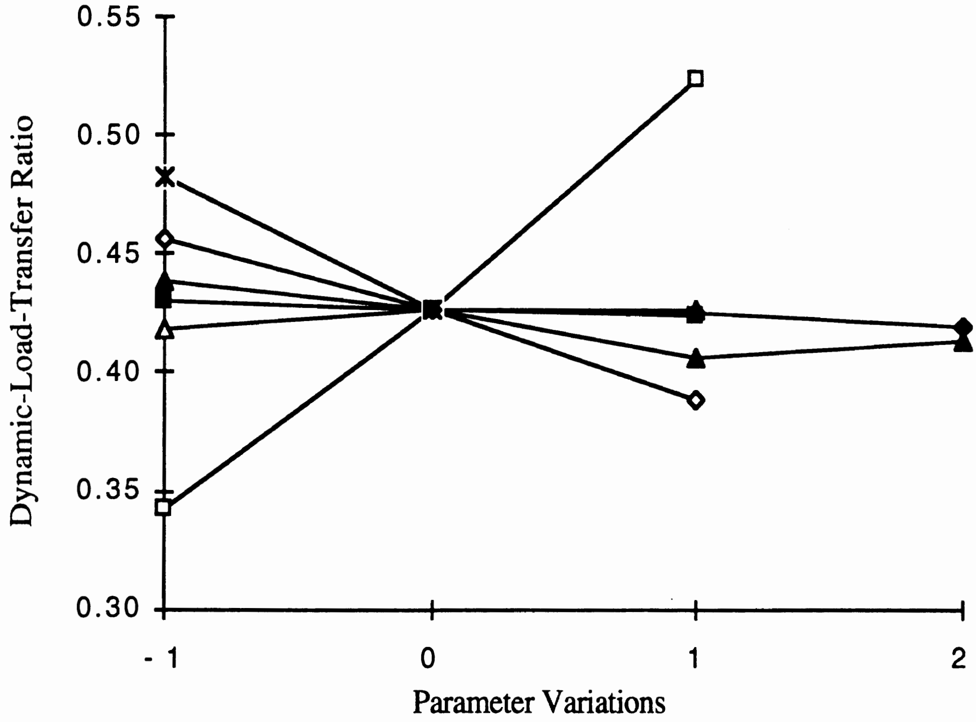


Figure C-209. Sensitivity of dynamic-load-transfer ratio: 32'x32' eight-axle 3C3-train double

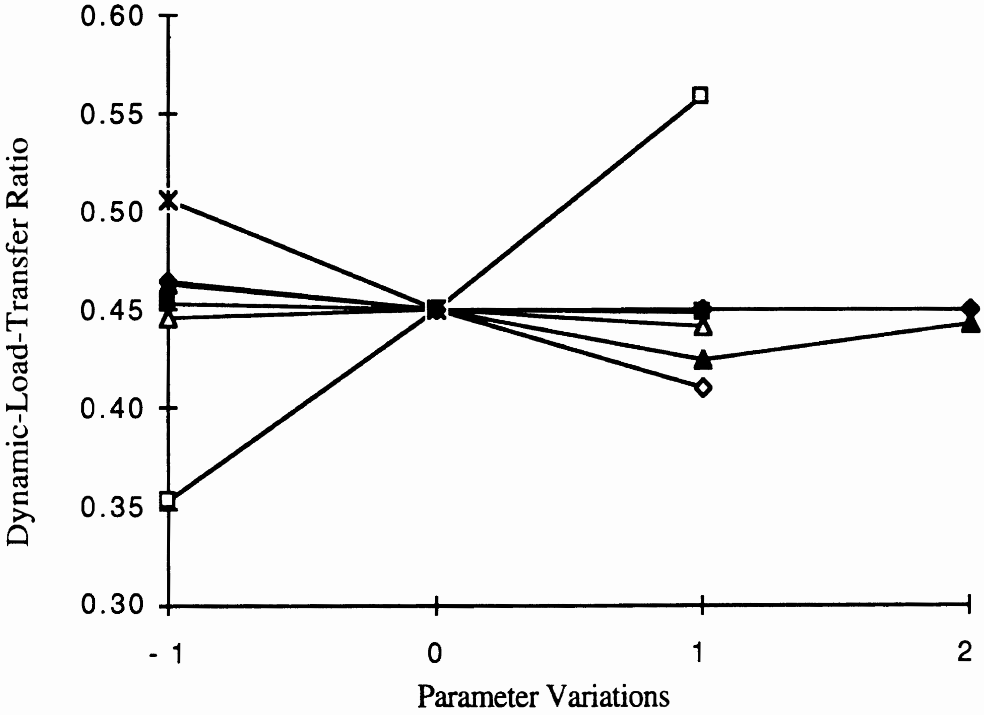


Figure C-210. Sensitivity of dynamic-load-transfer ratio: 38'x20' seven-axle 3C3-train double

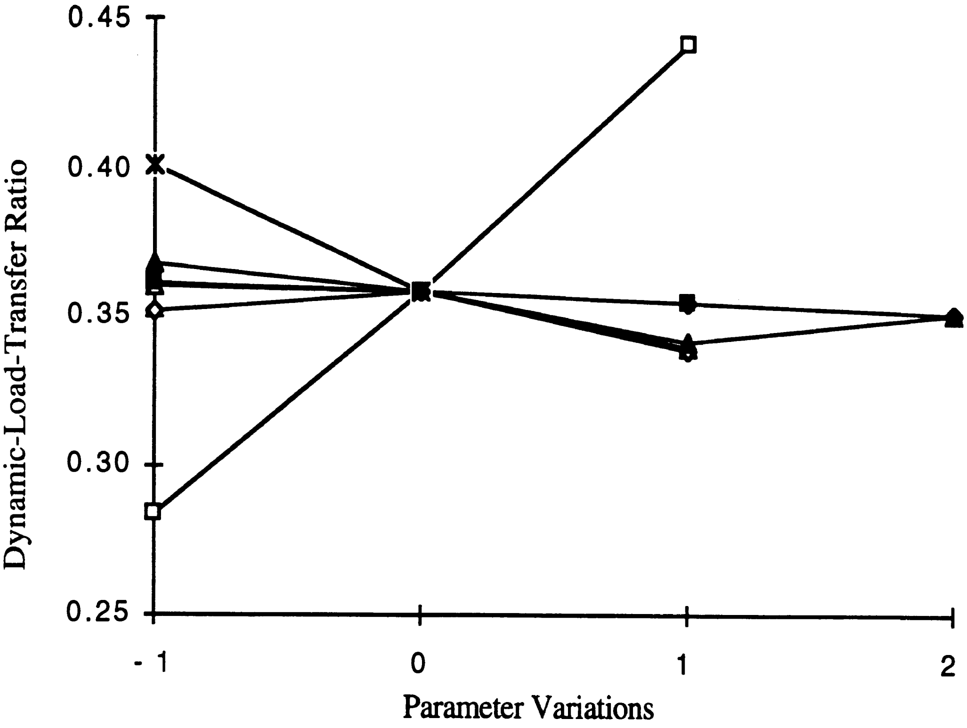


Figure C-211. Sensitivity of dynamic-load-transfer ratio: 45'x28' seven-axle 3C3-train double

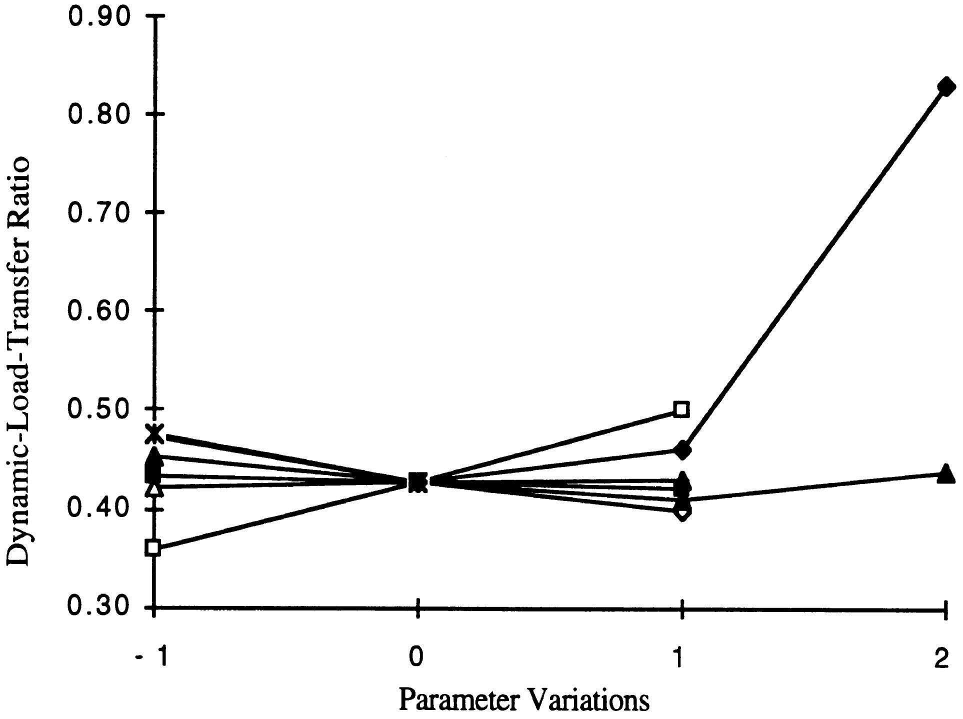


Figure C-212. Sensitivity of dynamic-load-transfer ratio: 28'x28'x28' seven-axle 3C3-train triple

Sensitivity Plots of Transient High-Speed Offtracking

Key for the sensitivity plots:

Symbol	*Parameter*	*Parameter Variations*			
		-1	*0*	*1*	*2*
—□—	Payload cg height, inches	70	85	100	None
—△—	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
—◇—	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
—▲—	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
—✳—	Overall axle width, inches	96	102	None	None
—■—	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
—◆—	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

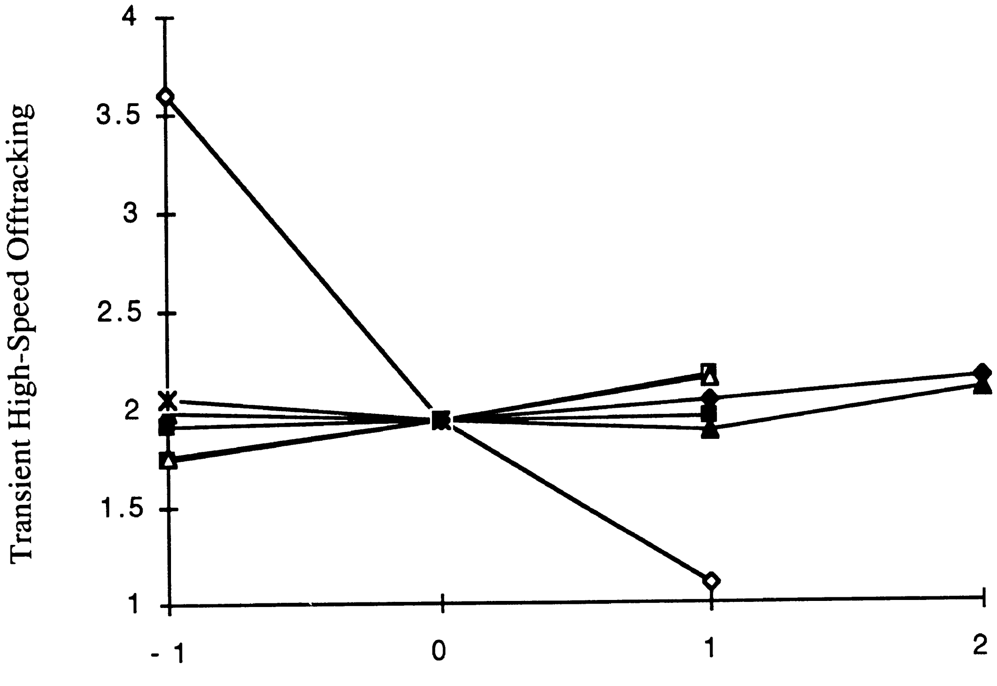


Figure C-213. Sensitivity of transient high-speed offtracking: 28'x28' five-axle 3C3-train double

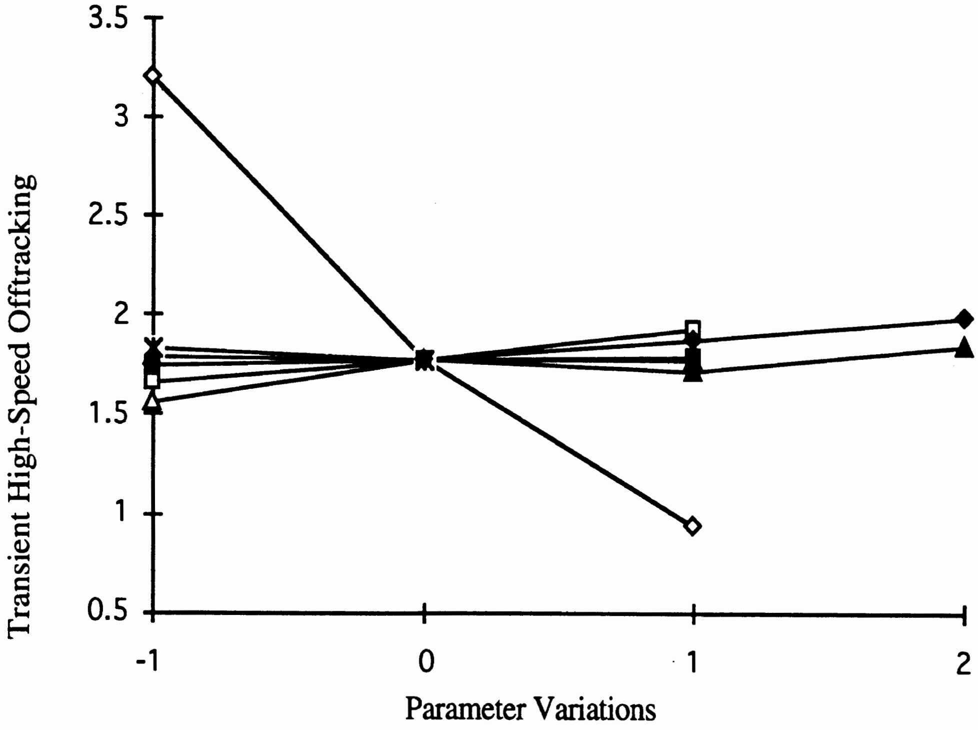


Figure C-214. Sensitivity of transient high-speed offtracking: 32'x32' eight-axle 3C3-train double

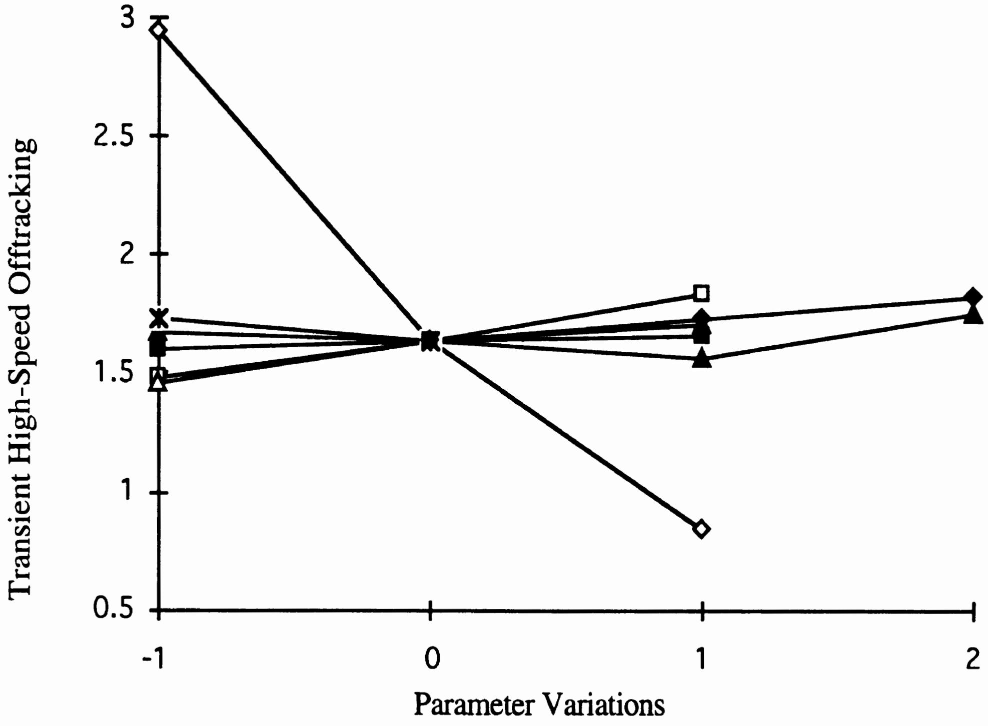


Figure C-215. Sensitivity of transient high-speed offtracking: 38'x20' seven-axle 3C3-train double

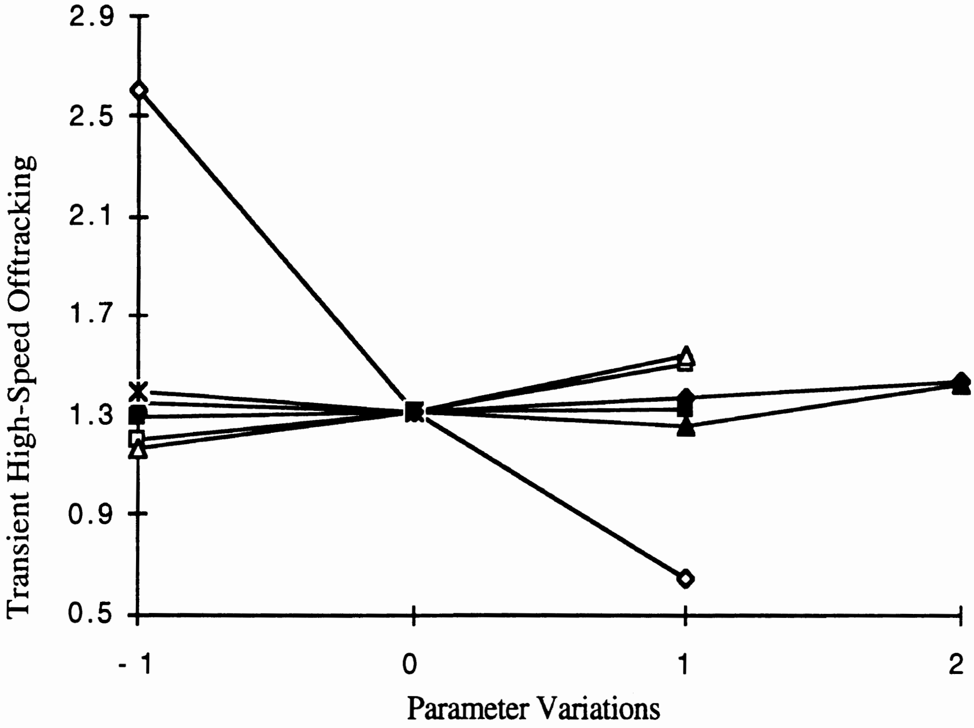


Figure C-216. Sensitivity of transient high-speed offtracking: 45'x28' seven-axle 3C3-train double

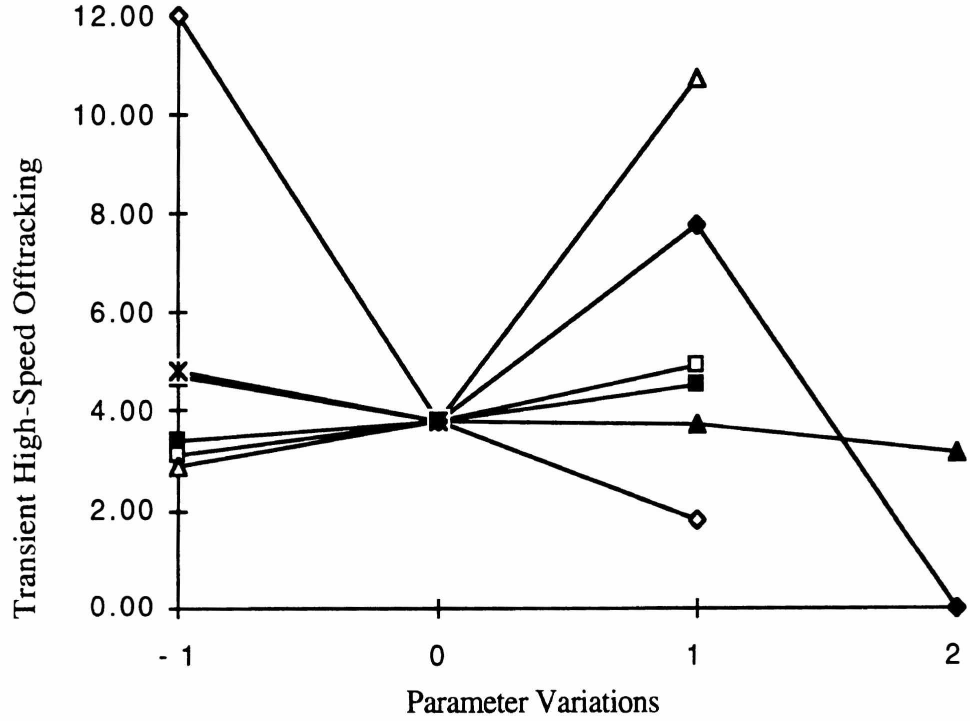


Figure C-217. Sensitivity of transient high-speed offtracking: 28'x28'x28' seven-axle 3C3-train triple

Sensitivity Plots of Damping Ratio in the RTAC-B Maneuver

Key for the sensitivity plots:

Symbol	Parameter	*Parameter Variations*			
		-1	*0*	*1*	*2*
□	Payload cg height, inches	70	85	100	None
△	Yaw moment of inertia, in-lb-sec^2	1/2 of Baseline	Baseline*	2 times Baseline	None
◇	Tire-cornering stiffness, lb/deg	New Bias 564	New Radial 881	Worn Radial 1124	None
▲	Suspension roll stiffness, in-lb/deg	117800* (nominal)	137600* (nominal)	175000* (nominal)	203700* (nominal)
✳	Overall axle width, inches	96	102	None	None
■	Pintle hitch overhang, inches	Baseline-12	Baseline*	Baseline+12	None
◆	Dolly tongue length (wheelbase), inches	None	80	100	120

* Vehicle Dependent

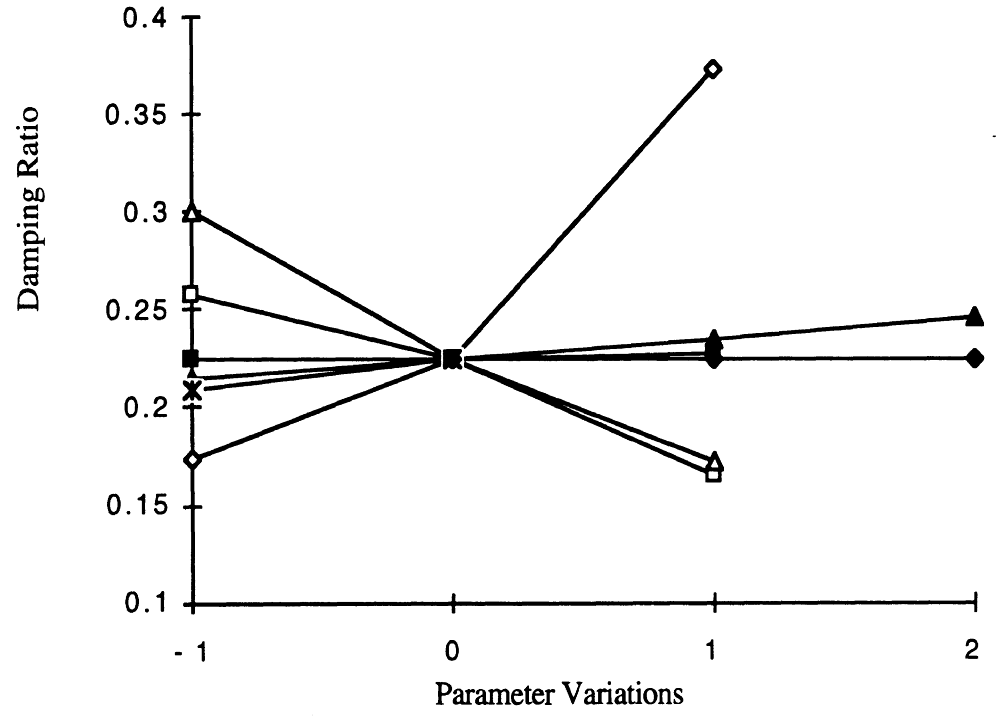


Figure C-218. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28' five-axle 3C3-train double

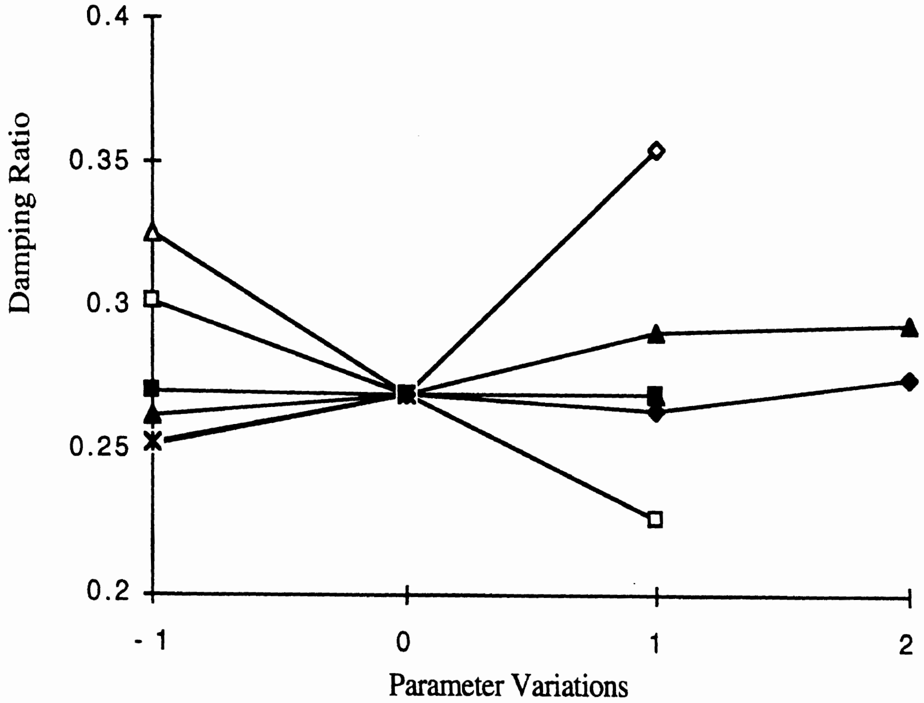


Figure C-219. Sensitivity of damping ratio in the RTAC-B maneuver: 32'x32' eight-axle 3C3-train double

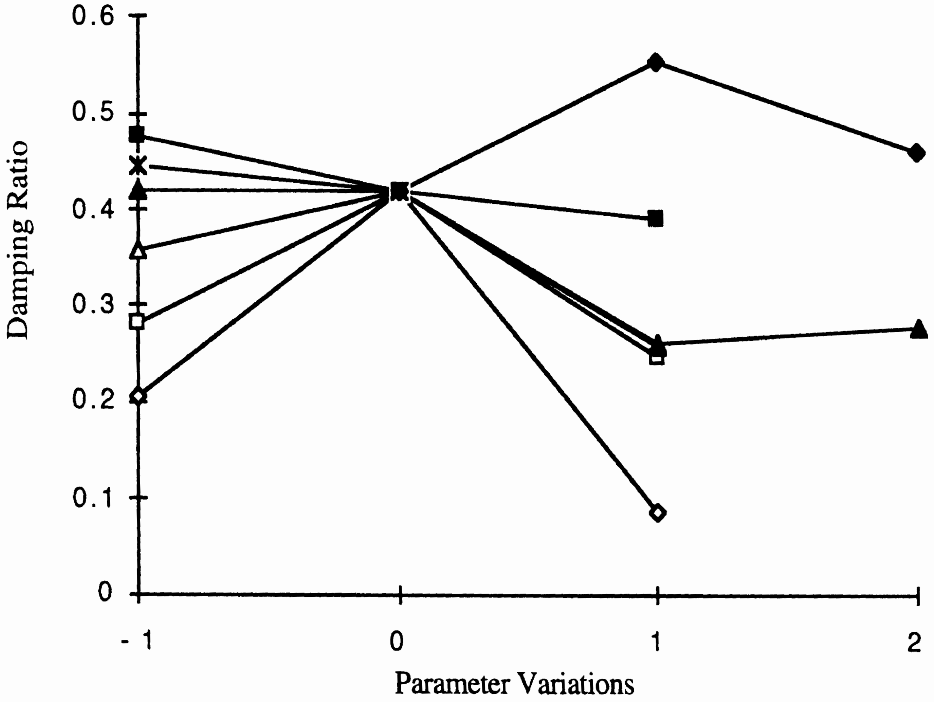


Figure C-220. Sensitivity of damping ratio in the RTAC-B maneuver: 38'x20' seven-axle 3C3-train double

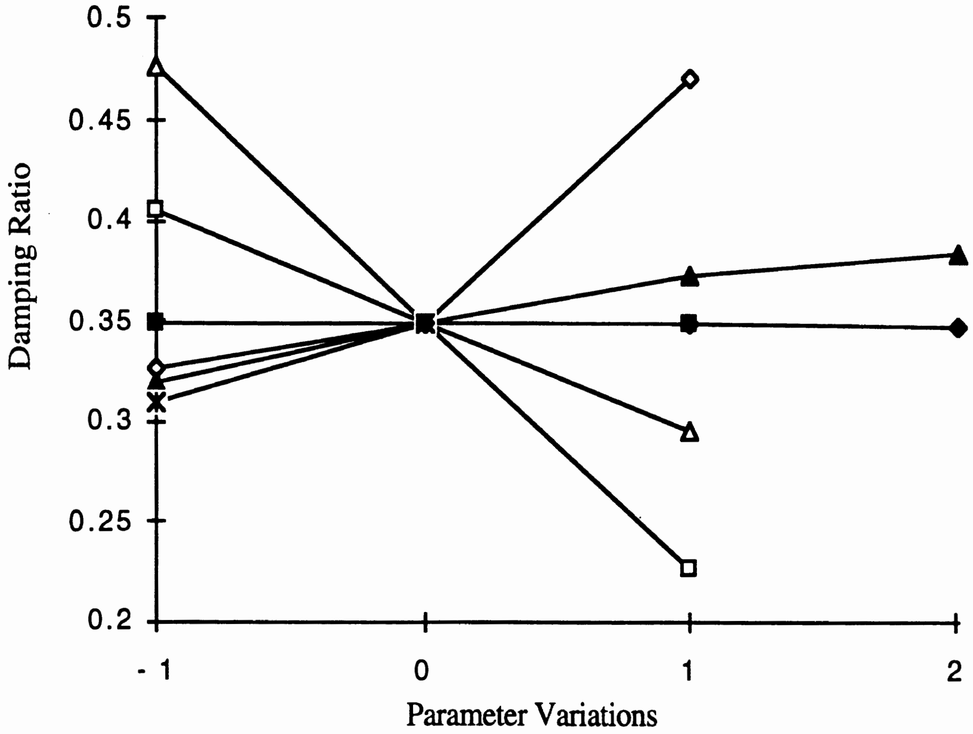


Figure C-221. Sensitivity of damping ratio in the RTAC-B maneuver: 45'x28' seven-axle 3C3-train double

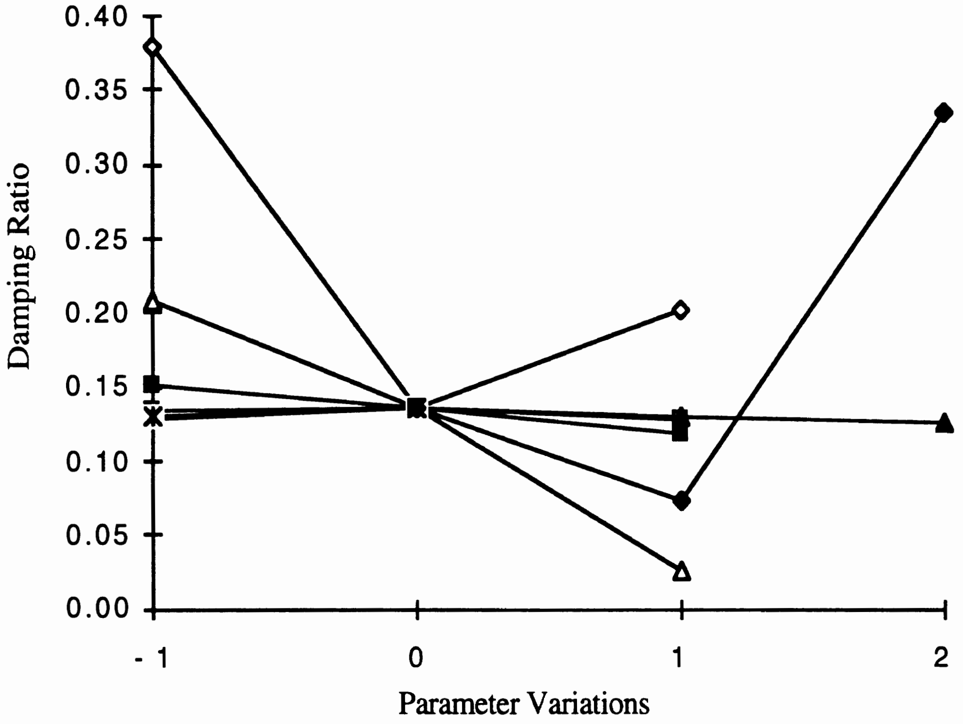


Figure C-222. Sensitivity of damping ratio in the RTAC-B maneuver: 28'x28'x28' seven-axle 3C3-train triple

APPENDIX D
REGRESSION MODEL PARAMETERS

Table D-1 below details the definitions used in the next section "Database for Predicting A-Train Performance Measures."

Table D-1. Definition of variables

Variable	*Definitions*
Cα	Tire-cornering stiffness; per tire; at nominal vertical load (lb/deg)
WB1	Tractor wheelbase (inches)
WB2	First trailer wheelbase (inches)
WB3	Second trailer wheelbase (inches)
WB4	Third trailer wheelbase (inches)
OH1	Tractor fifth wheel offset; negative if forward of rear suspension centerline (inches)
OH2	First trailer pintle hitch overhang (inches)
OH3	Second trailer pintle hitch overhang (inches)
TL1	First dolly tongue length, i.e., wheelbase (inches)
TL2	Second dolly tongue length, i.e., wheelbase (inches)
CG (also H)	Payload center-of-gravity height above ground (same for all trailers of vehicle) (inches)
Trk Width (also T)	Overall dolly and trailer track width (96 or 102 inches; all tractors 96 inches)
Roll Stf	Nominal trailer and dolly suspension roll stiffness; per axle (same for all trailers and dollies of vehicle) (inch-lb/deg)
Izz1	Sprung mass yaw moment of inertia of the first trailer (inch-lb-sec^2)
Izz2	Sprung mass yaw moment of inertia of the second trailer (inch-lb-sec^2)
Izz3	Sprung mass yaw moment of inertia of the third trailer (inch-lb-sec^2)
Radial	1 if radial tire; 0 if bias tire
Inertia Ratio	Ratio of trailer yaw inertia to baseline trailer yaw inertia
WHI Len	Characteristic length from the Western Highway Institute offtracking method; "square root of the sum of the squares" [w1] (feet)
Overall Len	longitudinal distance from first to last suspension centerline (feet)
Overall Len/Cα	Overall length divided by tire-cornering stiffness (feet-deg/lb)
Overall Len/Rep Cα	Overall length divided by representative tire-cornering stiffness (feet-deg/lb). Representative Cα values used: 880 lb/deg for radial tires, 560 lb/deg for bias tires

DATABASE FOR PREDICTING A-TRAIN PERFORMANCE MEASURES

The remaining pages of appendix D list the parameters used for predicting A-train performance. The parameter values for each vehicle configuration (28x28, 32x32, etc.) is organized into three separate tables. The first table, called "Base Parameters," contains the characteristic values for that particular vehicle configuration. The second table, called "Constructed Parameters," lists specific combinations of the base parameters used to calculate the performance values. The third table, called "Performance Measures," lists the various performance measures used to evaluate the handling and dynamic characteristics of the various A-trains.

Table D-2. 28x 28 Base Parameters

VEH	Cα lb/deg	WB1 in	WB2 in	WB3 in	OH1 in	OH2 in	TL1 in	CG in	TrkWdth in	Roll Stf in-lb/deg	Izz1 in-lb-s2	Izz2 in-lb-s2
BAS	881	135	258	258	-12	36	80	85	102	141923	794000	794000
DO1	881	135	258	258	-12	36	100	85	102	141923	794000	794000
DO2	881	135	258	258	-12	36	120	85	102	141923	794000	794000
PL1	881	135	258	258	-12	36	80	100	102	141923	794000	794000
PL2	881	135	258	258	-12	36	80	70	102	141923	794000	794000
PL3	881	135	258	258	-12	36	80	85	102	141923	1588000	1588000
PL4	881	135	258	258	-12	36	80	85	102	141923	397000	397000
SE1	881	135	258	258	-12	48	80	85	102	141923	794000	794000
SE2	881	135	258	258	-12	24	80	85	102	141923	794000	794000
SP2	881	135	258	258	-12	36	80	85	102	119046	794000	794000
SP3	881	135	258	258	-12	36	80	85	102	174788	794000	794000
SS4	881	135	258	258	-12	36	80	85	96	204875	794000	794000
SU1	881	135	258	258	-12	36	80	85	96	141923	794000	794000
TI1	1124	135	258	258	-12	36	80	85	102	141923	794000	794000
TI2	564	135	258	258	-12	36	80	85	102	141923	794000	794000

Table D-3. 28x28 Constructed Parameters

Veh	WB2*WB3 in2	Sq. Root WB2*WB3 in	T/2h	Radial true/false	Inertia Ratio	WHI Len ft	Overall		
							Len ft	Len/Cα ft-deg/lb	Len/Rep Cα ft-deg/lb
BAS	66,564	258	0.600	1	1.0	32.9	62.9	0.0715	0.0715
DO1	66,564	258	0.600	1	1.0	33.3	64.6	0.0733	0.0734
DO2	66,564	258	0.600	1	1.0	33.8	66.3	0.0752	0.0753
PL1	66,564	258	0.510	1	1.0	32.9	62.9	0.0715	0.0715
PL2	66,564	258	0.729	1	1.0	32.9	62.9	0.0715	0.0715
PL3	66,564	258	0.600	1	2.0	32.9	62.9	0.0715	0.0715
PL4	66,564	258	0.600	1	0.5	32.9	62.9	0.0715	0.0715
SE1	66,564	258	0.600	1	1.0	32.8	63.9	0.0726	0.0726
SE2	66,564	258	0.600	1	1.0	33.0	61.9	0.0703	0.0704
SP2	66,564	258	0.600	1	1.0	32.9	62.9	0.0715	0.0715
SP3	66,564	258	0.600	1	1.0	32.9	62.9	0.0715	0.0715
SS4	66,564	258	0.565	1	1.0	32.9	62.9	0.0715	0.0715
SU1	66,564	258	0.565	1	1.0	32.9	62.9	0.0715	0.0715
TI1	66,564	258	0.600	1	1.0	32.9	62.9	0.0560	0.0715
TI2	66,564	258	0.600	0	1.0	32.9	62.9	0.1115	0.1124

Table D-4. 28x28 Performance Measures

Veh	RA	Transient Offtrack (ft)	Dynamic Load Transient	Static Roll Threshold (g)	B-maneuver Damping	P-maneuver Damping	SS Hi-spd Offtrack (ft)	Low-spd Offtrack (ft)
BAS	2.381	2.323	0.850	0.438	0.195	0.276	-1.143	13.91
DO1	2.367	2.385	0.851	0.441	0.195	0.274	-1.180	14.26
DO2	2.345	2.439	0.848	0.440	0.198	0.275	-1.205	14.67
PL1	2.490	2.497	1.000	0.370	0.136	0.211	-1.195	13.91
PL2	2.221	1.989	0.702	0.526	0.263	0.339	-1.119	13.91
PL3	2.250	2.418	0.851	0.438	0.203	0.300	-1.141	13.91
PL4	2.425	2.273	0.851	0.439	0.192	0.253	-1.145	13.91
SE1	2.430	2.403	0.871	0.438	0.195	0.277	-1.174	13.89
SE2	2.324	2.243	0.835	0.438	0.196	0.273	-1.114	13.91
SP2	2.406	2.405	0.901	0.431	0.177	0.252	-1.148	13.91
SP3	2.297	2.247	0.836	0.444	0.220	0.301	-1.140	13.91
SS4	2.471	2.668	0.922	0.447	0.207	0.285	-1.239	13.91
SU1	2.350	2.433	0.982	0.396	0.155	0.226	-1.167	13.91
TI1	2.166	1.406	0.797	0.443	0.190	0.250	-0.733	13.91
TI2	2.954	4.180	0.995	0.440	0.177	0.285	-1.980	13.91

Table D-5. 32x32 Base Parameters

Veh.	Cα lb/deg	WB1 in	WB2 in	WB3 in	OH1 in	OH2 in	TL1 in	CG in	TrkWdth in	Roll Stf in-lb/deg	Izz1 in-lb-s2	Izz2 in-lb-s2
BAS	881	164	285	285	-18	57	80	85	102	132,461	1,787,000	1,787,000
DO1	881	164	285	285	-18	57	100	85	102	132,461	1,787,000	1,787,000
DO2	881	164	285	285	-18	57	120	85	102	132,461	1,787,000	1,787,000
PL1	881	164	285	285	-18	57	80	100	102	132,461	1,787,000	1,787,000
PL2	881	164	285	285	-18	57	80	70	102	132,461	1,787,000	1,787,000
PL3	881	164	285	285	-18	57	80	85	102	132,461	3,574,000	3,574,000
PL4	881	164	285	285	-18	57	80	85	102	132,461	893,500	893,500
SE1	881	164	285	285	-18	69	80	85	102	132,461	1,787,000	1,787,000
SE2	881	164	285	285	-18	45	80	85	102	132,461	1,787,000	1,787,000
SP2	881	164	285	285	-18	57	80	85	102	114,067	1,787,000	1,787,000
SP3	881	164	285	285	-18	57	80	85	102	175,508	1,787,000	1,787,000
SS4	881	164	285	285	-18	57	80	85	96	199,982	1,787,000	1,787,000
SU1	881	164	285	285	-18	57	80	85	96	132,461	1,787,000	1,787,000
TI1	1,124	164	285	285	-18	57	80	85	102	132,461	1,787,000	1,787,000
TI2	564	164	285	285	-18	57	80	85	102	132,461	1,787,000	1,787,000

Table D-6. 32x32 Constructed Parameters

							Overall		
	WB2*WB3 in2	WB2*WB3 in	T/2h	Radial true/false	Ratio	WHI Len ft	Len ft	Len/Cα ft-deg/lb	Len/Rep Cα ft-deg/lb
BAS	81,225	285	0.600	1	1.0	36.5	71.1	0.0807	0.0808
DO1	81,225	285	0.600	1	1.0	36.9	72.8	0.0826	0.0827
DO2	81,225	285	0.600	1	1.0	37.3	74.4	0.0845	0.0846
PL1	81,225	285	0.510	1	1.0	36.5	71.1	0.0807	0.0808
PL2	81,225	285	0.729	1	1.0	36.5	71.1	0.0807	0.0808
PL3	81,225	285	0.600	1	2.0	36.5	71.1	0.0807	0.0808
PL4	81,225	285	0.600	1	0.5	36.5	71.1	0.0807	0.0808
SE1	81,225	285	0.600	1	1.0	36.4	72.1	0.0819	0.0819
SE2	81,225	285	0.600	1	1.0	36.6	70.1	0.0796	0.0796
SP2	81,225	285	0.600	1	1.0	36.5	71.1	0.0807	0.0808
SP3	81,225	285	0.600	1	1.0	36.5	71.1	0.0807	0.0808
SS4	81,225	285	0.565	1	1.0	36.5	71.1	0.0807	0.0808
SU1	81,225	285	0.565	1	1.0	36.5	71.1	0.0807	0.0808
TI1	81,225	285	0.600	1	1.0	36.5	71.1	0.0632	0.0808
TI2	81,225	285	0.600	0	1.0	36.5	71.1	0.1260	0.1269

Table D-7. 32x32 Performance Measures

Veh	RA	Transient Offtrack (ft)	Dynamic Load Transient	Static Roll Threshold (g)	B-maneuver Damping	P-maneuver Damping	SS Hi-spd Offtrack (ft)	Low-spd Offtrack (ft)
BAS	2.116	1.974	0.756	0.447	0.257	0.324	-1.184	16.63
DO1	2.124	2.041	0.759	0.448	0.255	0.317	-1.216	16.98
DO2	2.126	2.080	0.757	0.449	0.246	0.314	-1.248	17.39
PL1	2.161	2.138	0.925	0.370	0.193	0.253	-1.220	16.63
PL2	1.993	1.766	0.596	0.558	0.313	0.390	-1.167	16.63
PL3	2.116	1.974	0.756	0.447	0.257	0.324	-1.184	16.63
PL4	2.172	1.862	0.749	0.447	0.269	0.305	-1.184	16.63
SE1	2.154	2.036	0.773	0.447	0.257	0.325	-1.208	16.59
SE2	2.078	1.912	0.739	0.448	0.257	0.323	-1.152	16.65
SP2	2.165	2.039	0.788	0.443	0.247	0.314	-1.191	16.63
SP3	2.042	1.889	0.719	0.455	0.297	0.368	-1.182	16.63
SS4	2.202	2.115	0.758	0.466	0.309	0.367	-1.267	16.63
SU1	2.138	2.083	0.879	0.397	0.223	0.273	-1.199	16.63
TI1	1.942	1.032	0.687	0.451	0.251	0.287	-0.675	16.63
TI2	2.461	3.487	0.896	0.449	0.221	0.290	-1.912	16.63

Table D-8. 38x20 Base Parameters

Veh.	Cα lb/deg	WB1 in	WB2 in	WB3 in	OH1 in	OH2 in	TL1 in	CG in	TrkWdth in	Roll Stf in-lb/deg	Izz1 in-lb-s2	Izz2 in-lb-s2
BAS	881	164	363	192	-18	51	80	85	102	134,716	2,314,000	366,000
DO1	881	164	363	192	-18	51	100	85	102	134,716	2,314,000	366,000
DO2	881	164	363	192	-18	51	120	85	102	134,716	2,314,000	366,000
PL1	881	164	363	192	-18	51	80	100	102	134,716	2,314,000	366,000
PL2	881	164	363	192	-18	51	80	70	102	134,716	2,314,000	366,000
PL3	881	164	363	192	-18	51	80	85	102	134,716	4,628,000	732,000
PL4	881	164	363	192	-18	51	80	85	102	134,716	1,157,000	183,000
SE1	881	164	363	192	-18	63	80	85	102	134,716	2,314,000	366,000
SE2	881	164	363	192	-18	39	80	85	102	134,716	2,314,000	366,000
SP2	881	164	363	192	-18	51	80	85	102	114,729	2,314,000	366,000
SP3	881	164	363	192	-18	51	80	85	102	175,197	2,314,000	366,000
SS4	881	164	363	192	-18	51	80	85	96	201,291	2,314,000	366,000
SU1	881	164	363	192	-18	51	80	85	96	134,716	2,314,000	366,000
TI1	1,124	164	363	192	-18	51	80	85	102	134,716	2,314,000	366,000
TI2	564	164	363	192	-18	51	80	85	102	134,716	2,314,000	366,000

Table D-9. 38x20 Constructed Parameters

Veh	WB2*WB3 in2	Sq. Root WB2*WB3 in	T/2h	Radial true/false	Inertia Ratio	WHI Len ft	Overall		
							Len ft	Len/Cα ft-deg/lb	Len/Rep Cα ft-deg/lb
BAS	69,696	264	0.600	1	1.0	37.2	69.3	0.0787	0.0788
DO1	69,696	264	0.600	1	1.0	37.5	71.0	0.0806	0.0807
DO2	69,696	264	0.600	1	1.0	37.9	72.7	0.0825	0.0826
PL1	69,696	264	0.510	1	1.0	37.2	69.3	0.0787	0.0788
PL2	69,696	264	0.729	1	1.0	37.2	69.3	0.0787	0.0788
PL3	69,696	264	0.600	1	2.0	37.2	69.3	0.0787	0.0788
PL4	69,696	264	0.600	1	0.5	37.2	69.3	0.0787	0.0788
SE1	69,696	264	0.600	1	1.0	37.0	70.3	0.0799	0.0799
SE2	69,696	264	0.600	1	1.0	37.3	68.3	0.0776	0.0777
SP2	69,696	264	0.600	1	1.0	37.2	69.3	0.0787	0.0788
SP3	69,696	264	0.600	1	1.0	37.2	69.3	0.0787	0.0788
SS4	69,696	264	0.565	1	1.0	37.2	69.3	0.0787	0.0788
SU1	69,696	264	0.565	1	1.0	37.2	69.3	0.0787	0.0788
TI1	69,696	264	0.600	1	1.0	37.2	69.3	0.0617	0.0788
TI2	69,696	264	0.600	0	1.0	37.2	69.3	0.1229	0.1238

Table D-10. 38x20 Performance Measures

Veh	RA	Transient Offtrack (ft)	Dynamic Load Transient	Static Roll Threshold (g)	B-maneuver Damping	P-maneuver Damping	SS Hi-spd Offtrack (ft)	Low-spd Offtrack (ft)
BAS	2.342	1.866	0.805	0.440	0.214	0.210	-1.089	16.41
DO1	2.319	1.922	0.804	0.440	0.216	0.215	-1.121	16.75
DO2	2.304	1.982	0.800	0.441	0.218	0.223	-1.153	17.15
PL1	2.430	2.062	1.000	0.364	0.150	0.163	-1.116	16.41
PL2	2.170	1.605	0.651	0.534	0.249	0.266	-1.083	16.41
PL3	2.366	1.938	0.800	0.440	0.202	0.212	-1.088	16.41
PL4	2.442	1.798	0.804	0.440	0.212	0.206	-1.089	16.41
SE1	2.391	1.920	0.821	0.440	0.214	0.211	-1.117	16.38
SE2	2.289	1.812	0.787	0.440	0.215	0.210	-1.062	16.43
SP2	2.352	1.923	0.841	0.427	0.201	0.188	-1.094	16.41
SP3	2.228	1.758	0.768	0.443	0.234	0.229	-1.087	16.41
SS4	2.450	2.072	0.837	0.457	0.219	0.214	-1.185	16.41
SU1	2.396	1.970	0.927	0.406	0.162	0.173	-1.093	16.41
TI1	2.104	1.030	0.747	0.441	0.193	0.192	-0.620	16.41
TI2	2.740	3.367	0.941	0.441	0.221	0.226	-1.871	16.41

Table D-11. 45x28 Base Parameters

Veh.	Cα lb/deg	WB1 in	WB2 in	WB3 in	OH1 in	OH2 in	TL1 in	CG in	TrkWdth in	Roll Stf in-lb/deg	Izz1 in-lb-s2	Izz2 in-lb-s2
BAS	881	164	445	258	-18	53	80	85	102	141,101	3,116,000	783,000
DO1	881	164	445	258	-18	53	100	85	102	141,101	3,116,000	783,000
DO2	881	164	445	258	-18	53	120	85	102	141,101	3,116,000	783,000
PL1	881	164	445	258	-18	53	80	100	102	141,101	3,116,000	783,000
PL2	881	164	445	258	-18	53	80	70	102	141,101	3,116,000	783,000
PL3	881	164	445	258	-18	53	80	85	102	141,101	6,232,000	1,566,000
PL4	881	164	445	258	-18	53	80	85	102	141,101	1,558,000	391,500
SE1	881	164	445	258	-18	65	80	85	102	141,101	3,116,000	783,000
SE2	881	164	445	258	-18	41	80	85	102	141,101	3,116,000	783,000
SP2	881	164	445	258	-18	53	80	85	102	118,560	3,116,000	783,000
SP3	881	164	445	258	-18	53	80	85	102	174,832	3,116,000	783,000
SS4	881	164	445	258	-18	53	80	85	96	204,463	3,116,000	783,000
SU1	881	164	445	258	-18	53	80	85	96	141,101	3,116,000	783,000
TI1	1,124	164	445	258	-18	53	80	85	102	141,101	3,116,000	783,000
TI2	564	164	445	258	-18	53	80	85	102	141,101	3,116,000	783,000

Table D-12. 45x28 Constructed Parameters

Veh	WB2*WB3 in2	Sq. Root WB2*WB3 in	T/2h	Radial true/false	Inertia Ratio	WHI Len ft	Overall		
							Len ft	Len/Cα ft-deg/lb	Len/Rep Cα ft-deg/lb
BAS	114,810	339	0.600	1	1.0	45.2	81.8	0.0929	0.0930
DO1	114,810	339	0.600	1	1.0	45.5	83.5	0.0948	0.0949
DO2	114,810	339	0.600	1	1.0	45.9	85.2	0.0967	0.0968
PL1	114,810	339	0.510	1	1.0	45.2	81.8	0.0929	0.0930
PL2	114,810	339	0.729	1	1.0	45.2	81.8	0.0929	0.0930
PL3	114,810	339	0.600	1	2.0	45.2	81.8	0.0929	0.0930
PL4	114,810	339	0.600	1	0.5	45.2	81.8	0.0929	0.0930
SE1	114,810	339	0.600	1	1.0	45.1	82.8	0.0941	0.0941
SE2	114,810	339	0.600	1	1.0	45.3	80.8	0.0918	0.0919
SP2	114,810	339	0.600	1	1.0	45.2	81.8	0.0929	0.0930
SP3	114,810	339	0.600	1	1.0	45.2	81.8	0.0929	0.0930
SS4	114,810	339	0.565	1	1.0	45.2	81.8	0.0929	0.0930
SU1	114,810	339	0.565	1	1.0	45.2	81.8	0.0929	0.0930
TI1	114,810	339	0.600	1	1.0	45.2	81.8	0.0728	0.0930
TI2	114,810	339	0.600	0	1.0	45.2	81.8	0.1450	0.1461

Table D-13. 45x28 Performance Measures

Veh	RA	Transient Offtrack (ft)	Dynamic Load Transient	Static Roll Threshold (g)	B-maneuver Damping	P-maneuver Damping	SS Hi-spd Offtrack (ft)	Low-spd Offtrack (ft)
BAS	1.903	1.643	0.698	0.448	0.277	0.276	-1.148	22.16
DO1	1.920	1.705	0.704	0.448	0.273	0.274	-1.180	22.51
DO2	1.927	1.742	0.703	0.448	0.271	0.276	-1.207	22.92
PL1	2.002	1.875	0.852	0.374	0.196	0.213	-1.184	22.16
PL2	1.734	1.399	0.541	0.555	0.345	0.339	-1.132	22.16
PL3	1.762	1.677	0.669	0.448	0.293	0.312	-1.150	22.16
PL4	2.001	1.600	0.708	0.448	0.262	0.256	-1.147	22.16
SE1	1.936	1.691	0.711	0.448	0.277	0.277	-1.177	22.16
SE2	1.870	1.595	0.686	0.448	0.277	0.275	-1.118	22.14
SP2	1.957	1.718	0.729	0.435	0.252	0.253	-1.153	22.16
SP3	1.830	1.531	0.653	0.451	0.304	0.300	-1.145	22.16
SS4	1.964	1.822	0.703	0.465	0.287	0.284	-1.265	22.16
SU1	1.969	1.791	0.809	0.399	0.221	0.228	-1.161	22.16
TI1	1.724	0.829	0.630	0.449	0.242	0.249	-0.591	22.16
TI2	2.277	3.152	0.811	0.450	0.277	0.293	-2.082	22.16

Table D-14. 45x45 Base Parameters

Veh.	Cα lb/deg	WB1 in	WB2 in	WB3 in	OH1 in	OH2 in	TL1 in	CG in	TrkWdth in	Roll Stf in-lb/deg	Izz1 in-lb-s2	Izz2 in-lb-s2
BAS	881	164	445	375	-18	53	80	85	102	131,921	3,751,000	3,243,000
DO1	881	164	445	375	-18	53	100	85	102	131,921	3,751,000	3,243,000
DO2	881	164	445	375	-18	53	120	85	102	131,921	3,751,000	3,243,000
PL1	881	164	445	375	-18	53	80	100	102	131,921	3,751,000	3,243,000
PL2	881	164	445	375	-18	53	80	70	102	131,921	3,751,000	3,243,000
PL3	881	164	445	375	-18	53	80	85	102	131,921	7,502,000	6,486,000
PL4	881	164	445	375	-18	53	80	85	102	131,921	1,875,500	1,621,500
SE1	881	164	445	375	-18	65	80	85	102	131,921	3,751,000	3,243,000
SE2	881	164	445	375	-18	41	80	85	102	131,921	3,751,000	3,243,000
SP2	881	164	445	375	-18	53	80	85	102	121,641	3,751,000	3,243,000
SP3	881	164	445	375	-18	53	80	85	102	174,568	3,751,000	3,243,000
SS4	881	164	445	375	-18	53	80	85	96	207,158	3,751,000	3,243,000
SU1	881	164	445	375	-18	53	80	85	96	131,921	3,751,000	3,243,000
TI1	1,124	164	445	375	-18	53	80	85	102	131,921	3,751,000	3,243,000
TI2	564	164	445	375	-18	53	80	85	102	131,921	3,751,000	3,243,000

Table D-15. 45x45 Constructed Parameters

Veh	WB2*WB3 in2	Sq. Root WB2*WB3 in	T/2h	Radial true/false	Inertia Ratio	WHI Len ft	Overall		
							Len ft	Len/Cα ft-deg/lb	Len/Rep Cα ft-deg/lb
BAS	166,875	409	0.600	1	1.0	50.6	91.6	0.1040	0.1041
DO1	166,875	409	0.600	1	1.0	50.9	93.3	0.1059	0.1060
DO2	166,875	409	0.600	1	1.0	51.2	94.9	0.1078	0.1079
PL1	166,875	409	0.510	1	1.0	50.6	91.6	0.1040	0.1041
PL2	166,875	409	0.729	1	1.0	50.6	91.6	0.1040	0.1041
PL3	166,875	409	0.600	1	2.0	50.6	91.6	0.1040	0.1041
PL4	166,875	409	0.600	1	0.5	50.6	91.6	0.1040	0.1041
SE1	166,875	409	0.600	1	1.0	50.5	92.6	0.1051	0.1052
SE2	166,875	409	0.600	1	1.0	50.7	90.6	0.1029	0.1029
SP2	166,875	409	0.600	1	1.0	50.6	91.6	0.1040	0.1041
SP3	166,875	409	0.600	1	1.0	50.6	91.6	0.1040	0.1041
SS4	166,875	409	0.565	1	1.0	50.6	91.6	0.1040	0.1041
SU1	166,875	409	0.565	1	1.0	50.6	91.6	0.1040	0.1041
TI1	166,875	409	0.600	1	1.0	50.6	91.6	0.0815	0.1041
TI2	166,875	409	0.600	0	1.0	50.6	91.6	0.1623	0.1635

Table D-16. 45x45 Performance Measures

Veh	RA	Transient Offtrack (ft)	Dynamic Load Transient	Static Roll Threshold (g)	B-maneuver Damping	P-maneuver Damping	SS Hi-spd Offtrack (ft)	Low-spd Offtrack (ft)
BAS	1.648	1.656	0.608	0.425	0.348	0.413	-1.331	27.05
DO1	1.668	1.723	0.617	0.425	0.344	0.405	-1.367	27.44
DO2	1.687	1.785	0.621	0.425	0.340	0.397	-1.403	27.87
PL1	1.807	2.067	0.781	0.345	0.253	0.336	-1.426	27.05
PL2	1.528	1.379	0.465	0.521	0.424	0.473	-1.284	27.05
PL3	1.564	1.727	0.600	0.424	0.385	0.435	-1.332	27.05
PL4	1.712	1.581	0.627	0.425	0.336	0.390	-1.330	27.05
SE1	1.670	1.696	0.619	0.425	0.348	0.413	-1.359	27.08
SE2	1.625	1.615	0.598	0.425	0.348	0.413	-1.305	27.01
SP2	1.708	1.758	0.641	0.409	0.312	0.388	-1.347	27.05
SP3	1.614	1.562	0.580	0.430	0.379	0.435	-1.322	27.05
SS4	1.710	1.854	0.617	0.443	0.376	0.444	-1.475	27.05
SU1	1.727	1.849	0.717	0.384	0.296	0.362	-1.360	27.05
TI1	1.462	0.828	0.544	0.425	0.319	0.399	-0.699	27.05
TI2	1.946	3.445	0.729	0.424	0.284	0.386	-2.533	27.05

Table D-17. 28x28x28 Base Parameters

Veh.	$C\alpha$ lb/deg	WB1 in	WB2 in	WB3 in	WB4 in	OH1 in	OH2 in	OH3 in	TL1 in	TL2 in	CG in	TW in	Roll Stf in-lb/deg	Izz1 in-lb-s2	Izz2 in-lb-s2	Izz3 in-lb-s2
BAS	881	135	258	258	258	-12	36	36	80	80	85	102	143,300	800k	800k	800k
DO1	881	135	258	258	258	-12	36	36	100	100	85	102	143,300	800k	800k	800k
DO2	881	135	258	258	258	-12	36	36	120	120	85	102	143,300	800k	800k	800k
PL1	881	135	258	258	258	-12	36	36	80	80	100	102	143,300	800k	800k	800k
PL2	881	135	258	258	258	-12	36	36	80	80	70	102	143,300	800k	800k	800k
PL3	881	135	258	258	258	-12	36	36	80	80	85	102	143,300	1600k	1600k	1600k
PL4	881	135	258	258	258	-12	36	36	80	80	85	102	143,300	400k	400k	400k
SE1	881	135	258	258	258	-12	48	48	80	80	85	102	143,300	800k	800k	800k
SE2	881	135	258	258	258	-12	24	24	80	80	85	102	143,300	800k	800k	800k
SP2	881	135	258	258	258	-12	36	36	80	80	85	102	119,849	800k	800k	800k
SP3	881	135	258	258	258	-12	36	36	80	80	85	102	174,717	800k	800k	800k
SS4	881	135	258	258	258	-12	36	36	80	80	85	96	205,567	800k	800k	800k
SU1	881	135	258	258	258	-12	36	36	80	80	85	96	143,300	800k	800k	800k
TI1	1,124	135	258	258	258	-12	36	36	80	80	85	102	143,300	800k	800k	800k
TI2	564	135	258	258	258	-12	36	36	80	80	85	102	143,300	800k	800k	800k

Table D-18. 28x28x28 Constructed Parameters

Veh		Sq. Root			Inertia		Overall		
	WB2*WB3 in2	WB2*WB3 in	T/2h	Radial true/false	Ratio	WHI Len ft	Len ft	Len/$C\alpha$ ft-deg/lb	Len/Rep $C\alpha$ ft-deg/lb
BAS	17,173,512	258	0.600	1	1.0	39.8	94.1	0.1068	0.1069
DO1	17,173,512	258	0.600	1	1.0	40.4	97.4	0.1106	0.1107
DO2	17,173,512	258	0.600	1	1.0	41.2	100.8	0.1144	0.1145
PL1	17,173,512	258	0.510	1	1.0	39.8	94.1	0.1068	0.1069
PL2	17,173,512	258	0.729	1	1.0	39.8	94.1	0.1068	0.1069
PL3	17,173,512	258	0.600	1	2.0	39.8	94.1	0.1068	0.1069
PL4	17,173,512	258	0.600	1	0.5	39.8	94.1	0.1068	0.1069
SE1	17,173,512	258	0.600	1	1.0	39.6	96.1	0.1091	0.1092
SE2	17,173,512	258	0.600	1	1.0	39.9	92.1	0.1046	0.1046
SP2	17,173,512	258	0.600	1	1.0	39.8	94.1	0.1068	0.1069
SP3	17,173,512	258	0.600	1	1.0	39.8	94.1	0.1068	0.1069
SS4	17,173,512	258	0.565	1	1.0	39.8	94.1	0.1068	0.1069
SU1	17,173,512	258	0.565	1	1.0	39.8	94.1	0.1068	0.1069
TI1	17,173,512	258	0.600	1	1.0	39.8	94.1	0.0837	0.1069
TI2	17,173,512	258	0.600	0	1.0	39.8	94.1	0.1667	0.1680

Table D-19. 28x28x28 Performance Measures

Veh	RA	Transient Offtrack (ft)	Dynamic Load Transient	Static Roll Threshold (g)	B-maneuver Damping	P-maneuver Damping	SS Hi-spd Offtrack (ft)	Low-spd Offtrack (ft)
BAS	4.050	3.700	1.000	0.436	0.212	0.311	-1.776	17.20
DO1	3.742	3.800	1.000	0.439	0.172	0.299	-1.841	17.62
DO2	3.620	4.200	1.000	0.441	0.133	0.292	-1.900	18.12
PL1	3.263	3.800	1.000	0.364		0.274	-1.850	17.20
PL2	3.053	3.100	0.947	0.520	0.259	0.335	-1.733	17.20
PL3	3.157	4.500	1.000	0.436	0.184	0.281	-1.774	17.20
PL4	4.324	3.800	1.000	0.435		0.310	-1.778	17.20
SE1	5.000	4.500	1.000	0.436	0.181	0.310	-1.832	17.09
SE2	3.093	3.700	1.000	0.436	0.191	0.309	-1.725	17.29
SP2	4.990	1.800	1.000	0.409	0.228	0.237	-1.806	17.20
SP3	3.325	2.600	1.000	0.423	0.203	0.298	-1.774	17.20
SS4	3.659	3.200	1.000	0.441	0.223	0.286	-1.605	17.20
SU1	2.813	2.700	1.000	0.413	0.198	0.286	-1.807	17.20
TI1	2.768	1.800	0.970	0.438	0.210	0.354	-1.145	17.20
TI2	3.841	6.500	1.000	0.432		0.213	-2.995	17.20

APPENDIX E

A- AND C-TRAIN PERFORMANCE COMPARISON

Table E-1. Comparison of A- and C-train performance

Steady-State Rollover Threshold, g

A-C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.0073	0.0088	0.0071	0.0058	-0.0084	0.0045	0.0060	0.0083	0.0041	0.0053	-0.0079	0.0068
32x32	0.0054	0.0086	0.0057	0.0111	-0.0120	0.0161	0.0039	0.0088	-0.0054	0.0268	-0.0116	0.0147
38x20	0.0033	0.0058	0.0106	0.0040	-0.0095	0.0112	-0.0005	0.0055	0.0057	0.0033	-0.0099	0.0108
45x28	0.0044	0.0104	0.0131	0.0068	-0.0047	0.0069	0.0009	0.0093	0.0082	0.0061	-0.0046	0.0073
All Doubles	0.0052	0.0087	0.0092	0.0080	-0.0086	0.0110	0.0026	0.0085	0.0032	0.0151	-0.0085	0.0108
28x28x28	0.0069	0.0069	0.0187	0.0111	-0.0159	0.0068	0.0029	0.0062	0.0105	0.0109	-0.0213	0.0094

A/C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	1.0173	0.0205	1.0169	0.0135	0.9816	0.0102	1.0141	0.0191	1.0096	0.0122	0.9832	0.0135
32x32	1.0112	0.0188	1.0117	0.0226	0.9761	0.0250	1.0079	0.0189	0.9928	0.0417	0.9766	0.0234
38x20	1.0081	0.0120	1.0248	0.0093	0.9805	0.0183	0.9992	0.0106	1.0131	0.0076	0.9794	0.0177
45x28	1.0111	0.0209	1.0298	0.0153	0.9903	0.0130	1.0029	0.0180	1.0182	0.0134	0.9905	0.0138
All Doubles	1.0121	0.0187	1.0209	0.0175	0.9822	0.0184	1.0061	0.0179	1.0085	0.0252	0.9825	0.0184
28x28x28	1.0156	0.0148	1.0445	0.0247	0.9650	0.0135	1.0062	0.0141	1.0243	0.0237	0.9541	0.0176

Steady-State High-Speed Offtracking, feet

A-C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	-0.0830	0.0745	-0.0376	0.0604	0.0530	0.0158	-0.0824	0.0739	-0.0378	0.0604	0.0499	0.0206
32x32	-0.0511	0.0582	-0.0143	0.0458	0.1049	0.0168	-0.0509	0.0582	-0.0141	0.0459	0.1053	0.0168
38x20	-0.0694	0.0646	-0.0231	0.0407	0.0661	0.0144	-0.0718	0.0659	-0.0231	0.0406	0.0663	0.0143
45x28	-0.0951	0.0793	-0.0416	0.0576	0.0581	0.0431	-0.0966	0.0804	-0.0413	0.0578	0.0700	0.0131
All Doubles	-0.0744	0.0714	-0.0290	0.0528	0.0706	0.0324	-0.0752	0.0719	-0.0290	0.0529	0.0728	0.0262
28x28x28	-0.1697	0.1321	-0.0833	0.1006	0.0661	0.0346	-0.1701	0.1323	-0.0838	0.1007	0.0665	0.0350

A/C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	1.0683	0.0468	1.0266	0.0403	-0.5129	1.3728	0.0622	0.8331	1.9149	0.1055	0.8846	1.4667
32x32	1.0378	0.0422	1.0065	0.0368	-4.6502	1.3165	0.0336	0.8940	1.9177	0.0973	0.8940	1.3750
38x20	1.0585	0.0457	1.0155	0.0347	-1.2446	1.3532	0.0490	0.8611	1.9986	0.0896	0.9103	1.4542
45x28	1.0771	0.0524	1.0281	0.0438	-0.5593	1.3233	0.0485	0.8499	2.0861	0.1164	0.8929	1.5705
All Doubles	1.0604	0.0491	1.0192	0.0400	-1.0807	1.3414	0.0545	0.8403	1.9788	0.1241	0.8732	1.4667
28x28x28	1.0952	0.0577	1.0417	0.0464	-0.1122	1.7117	0.3011	0.5769	2.7259	0.1859	0.8923	1.1272

Table E-1. (Cont.) Comparison of A- and C-Train Performance

Rearward Amplification

A-C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.6622	0.1269	0.6518	0.1260	0.4252	0.1035	0.6755	0.1253	0.6647	0.1241	0.4372	0.1018
32x32	0.5235	0.0660	0.5129	0.0623	0.3207	0.0549	0.5285	0.0680	0.5173	0.0646	0.3255	0.0566
38x20	0.6153	0.0951	0.6146	0.0924	0.3722	0.0727	0.6362	0.0947	0.6368	0.0925	0.3943	0.0725
45x28	0.4709	0.0827	0.4696	0.0818	0.3168	0.1080	0.4802	0.0840	0.4788	0.0833	0.3123	0.0698
All Doubles	**0.5678**	**0.1220**	**0.5621**	**0.1198**	**0.3585**	**0.0980**	**0.5799**	**0.1245**	**0.5742**	**0.1227**	**0.3673**	**0.0927**
28x28x28	1.5480	0.6589	1.5190	0.6570	0.7613	0.8305	1.5651	0.6610	1.5313	0.6578	0.7146	0.9357

A/C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	1.3810	0.0631	1.3728	0.0622	1.2151	0.0455	1.3916	0.0617	1.3829	0.0604	1.2226	0.0452
32x32	1.3251	0.0356	1.3165	0.0336	1.1778	0.0343	1.3292	0.0375	1.3202	0.0356	1.1811	0.0360
38x20	1.3537	0.0508	1.3532	0.0490	1.1881	0.0364	1.3702	0.0505	1.3707	0.0492	1.2016	0.0373
45x28	1.3244	0.0489	1.3233	0.0485	1.1981	0.0675	1.3329	0.0498	1.3316	0.0496	1.1944	0.0423
All Doubles	**1.3460**	**0.0559**	**1.3414**	**0.0545**	**1.1946**	**0.0493**	**1.3559**	**0.0571**	**1.3512**	**0.0561**	**1.1992**	**0.0431**
28x28x28	1.7359	0.3068	1.7117	0.3011	1.2929	0.3070	1.7506	0.3116	1.7218	0.3045	1.2924	0.3207

Dynamic-Load-Transfer Ratio

A-C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.4092	0.0472	0.4163	0.0494	0.3762	0.0408	0.4105	0.0475	0.4173	0.0498	0.3774	0.0404
32x32	0.3643	0.0504	0.3682	0.0514	0.3407	0.0438	0.3648	0.0503	0.3685	0.0515	0.3409	0.0435
38x20	0.4065	0.0478	0.4105	0.0490	0.3701	0.0439	0.4069	0.0481	0.4110	0.0492	0.3709	0.0442
45x28	0.3659	0.0508	0.3686	0.0514	0.3520	0.0525	0.3659	0.0507	0.3687	0.0513	0.3506	0.0490
All Doubles	**0.3863**	**0.0537**	**0.3907**	**0.0553**	**0.3596**	**0.0476**	**0.3868**	**0.0539**	**0.3912**	**0.0556**	**0.3598**	**0.0468**
28x28x28	0.6260	0.0226	0.6277	0.0225	0.5713	0.0269	0.6214	0.0227	0.6229	0.0230	0.5317	0.1005

A/C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	1.8853	0.0942	1.9149	0.1055	1.7585	0.0617	1.8903	0.0944	1.9190	0.1063	1.7628	0.0604
32x32	1.8988	0.0906	1.9177	0.0973	1.7936	0.0546	1.9014	0.0912	1.9193	0.0984	1.7948	0.0543
38x20	1.9791	0.0820	1.9986	0.0896	1.8190	0.0620	1.9806	0.0829	2.0007	0.0901	1.8220	0.0632
45x28	2.0698	0.1106	2.0861	0.1164	1.9905	0.1337	2.0694	0.1108	2.0871	0.1161	1.9810	0.1007
All Doubles	**1.9576**	**0.1199**	**1.9788**	**0.1241**	**1.8397**	**0.1219**	**1.9599**	**0.1191**	**1.9810**	**0.1241**	**1.8396**	**0.1102**
28x28x28	2.7131	0.1851	2.7259	0.1859	2.3630	0.1669	2.6796	0.1833	2.6905	0.1859	2.2184	0.3133

Table E-1. (Cont.) Comparison of A- and C-Train Performance

Transient High-Speed Offtracking, feet

A-C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.8126	0.2443	0.7757	0.2288	0.3531	0.0986	0.8372	0.2478	0.7997	0.2344	0.3855	0.1027
32x32	0.5890	0.1972	0.5625	0.1870	0.1830	0.0609	0.5995	0.1998	0.5725	0.1895	0.1973	0.0629
38x20	0.6325	0.1998	0.6100	0.1887	0.2082	0.0650	0.6534	0.2031	0.6299	0.1921	0.2387	0.0718
45x28	0.6420	0.2087	0.6292	0.2015	0.3403	0.2103	0.6626	0.2135	0.6487	0.2064	0.3279	0.1033
All Doubles	0.6686	0.2302	0.6439	0.2176	0.2706	0.1443	0.6877	0.2350	0.6623	0.2231	0.2875	0.1143
28x28x28	0.7820	0.9099	0.4120	0.8317	-0.3578	1.8415	0.7815	0.9138	0.3676	0.8744	-1.1916	2.5558

A/C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	1.4994	0.0645	1.4667	0.0612	1.1755	0.0494	1.5231	0.0667	1.4887	0.0638	1.1946	0.0524
32x32	1.3998	0.0576	1.3750	0.0533	1.1011	0.0328	1.4101	0.0583	1.3845	0.0540	1.1096	0.0332
38x20	1.4783	0.0566	1.4542	0.0502	1.1232	0.0355	1.5027	0.0571	1.4765	0.0512	1.1437	0.0391
45x28	1.5879	0.0802	1.5705	0.0775	1.2396	0.0926	1.6185	0.0841	1.5989	0.0814	1.2409	0.0637
All Doubles	1.4915	0.0940	1.4667	0.0932	1.1596	0.0782	1.5137	0.1005	1.4873	0.0996	1.1724	0.0700
28x28x28	1.2799	0.2856	1.1272	0.2402	0.8837	0.2894	1.2852	0.2901	1.1181	0.2469	0.8012	0.2797

B-Maneuver Damping Ratio

A-C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	-0.0302	0.0504	0.4163	0.0494	-0.0078	0.0764	-0.0584	0.0597	-0.0578	0.0603	-0.0269	0.0502
32x32	-0.0301	0.0501	0.3682	0.0514	-0.0027	0.0270	-0.0394	0.0467	-0.0401	0.0444	-0.0096	0.0297
38x20	-0.0452	0.0310	0.4105	0.0490	-0.0774	0.0934	-0.0717	0.0558	-0.0757	0.0513	-0.1414	0.1228
45x28	0.0124	0.0481	0.3686	0.0514	-0.0521	0.0478	0.0150	0.0718	0.0183	0.0747	-0.0871	0.0617
All Doubles	-0.0235	0.0503	0.3907	0.0553	-0.0348	0.0736	-0.0393	0.0673	-0.0396	0.0681	-0.0661	0.0914
28x28x28	-0.1336	0.0369	0.6277	0.0225	0.0099	0.1886	-0.1295	0.0294	-0.1295	0.0283	0.1147	0.0553

A/C

	— 2C1 Dollies —		— 2C2 Dollies —		— 2C3 Dollies —		— 3C1 Dollies —		— 3C2 Dollies —		— 3C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	1.0010	0.5429	1.1452	0.9532	1.0315	0.1932	0.8305	0.2150	0.8442	0.2821	0.9107	0.1657
32x32	0.9185	0.1238	0.9318	0.1263	0.9946	0.0822	0.8872	0.1131	0.8834	0.1083	0.9693	0.0903
38x20	0.8278	0.1128	1.0734	1.0004	0.7945	0.2460	0.7836	0.2399	0.7691	0.2302	0.7203	0.4473
45x28	1.0741	0.2064	1.0798	0.2175	0.8568	0.1289	1.1499	0.3924	1.1803	0.4397	0.7732	0.1241
All Doubles	0.9539	0.3171	1.0560	0.7120	0.9196	0.2002	0.9087	0.2926	0.9147	0.3259	0.8434	0.2718
28x28x28	0.6167	0.0833	0.6214	0.0796	1.5366	0.6175	0.6208	0.0780	0.6205	0.0752	2.8793	4.6863

Table E-1. (Cont.) Comparison of A- and C-train performance

Low-Speed Offtracking, feet

A-C

	— C1 Dollies —		— C2 Dollies —		— C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	-0.0240	0.2845	0.2682	0.3294	0.4140	na
32x32	0.1244	0.3423	0.3746	0.3743	0.7464	0.4311
38x20	0.4150	0.3928	0.5934	0.4061	1.0074	0.4628
45x28	0.1425	0.3164	0.3308	0.3506	1.0218	0.5385
All Doubles	0.1601	0.3425	0.3796	0.3580	0.9239	0.4877
28x28x28	0.0200	0.6368	0.5112	0.6924	1.7978	0.8306

A/C

	— C1 Dollies —		— C2 Dollies —		— C3 Dollies —	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.9982	0.0200	1.0193	0.0237	1.0307	na
32x32	1.0074	0.0205	1.0228	0.0228	1.0465	0.0271
38x20	1.0257	0.0244	1.0371	0.0256	1.0647	0.0304
45x28	1.0058	0.0132	1.0137	0.0147	1.0423	0.0210
All Doubles	1.0086	0.0197	1.0213	0.0212	1.0481	0.0251
28x28x28	1.0015	0.0369	1.0307	0.0419	1.1160	0.0570

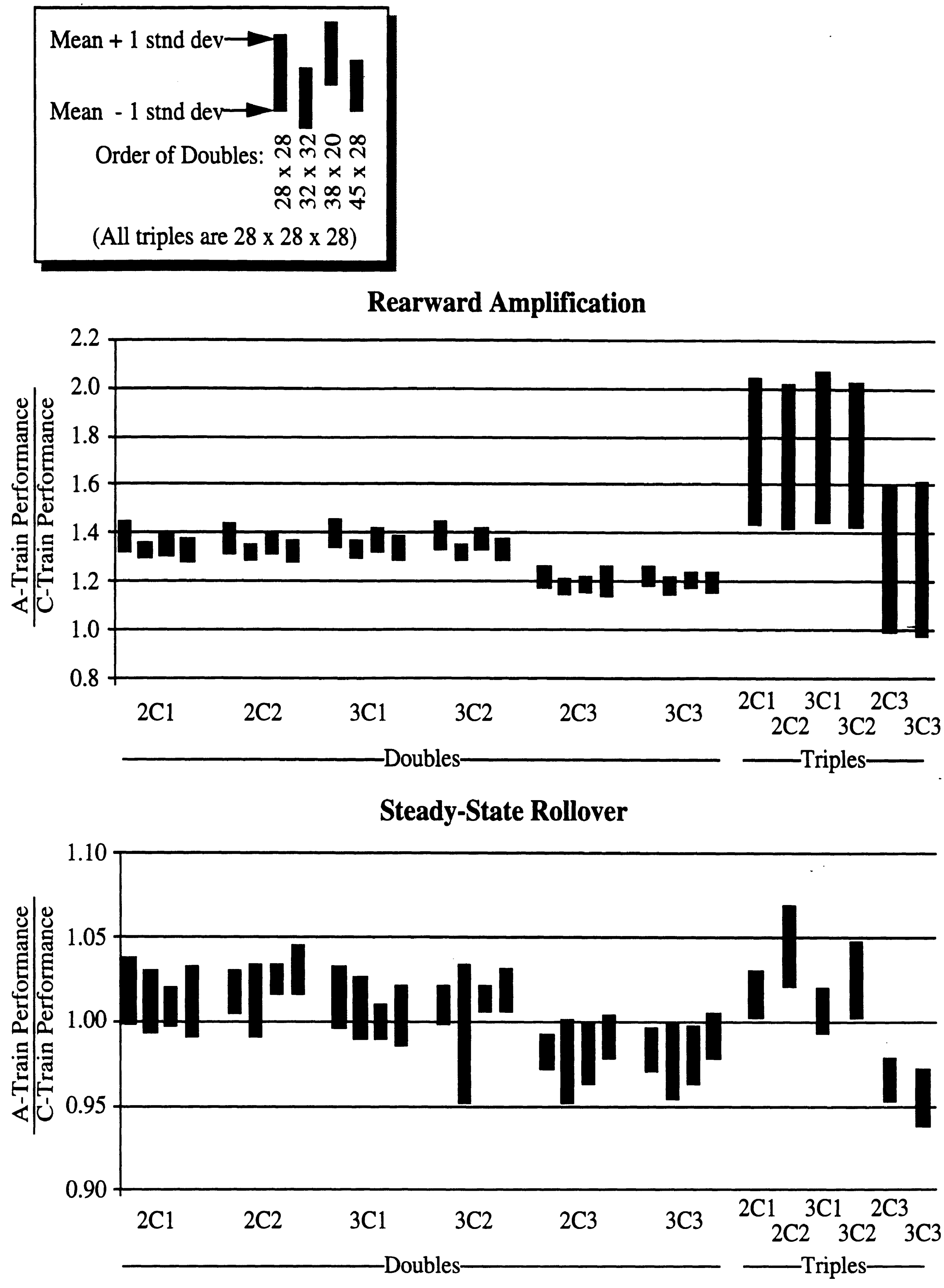


Figure E-1. A/C improvement factors

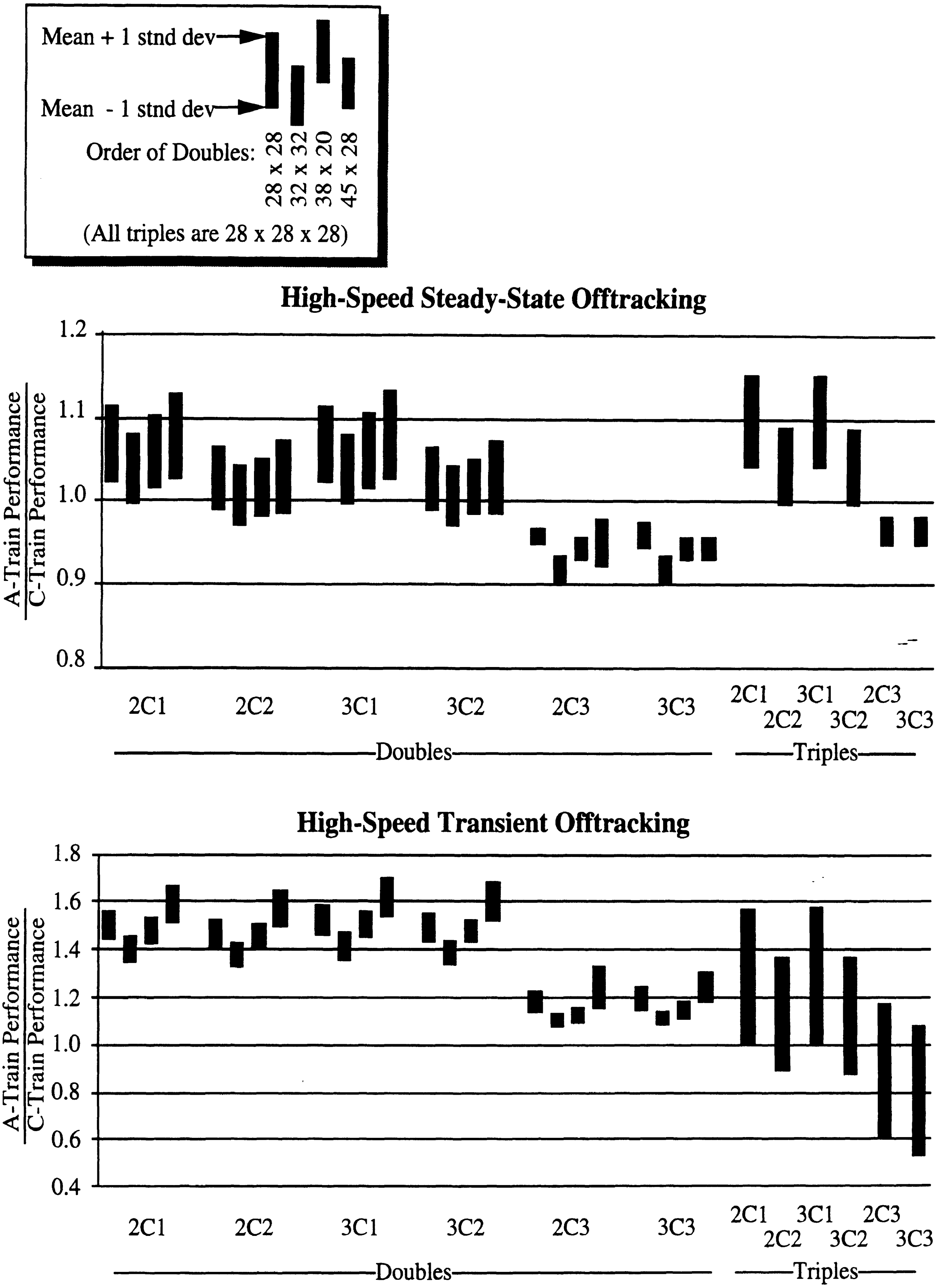
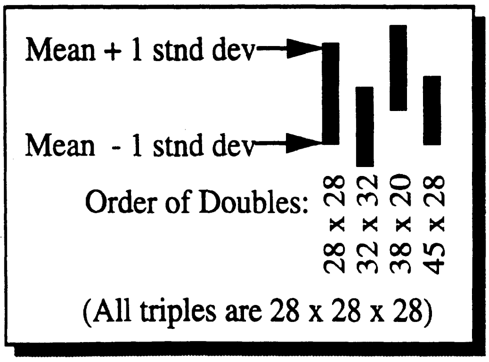
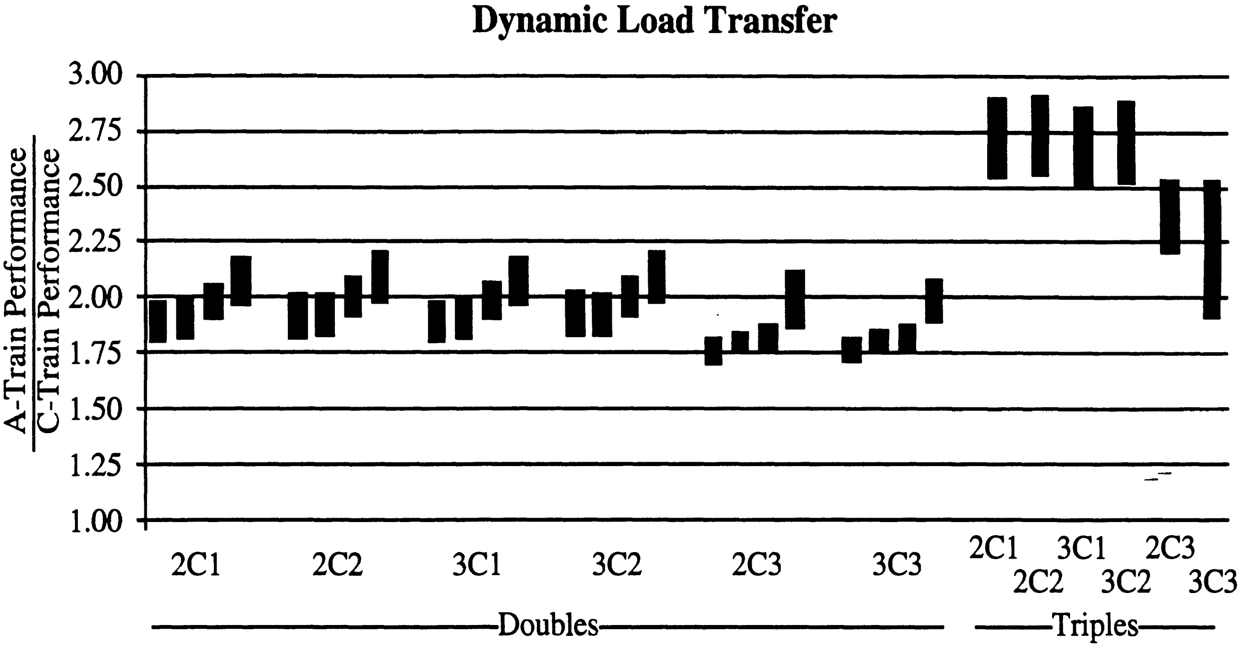


Figure E-1 (continued). A/C improvement factors





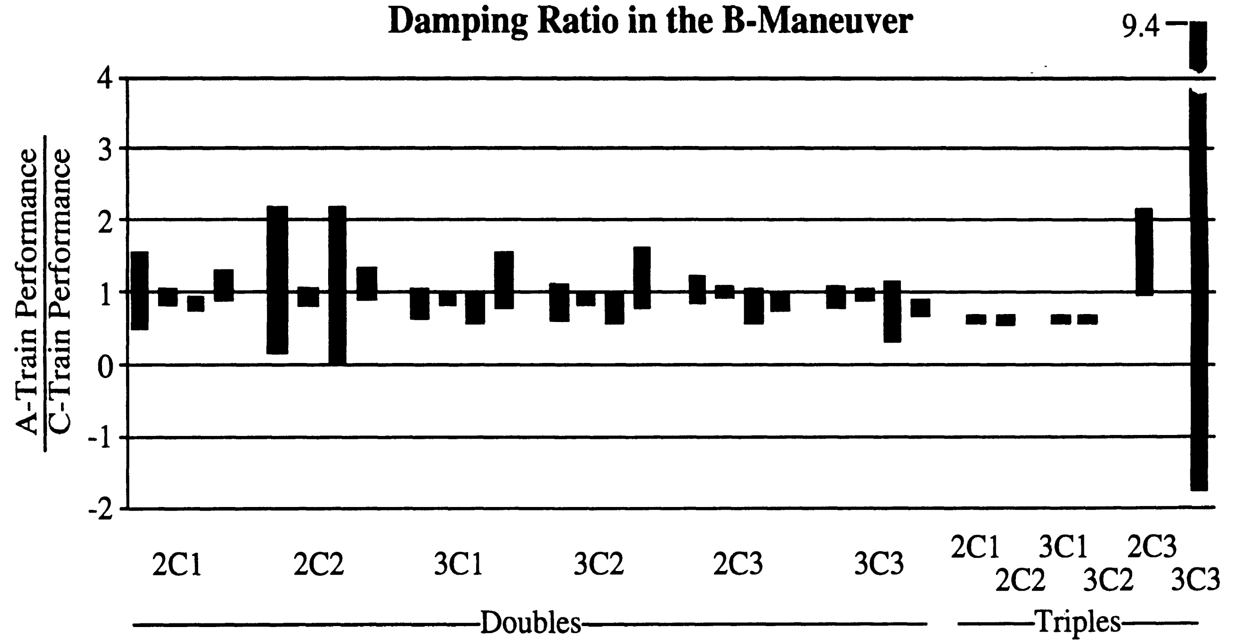


Figure E-1 (continued). A/C improvement factors

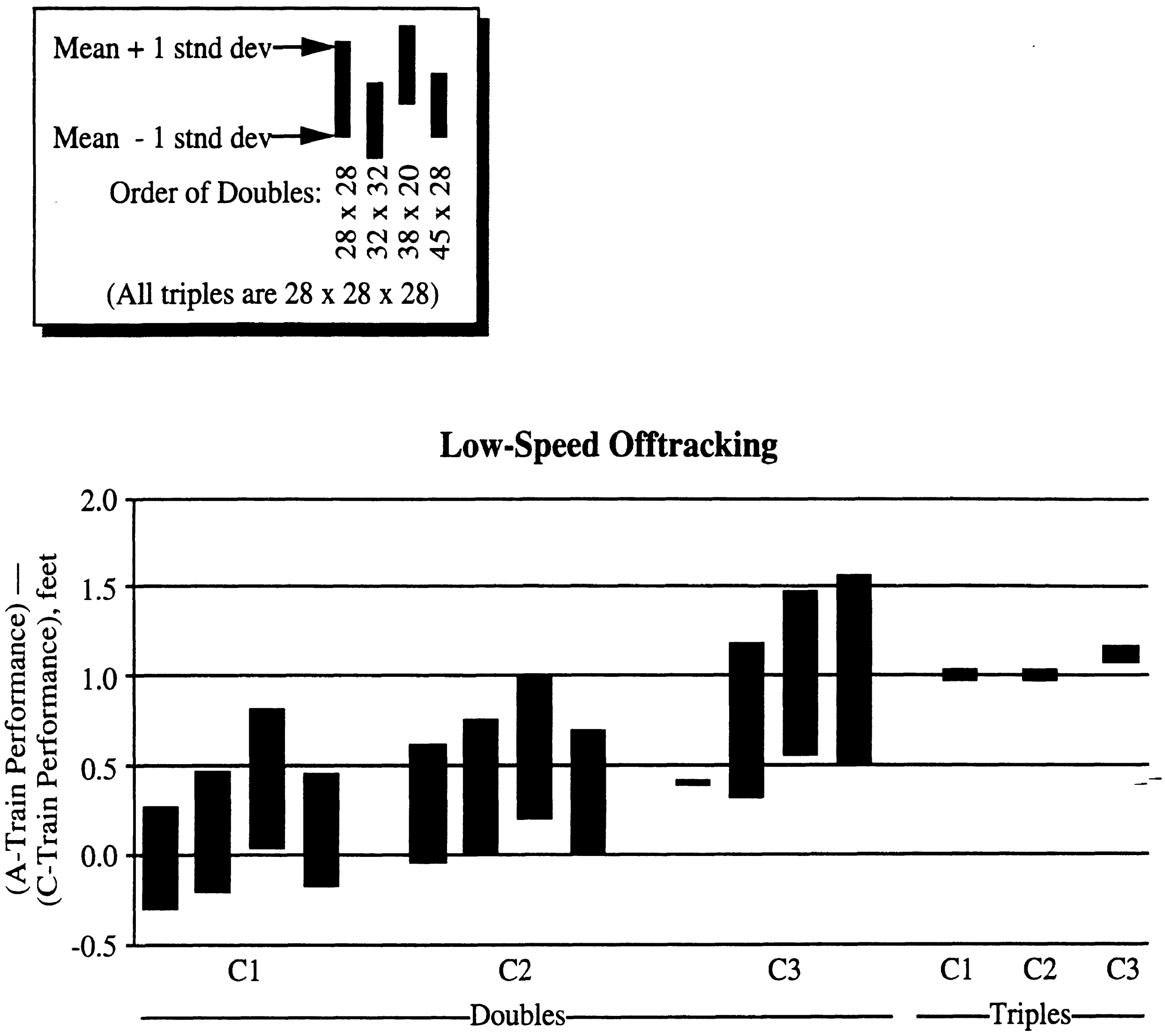


Figure E-1 (continued). A/C improvement factors

Table E-2. A-train and C-train performance measures—averages and standard deviations

Steady-State Rollover Threshold, g

	—A Dolly—		—2C1 Dolly—		—2C2 Dolly—		—2C3 Dolly—		—3C1 Dolly—		—3C2 Dolly—		—3C3 Dolly—	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.438	0.031	0.431	0.031	0.431	0.032	0.446	0.033	0.432	0.031	0.434	0.031	0.446	0.036
32x32	0.448	0.038	0.443	0.030	0.442	0.029	0.460	0.050	0.444	0.030	0.454	0.060	0.460	0.049
38x20	0.440	0.033	0.436	0.036	0.429	0.033	0.449	0.042	0.440	0.036	0.434	0.033	0.450	0.042
45x28	0.448	0.036	0.443	0.041	0.434	0.033	0.452	0.041	0.446	0.041	0.439	0.032	0.452	0.041
45x45	0.424	0.035												
All doubles	0.439	0.002	0.438	0.004	0.434	0.002	0.452	0.006	0.441	0.005	0.440	0.012	0.452	0.004
28x28x28	0.433	0.030	0.426	0.025	0.415	0.022	0.449	0.034	0.430	0.026	0.423	0.023	0.455	0.036

Steady-State High-Speed Offtracking, feet

	—A Dolly—		—2C1 Dolly—		—2C2 Dolly—		—2C3 Dolly—		—3C1 Dolly—		—3C2 Dolly—		—3C3 Dolly—	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	-1.188	0.239	-1.105	0.166	-1.151	0.180	-1.241	0.239	-1.106	0.167	-1.150	0.180	-1.238	0.230
32x32	-1.213	0.230	-1.162	0.173	-1.198	0.185	-1.318	0.238	-1.162	0.173	-1.198	0.184	-1.318	0.238
38x20	-1.125	0.235	-1.055	0.172	-1.101	0.195	-1.191	0.234	-1.053	0.171	-1.101	0.195	-1.191	0.234
45x28	-1.189	0.280	-1.095	0.205	-1.148	0.225	-1.248	0.249	-1.094	0.204	-1.149	0.225	-1.259	0.282
45x45	-1.392	0.349												
All doubles	-1.221	0.045	-1.104	0.015	-1.150	0.018	-1.249	0.006	-1.103	0.015	-1.150	0.018	-1.251	0.021
28x28x28	-1.823	0.357	-1.653	0.228	-1.739	0.259	-1.889	0.361	-1.653	0.228	-1.739	0.259	-1.889	0.361

Rearward Amplification

	—A Dolly—		—2C1 Dolly—		—2C2 Dolly—		—2C3 Dolly—		—3C1 Dolly—		—3C2 Dolly—		—3C3 Dolly—	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	2.396	0.171	1.734	0.065	1.744	0.066	1.971	0.094	1.720	0.063	1.731	0.063	1.959	0.097
32x32	2.133	0.111	1.609	0.064	1.620	0.068	1.812	0.101	1.604	0.063	1.615	0.068	1.807	0.102
38x20	2.355	0.140	1.740	0.081	1.740	0.082	1.983	0.113	1.719	0.079	1.718	0.081	1.961	0.115
45x28	1.918	0.131	1.448	0.068	1.449	0.070	1.603	0.075	1.439	0.066	1.440	0.067	1.606	0.094
45x45	1.676	0.118												
All doubles	2.096	0.021	1.633	0.007	1.638	0.006	1.842	0.014	1.621	0.007	1.626	0.007	1.833	0.008
28x28x28	3.647	0.679	2.099	0.066	2.128	0.061	2.885	0.471	2.081	0.073	2.115	0.063	2.932	0.708

Table E-2 (continued). A-train and C-train performance measures—averages and standard deviations

Dynamic-Load-Transfer Ratio

Vehicle	—A Dolly—		—2C1 Dolly—		—2C2 Dolly—		—2C3 Dolly—		—3C1 Dolly—		—3C2 Dolly—		—3C3 Dolly—	
	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.873	0.076	0.464	0.042	0.457	0.041	0.497	0.043	0.462	0.041	0.456	0.041	0.495	0.043
32x32	0.769	0.079	0.405	0.036	0.401	0.035	0.428	0.039	0.404	0.036	0.401	0.035	0.428	0.039
38x20	0.822	0.081	0.416	0.040	0.412	0.040	0.452	0.042	0.415	0.040	0.411	0.039	0.451	0.042
45x28	0.707	0.074	0.342	0.031	0.339	0.030	0.356	0.033	0.342	0.031	0.339	0.031	0.357	0.032
45x45	0.624	0.073												
All doubles	0.759	0.003	0.407	0.004	0.402	0.004	0.433	0.004	0.406	0.004	0.402	0.004	0.433	0.004
28x28x28	0.994	0.015	0.368	0.028	0.367	0.028	0.423	0.034	0.373	0.029	0.372	0.029	0.463	0.104

Transient High-Speed Offtracking, feet

Vehicle	—A Dolly—		—2C1 Dolly—		—2C2 Dolly—		—2C3 Dolly—		—3C1 Dolly—		—3C2 Dolly—		—3C3 Dolly—	
	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	2.421	0.546	1.608	0.314	1.645	0.330	2.068	0.494	1.583	0.311	1.621	0.325	2.035	0.488
32x32	2.029	0.468	1.440	0.274	1.466	0.284	1.846	0.442	1.429	0.272	1.456	0.282	1.831	0.437
38x20	1.935	0.454	1.303	0.261	1.325	0.271	1.727	0.412	1.282	0.257	1.305	0.268	1.696	0.404
45x28	1.718	0.452	1.078	0.260	1.091	0.267	1.380	0.286	1.057	0.255	1.071	0.263	1.390	0.384
45x45	1.768	0.521												
All doubles	1.974	0.038	1.357	0.022	1.382	0.025	1.755	0.077	1.338	0.022	1.363	0.025	1.738	0.039
28x28x28	3.573	1.127	2.791	0.512	3.161	0.606	3.931	1.693	2.791	0.552	3.205	0.656	5.105	2.891

B-Maneuver Damping Ratio

Vehicle	—A Dolly—		—2C1 Dolly—		—2C2 Dolly—		—2C3 Dolly—		—3C1 Dolly—		—3C2 Dolly—		—3C3 Dolly—	
	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	0.205	0.028	0.235	0.067	0.231	0.076	0.213	0.079	0.263	0.074	0.263	0.074	0.232	0.050
32x32	0.269	0.030	0.299	0.055	0.295	0.055	0.272	0.032	0.309	0.051	0.309	0.049	0.279	0.030
38x20	0.202	0.022	0.247	0.036	0.236	0.061	0.279	0.096	0.273	0.059	0.277	0.057	0.343	0.121
45x28	0.269	0.029	0.257	0.040	0.257	0.041	0.320	0.058	0.256	0.060	0.253	0.062	0.355	0.061
45x45	0.362	0.041												
All doubles	0.261	0.006	0.260	0.012	0.255	0.013	0.271	0.024	0.275	0.008	0.276	0.009	0.302	0.034
28x28x28	0.211	0.029	0.342	0.041	0.340	0.040	0.190	0.163	0.336	0.030	0.336	0.031	0.099	0.065

Table E-2 (continued). A-train and C-train performance measures—averages and standard deviations

Low-Speed Offtracking, feet

	—A Dolly—		— C1 Dolly—		— C2 Dolly—		— C3 Dolly—	
Vehicle	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev	Average	Stnd Dev
28x28	14.125	0.304	14.149	0.057	13.856	0.012	13.491	0.000
32x32	16.849	0.304	16.725	0.003	16.475	0.033	16.103	0.103
38x20	16.622	0.295	16.207	0.061	16.028	0.074	15.614	0.121
45x28	22.377	0.305	22.234	0.012	22.026	0.029	21.636	0.089
45x45	27.289	0.328	27.147	0.062	26.978	0.041	25.986	0.428
All doubles	**19.452**	**0.307**	**19.292**	**0.039**	**19.073**	**0.038**	**19.533**	**0.148**
28x28x28	17.465	0.373	17.445	0.212	16.954	0.267	15.667	0.371

Table E-3. Comparison of A-train and C-train performance— low-speed offtracking

	Offtracking, feet				*A-C Improvement, feet*		
Vehicle	*A-Dolly*	*C1-Dolly*	*C2-Dolly*	*C3-Dolly*	*C1-Dolly*	*C2-Dolly*	*C3-Dolly*
28x28bas	13.905	14.111	13.848	13.491	-0.206	0.057	0.414
28x28do1	14.256	14.160	13.857		0.096	0.399	
28x28do2	14.666	14.245	13.875		0.421	0.791	
28x28se1	13.885	14.150	13.861		-0.265	0.024	
28x28se2	13.911	14.077	13.841		-0.166	0.070	
32x32bas	16.630	16.729	16.497	16.167	-0.099	0.133	0.463
32x32do1	16.984	16.721	16.460	16.021	0.263	0.524	0.963
32x32do2	17.389	16.723	16.420	16.002	0.666	0.969	1.387
32x32se1	16.590	16.725	16.481	16.274	-0.135	0.109	0.316
32x32se2	16.654	16.727	16.516	16.051	-0.073	0.138	0.603
38x20bas	16.409	16.252	16.082	15.699	0.157	0.327	0.710
38x20do1	16.747	16.182	16.000	15.579	0.565	0.747	1.168
38x20do2	17.148	16.106	15.906	15.399	1.042	1.242	1.749
38x20se1	16.379	16.211	16.031	15.743	0.168	0.348	0.636
38x20se2	16.426	16.283	16.123	15.652	0.143	0.303	0.774
45x28bas	22.159	22.247	22.051	21.685	-0.088	0.108	0.474
45x28do1	22.509	22.228	22.014	21.623	0.281	0.495	0.886
45x28do2	22.921	22.212	21.975	21.514	0.709	0.946	1.407
45x28se1	22.155	22.240	22.035	21.775	-0.085	0.120	0.380
45x28se2	22.141	22.241	22.055	21.583	-0.100	0.086	0.558
45x45bas	27.051	27.051	27.051	25.149	0.000	0.000	1.902
45x45do1	27.438	27.188	26.970	26.199	0.250	0.468	1.239
45x45do2	27.870	27.224	26.982	26.087	0.646	0.888	1.783
45x45se1	27.075	27.171	26.965	26.354	-0.096	0.110	0.721
45x45se2	27.011	27.103	26.924	26.143	-0.092	0.087	0.868
28x28x28bas	17.204	17.597	17.144	15.936	-0.393	0.060	1.268
28x28x28do1	17.618	17.362	16.844	15.457	0.256	0.774	2.161
28x28x28do2	18.124	17.084	16.508	15.051	1.040	1.616	3.073
28x28x28se1	17.092	17.486	16.990	16.079	-0.394	0.102	1.013
28x28x28se2	17.286	17.695	17.282	15.812	-0.409	0.004	1.474
Average	19.121	18.984	18.720	18.789	0.137	0.402	1.092
Stnd Dev	4.492	4.469	4.516	4.311	0.395	0.418	0.651

Table E-4. Comparison of A-train and C-train performance —pooled results for self-steering and controlled-steering C-dollies

A-C

		Self-steer dollies (2C1, 2C2, 3C1, 3C2)		*Controlled-steer dollies (2C3, 3C3)*	
Performance Measure	*Vehicles*	*Average*	*Stnd Dev*	*Average*	*Stnd Dev*
Steady-State Rollover Threshold, g	All doubles	0.0051	0.0107	-0.0085	0.0108
	All triples	0.0098	0.0108	-0.0186	0.0086
Steady-State Hi-Speed Offtracking, feet	All doubles	-0.0519	0.0665	0.0717	0.0293
	All triples	-0.1268	0.1252	0.0663	0.0348
Rearward Amplification	All doubles	0.5710	0.1214	0.3629	0.0947
	All triples	1.5409	0.6589	0.7379	0.8850
Dynamic-Load-Transfer Ratio	All doubles	0.3888	0.0542	0.3597	0.0468
	All triples	0.6245	0.0229	0.5515	0.0762
Transient High-Speed Offtracking, feet	All doubles	0.6656	0.2252	0.2790	0.1294
	All triples	0.5858	0.9047	-0.9445	2.1089
B-Maneuver Damping Ratio	All doubles	-0.0303	0.0616	-0.0504	0.0837
	All triples	-0.1308	0.0327	0.0587	0.1507
Low-Speed Offtracking, feet	All doubles	0.2698	0.3502	0.9239	0.4877
	All triples	0.2656	0.6646	1.7978	0.8306

A/C

		Self-steer dollies (2C1, 2C2, 3C1, 3C2)		*Controlled-steer dollies (2C3, 3C3)*	
Performance Measure	*Vehicles*	*Average*	*Stnd Dev*	*Average*	*Stnd Dev*
Steady-State Rollover Threshold, g	All doubles	1.0119	0.0207	0.9823	0.0183
	All triples	1.0226	0.0244	0.9595	0.0166
Steady-State Hi-Speed Offtracking, feet	All doubles	1.0400	0.0492	0.9408	0.0226
	All triples	1.0686	0.0588	0.9643	0.0177
Rearward Amplification	All doubles	1.3486	0.0557	1.1973	0.0460
	All triples	1.7300	0.3064	1.2926	0.3139
Dynamic-Load-Transfer Ratio	All doubles	1.9693	0.1213	1.8397	0.1152
	All triples	2.7023	0.1860	2.2907	0.2612
Transient High-Speed Offtracking, feet	All doubles	1.4898	0.0975	1.1660	0.0739
	All triples	1.2026	0.2784	0.8425	0.2875
B-Maneuver Damping Ratio	All doubles	0.9583	0.4472	0.8815	0.2398
	All triples	0.6199	0.0791	2.2089	3.4824
Low-Speed Offtracking, feet	All doubles	1.0150	0.0204	1.0481	0.0251
	All triples	1.0161	0.0394	1.1160	0.0570

Table E-5. A-train and C-train performance measures —pooled results—averages and standard deviations

		A-dollies		*Self-steer dollies (2C1, 2C2, 3C1, 3C2)*		*Controlled-steer dollies (2C3, 3C3)*	
Performance Measure	*Vehicles*	*Average*	*Stnd Dev*	*Average*	*Stnd Dev*	*Average*	*Stnd Dev*
Steady-State Rollover Threshold, g	All doubles	0.4379	0.0309	0.4383	0.0363	0.4519	0.0425
	All triples	0.4333	0.0301	0.4235	0.0249	0.4519	0.0352
Steady-State Hi-Speed Offtracking, feet	All doubles	-1.1882	0.2392	-1.1268	0.1932	-1.2504	0.2478
	All triples	-1.8227	0.3573	-1.6960	0.2477	-1.8890	0.3607
Rearward Amplification	All doubles	2.3959	0.1711	1.6295	0.1368	1.8376	0.1795
	All triples	3.6465	0.6793	2.1057	0.0681	2.9086	0.6019
Dynamic-Load-Transfer Ratio	All doubles	0.8728	0.0759	0.4041	0.0563	0.4332	0.0641
	All triples	0.9945	0.0147	0.3700	0.0286	0.4430	0.0800
Transient High-Speed Offtracking, feet	All doubles	2.4206	0.5461	1.3599	0.3451	1.7465	0.4871
	All triples	3.5730	1.1273	2.9872	0.6161	4.4976	2.4210
B-Maneuver Damping Ratio	All doubles	0.2048	0.0275	0.2664	0.0635	0.2865	0.0862
	All triples	0.2112	0.0292	0.3385	0.0359	0.1430	0.1305

APPENDIX F

DOLLY HITCH LOADING RESULTS

The force results presented in the table F-1 below are the peak loads acting on one of the two pintle hitches of a C-dolly. The moment results were calculated for the linkage between the C-dolly and leading trailer. All results are in response to an RTAC-B maneuver.

Table F-1. Peak loads acting on one of the two pintle hitches of a C-dolly

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
28x28bas2C1	4651	1745	1964	4615	11627
28x28do12C1	6054	1812	2026	4713	15134
28x28do22C1	7488	1864	2080	4807	18719
28x28pl12C1	4983	1891	2502	6010	12457
28x28pl22C1	4303	1623	1458	3367	10757
28x28pl32C1	3876	1470	1984	4688	9689
28x28pl42C1	5219	1979	1928	4520	13048
28x28se12C1	4779	1797	1992	4683	11948
28x28se22C1	4501	1690	1933	4541	11253
28x28sp22C1	4761	1794	2240	5297	11902
28x28sp32C1	4502	1705	1633	3799	11255
28x28ss42C1	5228	1983	1731	4036	13070
28x28su12C1	4806	1815	2388	5798	12015
28x28ti12C1	4590	1815	1877	4400	11474
28x28ti22C1	5217	1933	2018	4844	13041
28x28bas2C2	4659	1748	1967	4623	11648
28x28do12C2	6064	1815	2030	4722	15161
28x28do22C2	7503	1868	2084	4817	18756
28x28pl12C2	4989	1914	2505	6015	12473
28x28pl22C2	4314	1627	1462	3375	10785
28x28pl32C2	3918	1579	1990	4699	9793
28x28pl42C2	5221	1980	1929	4522	13052
28x28se12C2	4788	1800	1996	4692	11969

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
28x28se22C2	4509	1693	1936	4548	11273
28x28sp22C2	4768	1797	2243	5303	11920
28x28sp32C2	4513	1710	1636	3806	11281
28x28ss42C2	5240	1988	1734	4044	13099
28x28su12C2	4813	1818	2391	5799	12032
28x28ti12C2	4669	1847	1877	4401	11672
28x28ti22C2	5207	1930	2033	4878	13016
28x28bas2C3	5506	2188	2068	4882	13765
28x28do12C3	7458	2382	2153	5032	18643
28x28do22C3	9562	2548	2223	5164	23906
28x28pl12C3	5917	2356	2887	6916	14792
28x28pl22C3	5014	1988	1519	3519	12534
28x28pl32C3	5839	2318	2054	4857	14597
28x28pl42C3	5412	2150	2049	4828	13528
28x28se12C3	5581	2215	2100	4958	13953
28x28se22C3	5473	2174	2034	4799	13683
28x28sp22C3	5535	2202	2338	5548	13838
28x28sp32C3	5366	2128	1724	4030	13413
28x28ss42C3	6115	2416	1830	4287	15287
28x28su12C3	5844	2329	2516	6224	14610
28x28ti12C3	5033	2001	1914	4498	12582
28x28ti22C3	6533	2598	2258	5358	16331
28x28bas3C1	4528	1705	3064	7376	11318
28x28do13C1	5932	1768	3157	7551	14830
28x28do23C1	7371	1829	3240	7720	18426
28x28pl13C1	4901	1850	3992	9680	12252
28x28pl23C1	4227	1590	2294	5463	10566
28x28pl33C1	3751	1398	3122	7527	9378
28x28pl43C1	5140	1949	3029	7284	12850
28x28se13C1	4673	1750	3115	7501	11682
28x28se23C1	4370	1654	3010	7243	10924

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
28x28sp23C1	4585	1718	3411	8240	11462
28x28sp33C1	4428	1673	2643	6331	11070
28x28ss23C1	5072	1921	2844	6825	12680
28x28su13C1	4666	1752	3615	8744	11665
28x28ti13C1	4497	1715	2937	7061	11241
28x28ti23C1	5084	1875	3233	7897	12708
28x28bas3C2	4538	1710	3070	7392	11344
28x28do13C2	5945	1773	3165	7570	14863
28x28do23C2	7387	1833	3249	7741	18468
28x28pl13C2	4909	1854	3997	9693	12273
28x28pl23C2	4239	1594	2301	5481	10597
28x28pl33C2	3778	1511	3133	7578	9445
28x28pl43C2	5143	1950	3032	7289	12857
28x28se13C2	4683	1755	3122	7519	11708
28x28se23C2	4380	1658	3016	7258	10950
28x28sp23C2	4595	1721	3418	8255	11486
28x28sp33C2	4442	1678	2649	6346	11104
28x28ss23C2	5085	1926	2850	6839	12711
28x28su13C2	4676	1756	3622	8763	11688
28x28ti13C2	4499	1727	2938	7065	11247
28x28ti23C2	5072	1872	3258	7999	12680
28x28bas3C3	5369	2132	3258	7867	13421
28x28do13C3	7193	2303	3391	8137	17982
28x28do23C3	9228	2459	3503	8376	23069
28x28pl13C3	5816	2312	4184	10165	14538
28x28pl23C3	4883	1935	2407	5747	12208
28x28pl33C3	5628	2233	3258	7871	14069
28x28pl43C3	5228	2076	3202	7723	13070
28x28se13C3	5404	2147	3315	8005	13508
28x28se23C3	5291	2101	3198	7719	13227
28x28sp23C3	5395	2147	3604	8727	13488

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
28x28sp33C3	5231	2074	2781	6682	13076
28x28ss23C3	5889	2327	2986	7186	14723
28x28su13C3	5549	2211	3853	9345	13872
28x28ti13C3	4785	1903	3018	7266	11962
28x28ti23C3	6201	2467	3617	8766	15501
32x32bas2C1	5525	2083	1536	3526	13813
32x32do12C1	7231	2179	1587	3599	18077
32x32do22C1	8993	2256	1628	3668	22481
32x32pl12C1	6033	2291	1998	4857	15081
32x32pl22C1	5063	1919	1128	2521	12656
32x32pl32C1	5525	2083	1536	3526	13813
32x32pl42C1	6354	2398	1520	3479	15885
32x32se12C1	5702	2153	1556	3573	14254
32x32se22C1	5332	2007	1516	3477	13329
32x32sp22C1	5610	2120	1742	4031	14025
32x32sp32C1	5281	1998	1172	2629	13202
32x32ss42C1	5700	2148	1128	2675	14249
32x32su12C1	5754	2180	1911	4549	14383
32x32ti12C1	5470	2092	1460	3340	13675
32x32ti22C1	5897	2193	1605	3741	14742
32x32bas2C2	5530	2085	1537	3529	13824
32x32do12C2	7238	2181	1588	3603	18094
32x32do22C2	9002	2259	1630	3671	22504
32x32pl12C2	6036	2293	1999	4864	15089
32x32pl22C2	5067	1922	1129	2524	12667
32x32pl32C2	5530	2085	1537	3529	13824
32x32pl42C2	6354	2398	1520	3479	15885
32x32se12C2	5707	2155	1557	3576	14267
32x32se22C2	5335	2008	1517	3479	13338
32x32sp22C2	5614	2122	1742	4033	14035
32x32sp32C2	5286	2001	1173	2631	13215

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
32x32ss42C2	5705	2151	1129	2683	14261
32x32su12C2	5758	2181	1912	4535	14393
32x32ti12C2	5470	2092	1460	3340	13675
32x32ti22C2	5915	2200	1612	3774	14788
32x32bas2C3	6778	2663	1604	3696	16944
32x32do12C3	9116	2897	1666	3798	22789
32x32do22C3	11438	3036	1715	3882	28595
32x32pl12C3	7352	2912	2109	5448	18380
32x32pl22C3	6105	2395	1189	2676	15262
32x32pl32C3	6778	2663	1604	3696	16944
32x32pl42C3	6691	2625	1608	3700	16726
32x32se12C3	6837	2688	1625	3747	17091
32x32se22C3	6684	2625	1581	3642	16710
32x32sp22C3	6818	2697	1810	4203	17043
32x32sp32C3	6473	2539	1231	2778	16182
32x32ss42C3	6968	2730	1175	2788	17418
32x32su12C3	7119	2813	1996	4882	17798
32x32ti12C3	6474	2532	1482	3393	16184
32x32ti22C3	8949	3509	1766	4183	22373
32x32bas3C1	5430	2043	2552	6072	13574
32x32do13C1	7115	2140	2624	6201	17788
32x32do23C1	8875	2223	2688	6325	22187
32x32pl13C1	5932	2248	3351	8052	14828
32x32pl23C1	5018	1902	1879	4403	12545
32x32pl33C1	5430	2043	2552	6072	13574
32x32pl43C1	6256	2357	2508	5958	15640
32x32se13C1	5611	2114	2586	6156	14026
32x32se23C1	5231	1968	2515	5982	13077
32x32sp23C1	5507	2076	2853	6818	13766
32x32sp33C1	5217	1975	1989	4676	13042
32x32ss43C1	5599	2118	1935	4799	13997

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
32x32su13C1	5620	2123	3097	7473	14050
32x32ti13C1	5386	2057	2415	5733	13463
32x32ti23C1	5813	2157	2689	6478	14533
32x32bas3C2	5435	2045	2554	6077	13588
32x32do13C2	7123	2143	2627	6208	17808
32x32do23C2	8887	2227	2691	6332	22217
32x32pl13C2	5936	2249	3353	8056	14839
32x32pl23C2	5025	1904	1881	4408	12562
32x32pl33C2	5435	2045	2554	6077	13588
32x32pl43C2	6256	2357	2508	5958	15640
32x32se13C2	5616	2116	2589	6162	14041
32x32se23C2	5235	1970	2517	5987	13088
32x32sp23C2	5511	2078	2855	6823	13778
32x32sp33C2	5222	1978	1991	4681	13054
32x32ss43C2	5604	2121	1937	4815	14009
32x32su13C2	5625	2125	3100	7457	14063
32x32ti13C2	5386	2057	2415	5733	13463
32x32ti23C2	5827	2166	2700	6515	14568
32x32bas3C3	6633	2605	2675	6382	16581
32x32do13C3	8924	2836	2769	6563	22310
32x32do23C3	11231	2981	2846	6716	28077
32x32pl13C3	7214	2854	3493	8892	18034
32x32pl23C3	6006	2355	1976	4647	15014
32x32pl33C3	6633	2605	2675	6382	16581
32x32pl43C3	6542	2565	2666	6353	16354
32x32se13C3	6706	2634	2713	6473	16765
32x32se23C3	6529	2563	2635	6284	16321
32x32sp23C3	6688	2630	2981	7140	16720
32x32sp33C3	6365	2495	2083	4912	15912
32x32ss43C3	6812	2678	2008	4990	17030
32x32su13C3	6961	2740	3255	7880	17402

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
32x32ti13C3	6286	2466	2460	5844	15714
32x32ti23C3	8731	3423	2962	7101	21827
38x20bas2C1	5313	2013	1670	3891	13282
38x20do12C1	6964	2110	1733	3989	17409
38x20do22C1	8717	2199	1788	4086	21791
38x20pl12C1	5779	2205	2186	5158	14446
38x20pl22C1	4756	1810	1191	2714	11890
38x20pl32C1	4814	1819	1709	3993	12033
38x20pl42C1	5935	2266	1626	3777	14836
38x20se12C1	5493	2083	1696	3956	13732
38x20se22C1	5121	1938	1642	3824	12802
38x20sp22C1	5430	2062	1873	4392	13575
38x20sp32C1	5090	1920	1286	2945	12724
38x20ss42C1	5772	2181	1362	3128	14431
38x20su12C1	5551	2113	2088	4921	13877
38x20ti12C1	5097	1956	1583	3680	12743
38x20ti22C1	5833	2186	1711	3991	14581
38x20bas2C2	5315	2013	1670	3893	13287
38x20do12C2	6968	2111	1734	3992	17419
38x20do22C2	8724	2201	1790	4090	21809
38x20pl12C2	5780	2206	2186	5160	14449
38x20pl22C2	4758	1811	1192	2715	11895
38x20pl32C2	4819	1820	1709	3995	12047
38x20pl42C2	5935	2266	1626	3777	14836
38x20se12C2	5496	2084	1697	3958	13739
38x20se22C2	5122	1938	1642	3825	12805
38x20sp22C2	5432	2063	1874	4394	13580
38x20sp32C2	5092	1921	1286	2946	12729
38x20ss42C2	5776	2182	1362	3129	14438
38x20su12C2	5553	2114	2089	4922	13881
38x20ti12C2	5097	1956	1583	3680	12743

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
38x20ti22C2	5862	2198	1723	4020	14653
38x20bas2C3	5369	2132	1802	4234	13421
38x20do12C3	7155	2291	1886	4385	17886
38x20do22C3	9147	2446	1963	4534	22868
38x20pl12C3	5800	2308	2460	5884	14499
38x20pl22C3	4655	1852	1280	2946	11636
38x20pl32C3	4793	1917	1802	4235	11982
38x20pl42C3	5339	2121	1776	4166	13347
38x20se12C3	5446	2163	1834	4311	13614
38x20se22C3	5272	2094	1768	4154	13180
38x20sp22C3	5420	2154	2006	4739	13549
38x20sp32C3	5066	2011	1398	3235	12663
38x20ss42C3	5875	2321	1494	3469	14687
38x20su12C3	5731	2278	2241	5318	14326
38x20ti12C3	4839	1923	1648	3851	12098
38x20ti22C3	6402	2543	1906	4503	16005
38x20bas3C1	5162	1950	2672	6409	12905
38x20do13C1	6784	2050	2763	6575	16960
38x20do23C1	8512	2142	2847	6744	21279
38x20pl13C1	5669	2157	3563	8615	14171
38x20pl23C1	4681	1779	1924	4552	11702
38x20pl33C1	4638	1757	2757	6622	11593
38x20pl43C1	5839	2226	2630	6296	14597
38x20se13C1	5347	2022	2719	6523	13368
38x20se23C1	4965	1877	2624	6291	12411
38x20sp23C1	5270	1995	2977	7164	13175
38x20sp33C1	4992	1880	2137	5080	12480
38x20ss43C1	5604	2114	2291	5456	14009
38x20su13C1	5371	2037	3259	7864	13427
38x20ti13C1	5004	1917	2535	6068	12508
38x20ti23C1	5710	2135	2798	6716	14275

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
38x20bas3C2	5165	1951	2674	6412	12911
38x20do13C2	6789	2052	2765	6581	16972
38x20do23C2	8520	2145	2850	6752	21300
38x20pl13C2	5670	2158	3564	8617	14176
38x20pl23C2	4684	1780	1926	4555	11708
38x20pl33C2	4644	1759	2759	6627	11609
38x20pl43C2	5839	2226	2630	6296	14597
38x20se13C2	5351	2023	2721	6528	13376
38x20se23C2	4967	1877	2625	6294	12416
38x20sp23C2	5273	1996	2979	7168	13182
38x20sp33C2	4995	1881	2138	5083	12486
38x20ss43C2	5607	2115	2292	5460	14017
38x20su13C2	5373	2038	3261	7868	13432
38x20ti13C2	5004	1917	2535	6068	12508
38x20ti23C2	5739	2146	2820	6772	14347
38x20bas3C3	5181	2059	2923	7044	12952
38x20do13C3	6931	2222	3055	7315	17326
38x20do23C3	8905	2384	3182	7590	22263
38x20pl13C3	5755	2281	3821	9284	14386
38x20pl23C3	4553	1812	2078	4940	11383
38x20pl33C3	4569	1828	2937	7080	11422
38x20pl43C3	5111	2032	2862	6888	12778
38x20se13C3	5273	2095	2980	7184	13182
38x20se23C3	5071	2016	2864	6900	12676
38x20sp23C3	5249	2087	3227	7801	13121
38x20sp33C3	4921	1955	2336	5586	12303
38x20ss43C3	5642	2231	2512	6019	14105
38x20su13C3	5527	2198	3559	8626	13816
38x20ti13C3	4561	1814	2666	6403	11402
38x20ti23C3	6051	2408	3168	7653	15126
45x28bas2C1	4919	1870	1609	3737	12298

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
45x28do12C1	6420	1952	1663	3814	16051
45x28do22C1	8008	2027	1709	3890	20020
45x28pl12C1	5414	2071	2113	4976	13533
45x28pl22C1	4421	1670	1152	2612	11051
45x28pl32C1	3759	1436	1587	3693	9397
45x28pl42C1	5690	2161	1603	3715	14225
45x28se12C1	5070	1928	1629	3785	12674
45x28se22C1	4759	1808	1588	3687	11897
45x28sp22C1	5048	1924	1828	4276	12620
45x28sp32C1	4709	1783	1258	2871	11772
45x28ss42C1	5294	2006	1304	2980	13234
45x28su12C1	5135	1961	2010	4724	12837
45x28ti12C1	4746	1810	1531	3545	11865
45x28ti22C1	5319	2002	1650	3836	13297
45x28bas2C2	4919	1870	1609	3737	12298
45x28do12C2	6420	1952	1663	3814	16051
45x28do22C2	8008	2027	1709	3890	20020
45x28pl12C2	5414	2071	2113	4976	13533
45x28pl22C2	4421	1670	1152	2612	11051
45x28pl32C2	3759	1436	1587	3693	9398
45x28pl42C2	5690	2161	1603	3715	14225
45x28se12C2	5070	1928	1629	3785	12674
45x28se22C2	4759	1808	1588	3687	11897
45x28sp22C2	5048	1924	1828	4276	12620
45x28sp32C2	4709	1783	1258	2871	11772
45x28ss42C2	5294	2006	1304	2980	13234
45x28su12C2	5135	1961	2010	4724	12837
45x28ti12C2	4746	1810	1531	3545	11865
45x28ti22C2	5325	2004	1654	3848	13311
45x28bas2C3	4823	1903	1663	3877	12057
45x28do12C3	6377	2025	1727	3978	15942

FILENAME	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
45x28do22C3	8129	2155	1782	4076	20323
45x28pl12C3	5485	2162	2196	5197	13712
45x28pl22C3	4412	1707	1204	2744	11029
45x28pl32C3	4657	1840	1612	3765	11642
45x28pl42C3	5259	2026	1679	3911	13147
45x28se12C3	4887	1928	1685	3930	12217
45x28se22C3	4746	1873	1640	3822	11864
45x28sp22C3	4964	1960	1882	4415	12409
45x28sp32C3	4576	1784	1312	3010	11439
45x28ss42C3	5157	2025	1365	3138	12893
45x28su12C3	5192	2052	2070	4881	12978
45x28ti12C3	4686	1807	1541	3575	11715
45x28ti22C3	4989	1907	1684	3920	12471
45x28bas3C1	4794	1818	2593	6206	11986
45x28do13C1	6267	1901	2668	6336	15666
45x28do23C1	7830	1978	2736	6468	19573
45x28pl13C1	5289	2018	3433	8289	13221
45x28pl23C1	4330	1640	1868	4405	10825
45x28pl33C1	3631	1383	2578	6178	9078
45x28pl43C1	5562	2107	2570	6142	13905
45x28se13C1	4948	1877	2628	6292	12369
45x28se23C1	4632	1755	2556	6116	11579
45x28sp23C1	4888	1857	2906	6983	12219
45x28sp33C1	4613	1744	2083	4938	11532
45x28ss43C1	5138	1944	2182	5182	12845
45x28su13C1	4975	1893	3159	7611	12436
45x28ti13C1	4608	1761	2471	5903	11518
45x28ti23C1	5233	1964	2711	6497	13081
45x28bas3C2	4794	1818	2593	6206	11986
45x28do13C2	6267	1901	2668	6336	15666
45x28do23C2	7830	1978	2736	6468	19573

FILENAME-1st Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
45x28pl13C2	5289	2018	3433	8289	13221
45x28pl23C2	4330	1640	1868	4405	10825
45x28pl33C2	3632	1383	2578	6178	9079
45x28pl43C2	5562	2107	2570	6142	13905
45x28se13C2	4948	1877	2628	6292	12369
45x28se23C2	4632	1755	2556	6116	11579
45x28sp23C2	4888	1857	2906	6983	12219
45x28sp33C2	4613	1744	2083	4938	11532
45x28ss43C2	5138	1944	2182	5182	12845
45x28su13C2	4975	1893	3159	7611	12436
45x28ti13C2	4608	1761	2471	5903	11518
45x28ti23C2	5240	1967	2720	6518	13100
45x28bas3C3	4641	1829	2705	6490	11601
45x28do13C3	6158	1956	2799	6667	15395
45x28do23C3	7865	2085	2886	6845	19661
45x28pl13C3	5308	2093	3552	8599	13269
45x28pl23C3	4373	1691	1936	4580	10933
45x28pl33C3	4534	1791	2620	6282	11336
45x28pl43C3	5170	1997	2714	6508	12925
45x28se13C3	4795	1857	2744	6586	11987
45x28se23C3	4553	1796	2664	6390	11383
45x28sp23C3	4745	1874	3018	7266	11862
45x28sp33C3	4528	1753	2185	5198	11320
45x28ss43C3	5027	1943	2292	5460	12566
45x28su13C3	4912	1942	3290	7942	12280
45x28ti13C3	4593	1769	2505	5991	11481
45x28ti23C3	5450	2156	2906	6997	13623
3x28bas2C1	3703	1656	1361	3266	10642
3x28do12C1	5175	1723	1390	3340	14100
3x28do22C1	6982	1890	1415	3405	18155
3x28pl12C1	4488	1793	1857	4533	11939

FILENAME 1st Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
3x28pl22C1	3491	1466	885	2077	9777
3x28pl32C1	3387	1527	1406	3385	9972
3x28pl42C1	4102	1708	1309	3134	11203
3x28se12C1	3942	1709	1376	3304	11172
3x28se22C1	3461	1566	1346	3230	10016
3x28sp22C1	3965	1714	1847	4505	11145
3x28sp32C1	3653	1575	1027	2458	10290
3x28SS42C1	3779	1667	1503	3647	10567
3x28su12C1	3907	1701	1622	3919	11117
3x28ti12C1	3734	1862	1255	3023	11921
3x28ti22C1	5022	1867	1550	3738	12555
3x28bas2C2	3945	1743	1358	3257	11122
3x28do12C2	5685	1875	1384	3324	15339
3x28do22C2	7807	2044	1410	3392	19518
3x28pl12C2	4728	1884	1859	4540	12079
3x28pl22C2	3501	1563	890	2090	9986
3x28pl32C2	4024	1590	1411	3396	10190
3x28pl42C2	4076	1785	1311	3139	11577
3x28se12C2	4325	1824	1371	3291	11780
3x28se22C2	3686	1694	1345	3227	10885
3x28sp22C2	4044	1713	1848	4508	11301
3x28sp32C2	3788	1666	1027	2454	10577
3x28SS42C2	3824	1680	1509	3661	10643
3x28su12C2	4267	1785	1622	3919	11797
3x28ti12C2	3871	1940	1256	3026	12382
3x28ti22C2	4876	1799	1544	3724	12189
3x28bas2C3	5992	2598	1482	3554	16411
3x28do12C3	16134	6330	1527	3665	40334
3x28do22C3	N/A	6493	1490	N/A	N/A
3x28pl12C3	6463	5521	2006	4868	17435
3x28pl22C3	5522	2377	969	2272	15253

FILENAME 1st Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
3x28pl32C3	16427	6764	1750	4256	41067
3x28pl42C3	6171	2609	1421	3399	16754
3x28se12C3	6322	2682	1496	3589	17247
3x28se22C3	5834	2510	1469	3522	15858
3x28sp22C3	5857	2508	1958	4757	16298
3x28sp32C3	5804	2452	1124	2665	15803
3x28SS42C3	5716	2274	1592	3875	15248
3x28su12C3	6143	2719	1762	4254	16928
3x28ti12C3	5025	2377	1291	3100	15145
3x28ti22C3	7600	2995	1471	3577	19000
3x28bas3C1	3642	1563	2278	5558	9997
3x28do13C1	5006	1638	2315	5650	13473
3x28do23C1	6517	1791	2345	5725	17345
3x28pl13C1	3916	1703	3072	7546	11293
3x28pl23C1	3484	1440	1469	3537	9703
3x28pl33C1	3098	1397	2347	5737	8990
3x28pl43C1	4004	1641	2192	5342	11103
3x28se13C1	3847	1605	2295	5598	10482
3x28se23C1	3424	1484	2264	5524	9488
3x28sp23C1	3884	1628	2978	7308	10672
3x28sp33C1	3595	1500	1754	4250	10136
3x28SS43C1	3798	1626	2554	6271	10349
3x28su13C1	3752	1591	2689	6584	10168
3x28ti13C1	3409	1743	2076	5072	11160
3x28ti23C1	4890	1815	2588	6332	12223
3x28bas3C2	3590	1665	2268	5531	10601
3x28do13C2	5288	1774	2298	5608	14336
3x28do23C2	7400	1969	2324	5674	18785
3x28pl13C2	4268	1777	3079	7563	11549
3x28pl23C2	3463	1497	1488	3584	9662
3x28pl33C2	3786	1519	2357	5759	9635

FILENAME 1st Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
3x28pl43C2	4012	1710	2196	5350	11097
3x28se13C2	4071	1729	2280	5561	11105
3x28se23C2	3416	1605	2259	5509	10282
3x28sp23C2	3920	1627	2965	7276	10687
3x28sp33C2	3621	1591	1755	4251	10217
3x28SS43C2	3762	1639	2557	6280	10439
3x28su13C2	3797	1698	2673	6542	10760
3x28ti13C2	3638	1814	2076	5071	11591
3x28ti23C2	4729	1744	2570	6286	11821
3x28bas3C3	5730	2519	2470	6020	16043
3x28do13C3	17869	5873	2525	6157	44671
3x28do23C3	N/A	21219	11284	N/A	N/A
3x28pl13C3	6256	2653	3348	8218	16948
3x28pl23C3	5344	2317	1616	3890	14889
3x28pl33C3	19856	8699	2786	6905	49639
3x28pl43C3	5915	2532	2367	5763	16234
3x28se13C3	6024	2591	2484	6055	16552
3x28se23C3	5516	2415	2457	5989	15384
3x28sp23C3	5647	2402	3180	7806	15250
3x28sp33C3	5582	2391	1918	4648	15393
3x28SS43C3	5553	2303	2688	6611	15227
3x28su13C3	5772	2568	2933	7178	16189
3x28ti13C3	4660	2294	2175	5297	14689
3x28ti23C3	7797	5560	2825	6905	19492

FILENAME 2nd Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
3x28bas2C1	4792	1738	1683	4062	11980
3x28do12C1	6320	1867	1758	4231	15799
3x28do22C1	7802	2007	1828	4387	19505
3x28pl12C1	5546	2201	2674	6499	13865
3x28pl22C1	4516	1646	1126	2706	11290
3x28pl32C1	4170	1649	1771	4251	10423

FILENAME 2nd Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
3x28pl42C1	5442	1994	1589	3872	13604
3x28se12C1	4970	1800	1727	4160	12424
3x28se22C1	4597	1675	1645	3982	11492
3x28sp22C1	4879	1810	2145	5167	12196
3x28sp32C1	4648	1693	1192	2798	11621
3x28SS42C1	4622	1690	1784	4264	11554
3x28su12C1	4976	1878	2351	5681	12439
3x28ti12C1	4737	1858	1448	3504	11843
3x28ti22C1	5616	2034	2142	5124	14040
3x28bas2C2	5018	2014	1678	4036	12543
3x28do12C2	6923	2168	1764	4227	17308
3x28do22C2	8891	2342	1854	4431	22226
3x28pl12C2	6210	2400	2680	6502	15526
3x28pl22C2	4467	1640	1103	2610	11167
3x28pl32C2	5849	2285	1769	4234	14623
3x28pl42C2	5371	2014	1574	3787	13426
3x28se12C2	5350	2081	1714	4113	13374
3x28se22C2	4685	1863	1637	3941	11712
3x28sp22C2	5459	2146	2196	5290	13647
3x28sp32C2	4798	1912	1220	2853	11994
3x28SS42C2	5199	2060	1827	4379	12996
3x28su12C2	5856	2250	2384	5760	14640
3x28ti12C2	5041	1954	1466	3479	12601
3x28ti22C2	7654	2974	2219	5317	19135
3x28bas2C3	6507	2658	2790	6749	16266
3x28do12C3	26550	7761	7479	18573	66374
3x28do22C3	N/A	6780	18769	N/A	N/A
3x28pl12C3	20001	9851	10859	27044	50001
3x28pl22C3	5500	2189	1600	3754	13750
3x28pl32C3	27315	10189	7988	19881	68287
3x28pl42C3	6419	2495	2121	5075	16047

FILENAME 2nd Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
3x28se12C3	6389	2568	2967	7180	15972
3x28se22C3	6423	2597	2671	6436	16058
3x28sp22C3	6538	2605	3550	8627	16344
3x28sp32C3	5999	2359	2099	5000	14997
3x28SS42C3	6828	2710	2183	5192	17069
3x28su12C3	6694	2786	4669	11460	16735
3x28ti12C3	5580	2191	1621	3932	13951
3x28ti22C3	7538	3117	3522	8553	18845
3x28bas3C1	4834	1779	2840	7044	12085
3x28do13C1	6363	1865	2858	7076	15907
3x28do23C1	7868	1945	2952	7196	19670
3x28pl13C1	5154	1941	4000	9795	12884
3x28pl23C1	4526	1647	1866	4626	11314
3x28pl33C1	4004	1562	2894	7058	10008
3x28pl43C1	5444	2002	2687	6675	13609
3x28se13C1	4942	1825	2850	7061	12354
3x28se23C1	4687	1711	2813	6987	11717
3x28sp23C1	4811	1780	3408	8341	12028
3x28sp33C1	4635	1687	2038	4930	11587
3x28SS43C1	4630	1675	2990	7281	11575
3x28su13C1	4978	1821	3579	8880	12445
3x28ti13C1	4454	1759	2484	6163	11135
3x28ti23C1	5386	2086	3435	8359	13465
3x28bas3C2	4894	1908	2749	6787	12236
3x28do13C2	6632	2105	2844	6927	16579
3x28do23C2	8536	2290	2972	7224	21340
3x28pl13C2	5844	2279	4066	9972	14610
3x28pl23C2	4471	1642	1841	4494	11177
3x28pl33C2	5661	2227	2974	7242	14152
3x28pl43C2	5402	1999	2635	6544	13505
3x28se13C2	5091	2009	2782	6782	12727

FILENAME 2nd Dolly	FX (lbs)	FY (lbs)	FZ (lbs)	Mx (ft-lbs)	Mz (ft-lbs)
3x28se23C2	4574	1776	2729	6773	11435
3x28sp23C2	5079	2017	3519	8602	12698
3x28sp33C2	4656	1861	2054	4954	11641
3x28SS43C2	5079	2009	3039	7390	12698
3x28su13C2	5287	2063	3731	9148	13216
3x28ti13C2	4805	1893	2438	6047	12012
3x28ti23C2	7672	2988	3512	8532	19180
3x28bas3C3	6305	2572	4439	10838	15762
3x28do13C3	31240	9161	14190	35292	78100
3x28do23C3	N/A	23827	32786	N/A	N/A
3x28pl13C3	7224	2883	9314	23065	18058
3x28pl23C3	5335	2109	2717	6560	13337
3x28pl33C3	29025	9935	14039	34987	72561
3x28pl43C3	6083	2375	3579	8716	15206
3x28se13C3	6448	2636	4793	11732	16120
3x28se23C3	6537	2519	4246	10359	16342
3x28sp23C3	6376	2624	5221	12792	15938
3x28sp33C3	5831	2325	3279	7942	14578
3x28SS43C3	6286	2495	3622	8880	15714
3x28su13C3	6639	2608	7005	17247	16597
3x28ti13C3	5209	2066	2819	6890	13021
3x28ti23C3	11558	4783	14805	36771	28893

APPENDIX G

ECONOMIC ANALYSIS

ACCIDENT ANALYSIS

In the current study, it was possible to tap a number of new data resources in accomplishing a study of the accident savings that might be achieved through the use of innovative dollies. The Trucks Involved in Fatal Accidents (TIFA) file had added six more data years since the original UMTRI study of dollies for FHWA[1], roughly tripling the number of cases. The National Highway Traffic Safety Administration (NHTSA) was now making available the results from the General Estimates System (GES), a follow-on to the National Accident Sampling System (NASS) with more cases and better coverage of the overall accident population. Finally, data from the National Truck Trip Information Survey (NTTIS) made it possible to calculate accident rates for singles (tractor-semitrailer) and doubles (tractor-semitrailer-full trailer) combinations by road type, area type, and time of day. The availability of accident rate data thus allowed many differences in exposure and usage to be considered in a manner that would directly compare single and double trailer combinations. Because of the availability of new data, it was useful to revisit the analysis of the traffic safety benefits of innovative dollies. The objective primarily was to bring the analysis up to date with new and more complete data. In some cases, approaches taken earlier have been rethought and different ones are taken here. Also, the scope of the information on the costs of accidents is expanded.

Overall, the approach is the same as that taken previously. The objective was to determine the safety benefits of an innovative dolly. The most direct comparison would match the safety experience of A-dollies with that of C-dollies. Since there are currently no data on the operating experience of the innovative dolly in nationally representative accident files, however, it is impossible to measure directly the safety improvements that the redesigned dolly may produce.

The key to the accident analysis method is the observation that engineering analyses and full-scale tests show that innovative dollies will improve the stability of doubles so that they handle more or less like single tractor semitrailers (singles, in this discussion). The important dimensions of this improvement are in the yaw stability of the combination and its resistance to rollover. Innovative dollies are designed to approximate the lateral and roll stability characteristics achieved through fifth-wheel style couplings between trailers. Since doubles using the new dollies should handle similarly to singles, accident data collected on the tractor-semitrailer combination serve as a convenient surrogate for data actually showing the accident experience of doubles combination using the improved dolly.

The accident analysis is divided into three parts. In the first, the new or improved data sources for the analysis are described. The next section compares the accident experience of singles with that of doubles. Accident rates are compared for different operating environments, exposing differences in how singles and doubles operate as well as identifying environments where doubles are over involved. A particular focus is accident types that should be helped by the innovative dolly. In the final section, the economic benefits of the increased safety expected from the use of innovative dollies are estimated.

Data Sources

Three data sets—two accident files and one travel file—were used to estimate accident rates and accident frequencies for singles and doubles. The accident files derive from the TIFA file, produced and maintained by UMTRI, and the GES file, developed by the National Highway Traffic Safety Administration. TIFA data were used covering the years 1980 through 1988, documenting fatal accidents for all trucks having a gross vehicle weight rating (GVWR) over 10,000 pounds. The file provides extensive information on vehicle configuration as well as very accurate accident counts. GES is a sample file covering all levels of accident severity, allowing the analysis to be expanded beyond fatal accidents. The travel data used to calculate accident rates is from the UMTRI-sampled truck usage effort called NTTIS. The data from NTTIS provide detailed estimates of travel broken down by vehicle type, road type, area of operation (urban or rural), and time of day. The use of the NTTIS file, together with the nationally representative accident files, allows the calculation of involvement rates for selected vehicle types.

Data files from the Office of Motor Carriers (OMC), formerly the Bureau of Motor Carrier Safety (BMCS), and the National Accident Sampling System (NASS), developed by NHTSA, are used primarily in the section of this analysis in which we estimate the economic benefits of an improved dolly. The OMC file has information on accident costs of different types of accidents. These figures are used to calculate one part of the economic benefits of reducing or eliminating certain accidents. The NASS file is also used in that section to estimate savings in injury severity. These files will be discussed in more detail as their data are addressed in the presentation.

Trucks Involved in Fatal Accidents (TIFA). TIFA is produced by the Center for National Truck Statistics (CNTS) at UMTRI. In 1981, UMTRI initiated a survey of all large trucks involved in fatal accidents in the continental United States. 1980 was the first year covered. The survey combines information from the Fatal Accident Reporting System (FARS) of the U.S. Department of Transportation National Highway Traffic Safety Administration (NHTSA) with data from the Federal Highway Administration Office of Motor Carriers (OMC) MCS 50-T report, state police accident reports, and comprehensive follow-up telephone interviews conducted by UMTRI research staff. The end-product is the TIFA file. At the time of this study, the TIFA was complete for accident years 1980 through 1988. The dataset provides detailed descriptions of medium and heavy trucks (greater than 10,000 lbs. gross vehicle weight rating, GVWR) involved in a fatal accident in the United States, excluding Alaska and Hawaii. Pickup trucks, vans, and utility vehicles are excluded from the file, as are fire trucks and passenger vehicles such as buses and ambulances.

For data years 1980 through 1986, TIFA is a census file, meaning that it contains records for all medium and heavy trucks involved in a fatal accident. Data years 1987 and 1988 include some limited sampling, such that the raw number of cases is about 1,000 records fewer in each year than if all cases had been taken. Appropriate weights have been determined that allow national population totals to be estimated. Statistical work has shown that the sampling has had little effect on the accuracy of estimates from the files. The 1980–88 TIFA file contains records on 44,162 trucks, with a weighted total of 46,654 vehicles.

Cases for TIFA are originally identified by subsetting medium and heavy trucks from the FARS file. FARS includes a long list of variables about the accident environment, the events of the accident, and the people involved. Detail about the vehicles involved is limited. The FARS Accident, Vehicle, and Person variables relating to the truck are all incorporated into the TIFA file. The MCS 50-T report includes a detailed physical description of the involved truck. Carriers engaged in interstate commerce are required to file an MCS 50-T report with the OMC on any accident involving a truck that involves a fatality, injury, or property damage above a certain value. The first step in building the TIFA file is to match cases subset from FARS with the matching MCS 50-T report. Where cases match, most of the OMC variables are incorporated into the TIFA file. However, the matching process only accounts for about one-third of the FARS cases. For the remaining two-thirds, a follow-up telephone survey is conducted to collect a detailed physical description of the involved truck. The information collected in the telephone interviews includes all the variables from the MCS 50-T along with some additional detail. The object of the work is to produce a file that combines the accident level information of FARS with the physical detail of OMC, for every large truck involved in a fatal accident.

Every case produced by the telephone survey is subjected to extensive editing to ensure the accuracy and completeness of the data. The VIN (vehicle identification number) is decoded to identify the vehicle and the physical description from the phone interview is compared with manufacturer's specifications. Inconsistencies or contradictions are resolved by further interviews, whenever possible. Computerized consistency checks are made on the entire file. Where problems are found with the OMC cases, calls are made to resolve them. The result is a file with a low rate of missing data.

In the 1980–88 file, for example, the variable, "combination type" could not be identified for only 0.3 percent of the tractors. Given the extensive checking and verification of data, the description of vehicles and accidents in TIFA is believed to be unusually high in reliability among all mass files of accident data.

The 1980–88 file provides much larger sample sizes than were available in the previous analysis. There are 29,917 tractor-semitrailers and 1,704 doubles combinations in the nine-year file. The earlier analysis used the 1980–82 TIFA file, which had 9,914 singles and 448 doubles. The added sample size should clearly enable a more reliable statistical estimate of accident experience, comparing singles versus doubles.

The General Estimates System (GES). The General Estimates System (GES) is a probability-based sample of police-reported accidents. The GES file was developed by the National Highway Traffic Safety Administration (NHTSA) as a follow-on to their National Accident Sampling System (NASS). The NASS file is also a probability sample of police-reported accidents that is intended to be nationally representative. Unlike GES, NASS includes an ambitious list of accident variables, primarily directed at injury studies, which are gathered by investigative teams sent to each sampled accident. The NASS file includes a relatively small number of cases for large trucks because the investigations are so detailed. Consequently, sampling errors for the file are large. To remedy this and improve the accuracy of national estimates of accident totals, GES was designed to include many more cases for a much shorter list of variables. The variables for GES are coded exclusively from police accident reports. The first year of GES was 1988. Files through 1990 were available for this study.

GES uses a three-stage sampling protocol similar to that of NASS. In the first stage, the U.S. is divided into Primary Sampling Units (PSUs) and the PSUs are grouped by geographical region (Northeast, South, Central, and West) and type (large central city, large suburban areas, and other). Police jurisdictions are sampled within the geographical areas during the second stage. Finally, GES investigators periodically visit the sampled police jurisdiction and select cases for inclusion in the GES file. Accidents are classified into three groups (involving a towed vehicle, not involving a towed vehicle but including an injury, and other) and a random sample of cases is drawn from each group. In 1990, changes were implemented to increase the sample of large trucks. The GES variables were then coded from the selected police reports. Unlike NASS, there is no further investigation beyond the police report, itself.

Though sample sizes are larger than NASS, all available years of GES were used in the accident analysis. When the three years are combined, there are records for 4,790 singles and 177 doubles. This compares to the 2,700 cases in four years of NASS used in the previous analysis. Moreover, while NASS focused on crashworthiness issues, GES is explicitly designed to be nationally representative of the accident population.

National Truck Trip Information Survey (NTTIS). NTTIS was conducted by UMTRI in 1985–87. The objective was to estimate the number of large trucks in the U.S. and provide detailed data on their mileage and travel patterns. The survey was designed to provide travel estimates appropriate for calculating accident rates using the TIFA file. The same truck, configuration, and other definitions were used in both so that appropriate travel and accident data could be matched.

NTTIS was carried out via multiple telephone interviews with truck owners to collect data on the use of their vehicles on particular days. The sampling frame for NTTIS was formed from registration files maintained by the R.L. Polk Company. Versions of these files reflecting registrations as of July 1, 1983 were used, and the files were extensively processed to eliminate duplicate registrations from state to state. A total of 8,144 trucks was selected from the Polk registration lists to form the sample for the survey.

Once the sample was drawn, the survey work was carried out in two phases. During the implementation phase, conducted from January to May of 1985, each truck selected in the sample was located, and a description obtained. Survey interviewers tried to contact the most knowledgeable person available for implementation information. Once the initial contact was made, interviewers secured the owner's cooperation, confirmed the vehicle's identification, obtained descriptive information on the company and truck, and arranged to acquire detailed mileage information on four random survey days.

During the trip phase of the survey, supplemental information was gathered about the 5,112 vehicles selected for trip calls. Most of the trip phase of the survey was devoted to collecting detailed information on the routes traveled by the selected vehicles and on the truck configuration, cargo, driver, and operating authority. Tractor trip calls ran from November 1985 through November 1986. The travel data were collected according to trips. A new trip began whenever driver, operating authority, vehicle configuration (e.g., adding or changing trailers), or cargo type or amount changed. Thus if the driver changed, or cargo was loaded or unloaded, or one trailer type was exchanged for another, the interviewer began a new trip form to track the mileage travel of the new configuration. For each survey day, the owner was asked to describe every trip made and to provide information on trailer use (if any), cargo and cargo weight, and driver age. The trips were traced on specially prepared maps and the mileage broken down by road type, rural/urban, and day/night. This methodology allows trip mileage to be aggregated across different travel categories for truck configurations of interest.

Roads were divided into limited access highways, major arteries, and all other roads. The limited access roads include all U.S. interstate highways, as well as state highways with fully controlled access. Major arteries include all U.S. and state routes that are not limited access, plus some other primary thoroughfares in large urban areas. All public roads that do not fall in the previous two categories comprise the “other” road type group.

Areas were classified according to Federal Highway Administration definitions of population type. Areas with a population of more than 5,000 are considered urban; areas with a population less than 5,000 are classed as rural. Time of day was divided into daytime, defined as 6:00 am to 9:00 pm, and nighttime, 9:00 pm to 6:00 am.

The vehicles selected for trip calls took a total of 13,097 trips, 4,966 by straight trucks and 8,131 by tractors. The trips were traced as defined above. The straight trucks traveled a combined 206,276 miles, and the tractors logged 707,000 miles, for an overall total of 913,276 miles. Weights included in the file allow national estimates of travel by many factors of interest. Accordingly, NTTIS provides the appropriate travel information to calculate fatal accident rates by truck configuration and operating environment.

Validating Data Sources

At the time of this study, no nationally representative accident data file existed that could provide all the needed variables with sample sizes large enough to be statistically reliable. The TIFA file covers fatal accidents comprehensively but does not cover all the accident types of interest. GES includes all accident severities, including injury and property-damage-only accidents, but GES and TIFA do not agree on, for example, the number of fatal truck accidents. Accordingly, it is necessary to evaluate the two files with a view toward reconciling them and putting together a composite file that draws on the strengths of each.

First, however, a few words on why the NASS and OMC (formerly BMCS) files will be used only as supplements. NASS dropped truck accidents from its collection protocol in 1986. Since the focus of NASS was always on passenger car accidents, not trucks, the size of its truck accident sample is small, resulting in large variances for estimates of frequencies and proportions, particularly for minority configurations like doubles. GES was explicitly conceived to produce much larger sample sizes and more reliable population estimates. So GES is a natural replacement for NASS in this work.

GES is also an appropriate replacement for some uses of the OMC file. The OMC file consists of carrier-reported accidents that achieve a certain threshold, currently $4,400, of property damage or include an injury or death. Only interstate carriers are required to file reports with the OMC, so the file provides only partial coverage of truck accidents. Moreover, OMC suffers from underreporting of accidents. Among fatal accidents, which should constitute the most completely reported set, only about 70 percent of reportable accidents are in fact reported. It is expected that nonreporting is higher in less severe accidents. Moreover, the high property damage threshold leads to bias in the proportion of certain accident types. For example, the proportion of rollovers among property damage accidents are high since a truck rollover will almost always incur a damage loss greater than $4400. Calculating the percent-rollover figure from the OMC file thus gives an overestimate of the proportion of such rollovers, even if reporting is perfect.

One problem with using TIFA and GES together is that GES estimates smaller numbers of fatal singles and doubles accidents than TIFA. The average number of singles involved in fatal accidents for the three years of GES, 1988–90, is 2,769, and the average number of doubles involvements is 108. Using TIFA data, the average number of singles involvements for the three most recent years, 1986–88, is 3,317, with a corresponding doubles involvement rate of 232. Given the comprehensiveness of the TIFA file, and the numerous checks to ensure its accuracy, the TIFA file is considered to be the authoritative source. Accordingly, the TIFA values were used in this study to obtain estimates of the number of fatal accidents.

The next step in estimating the total number of accidents is to consider the number of injury and property-damage-only (PDO) accidents. GES estimate for the number of fatalities is low by the TIFA yardstick, but, while the frequencies may be low, the proportions of different accident types are reasonable. Table G-1 below shows the ratio of fatal to injury to PDO accidents in GES, 1988–90. The order of the numbers seems correct, namely there are more PDOs than injury accidents and more injury accidents than fatalities, but the ratios are not the same for singles and doubles.

Table G-1. Ratio of accident severity for singles and doubles 1988–90 GES data

	Single	*Doubles*
PDO	38.27	15.97
Injury	13.17	9.82
Fatal	1.00	1.00

The same ratios in the 1980-82 NASS data are 36:16:1 for singles and 10:17:1 for doubles. The doubles ratio indicates substantially more injury accidents than PDOs, which is not a credible finding. The GES ratios are far more reasonable. Moreover, there are methodological reasons for preferring the GES ratios. The GES file is based on substantially more data than NASS. The sampling procedures are similar, but GES takes many more cases. Finally, GES is coded from police reports, while NASS is based on an extensive follow-up investigation. The result is that GES has much lower missing data rates. In the case of NASS, it is likely that some of the vehicles have left the scene before the investigators can arrive. There is a greater chance of this outcome in minor accidents, particularly for long-distance freight haulers, thus perhaps partially explaining the underreporting of damage-only accidents by NASS.

In sum, the GES ratios of PDOs to injury to fatal accidents are the best available. These ratios are used to estimate the total number of accidents in this report.

Comparison of Accident Rates and Frequencies

Table G-2 shows the estimated number of involvements by accident severity for singles and doubles. The number of fatalities comes from TIFA, from 1986 to 1988. The number of PDOs and injury accidents is determined by applying the GES ratio to the TIFA number of fatalities. These numbers will be used as the best available estimates of the true number of accidents for singles and doubles.

Table G-2. Estimated number of involvements (annualized) by combination type and accident severity 1986–88 TIFA data for fatalities, 1988–90 GES data for ratio of PDO/injury/fatal

	Single	*Doubles*
PDO	126,942	3,695
Injury	43,685	2,278
Fatal	3,317	232
Total	173,944	6,205

Table G-3 shows travel, fatal involvements, and involvement rates for singles and doubles by eight travel categories. The travel categories are formed by all combinations of road type (limited access/other), time of day (day/night), and area type (urban/rural). The percent columns for both singles and doubles are column percents and show the portion of travel in each category. The mile totals are annualized. The fatal involvement numbers and the involvement rates are totals for the overall time period of the data files. The involvement rate column is determined by dividing the percent of involvements by the percent of travel. The involvement rate for the overall data set is 1.0. Involvement rates less than one are underinvolved; rates over one are overinvolved. TIFA data used are limited to the period 1980–86 in these computations since the NTTIS exposure data were collected in 1986. Also, model years after 1983 were excluded from the TIFA data since NTTIS sampled registration files as of the registration year 1983.

Overall, the rates of singles and doubles are roughly comparable, with doubles being slightly underinvolved at a rate of 0.91. Doubles are underinvolved in all the travel cells that include limited access roads and overinvolved on other roads. That overall doubles do as well or possibly better than singles is in part because they operate most of the time on limited access roads. Of the doubles total of 1.935 billion miles, almost 1.4 billion (72 percent) are accumulated on limited access roads, which are the safest in the highway system. In contrast, only about 58 percent of singles miles are on limited access roads.

Table G-3. Travel, fatal involvements, and involvement rates singles and doubles, NTTIS and 1980–86 TIFA data

Travel Category	*Miles (10^8)*	*Percent*	*Fatal Involvement*	*Percent*	*Involvement Rate*
			Singles		
Limited/day/rural	96.78	27.5	1,672	7.6	0.28
Limited/day/urban	52.05	14.8	1,462	6.6	0.45
Limited/night/rural	31.44	8.9	1,734	7.9	0.88
Limited/night/urban	13.71	3.9	1,040	4.7	1.21
Other/day/rural	84.47	24.0	8,076	36.6	1.52
Other/day/urban	36.74	10.4	2,497	11.3	1.08
Other/night/rural	13.33	3.8	3,379	15.3	4.04
Other/night/urban	3.77	1.1	1,095	5.0	4.63
Single Subtotal	332.28	94.5	20,955	95.0	1.01
			Doubles		
Limited/day/rural	5.36	1.5	90	0.4	0.27
Limited/day/urban	3.47	1.0	82	0.4	0.38
Limited/night/rural	3.09	0.9	135	0.6	0.70
Limited/night/urban	2.04	0.6	88	0.4	0.69
Other/day/rural	2.27	0.6	361	1.6	2.53
Other/day/urban	1.47	0.4	103	0.5	1.12
Other/night/rural	1.27	0.4	197	0.9	2.48
Other/night/urban	0.39	0.1	52	0.2	2.11
Double Subtotal	19.35	5.5	1,108	5.0	0.91
Grand total	351.63	100.0	22,063	100.0	1.00

Table G-4 illustrates the magnitude of the road-type problem more clearly. In table G-4, the eight exposure cells are collapsed into just two—limited access and other roads. Doubles clearly have many more problems when they operate off limited access roads. On limited access roads, the doubles involvement rate is comparable to that of singles. On other roads, however, the doubles rate is significantly higher, 2.11 compared to 1.73 for singles. The good overall showing of doubles appears to be related to the disproportionate amount of time they spend on interstate-quality roads.

Table G-4. Travel, fatal involvements, and involvement rates by road type, singles and doubles, NTTIS and 1980–86 TIFA data

Road Type	*Miles (10⁸)*	*Percent*	*Fatal Involvement*	*Percent*	*Involvement Rate*
Singles					
Limited Access	193.97	55.2	5,908	26.8	0.49
Other	138.30	39.3	15,047	68.2	1.73
Single Subtotal	332.28	94.5	20,955	95.0	1.01
Doubles					
Limited Access	13.96	4.0	395	1.8	0.45
Other	5.40	1.5	713	3.2	2.11
Double Subtotal	19.35	5.5	1,108	5.0	0.91
Grand Total	351.63	100.0	22,063	100.0	1.00

Table G-5. Travel, fatal involvements, and involvement rates by time of day, singles and doubles, NTTIS and 1980–86 TIFA data

Time of Day	*Miles (10⁸)*	*Percent*	*Fatal Involvement*	*Percent*	*Involvement Rate*
Singles					
Day	270.03	76.8	13,707	62.1	0.81
Night	62.24	17.7	7,248	32.9	1.86
Single subtotal	332.28	94.5	20,955	95.0	1.01
Doubles					
Day	12.56	3.6	636	2.9	0.81
Night	6.79	1.9	472	2.1	1.11
Double subtotal	19.35	5.5	1,108	5.0	0.91
Grand Total	351.63	100.0	22,063	100.0	1.00

Tables G-5 and G-6 show similar splits by time of day and the type of geographic area, respectively. Table G-5 shows that both singles and doubles have higher rates at night, although the increase in the rate is less extreme for doubles. In general, night is expected to be associated with higher rates because of driver fatigue, shorter sight distances, conspicuity problems, etc. Doubles may do better than singles at night because more of their night travel is on limited access roads. Doubles involved in long-haul freight are also more likely to be operated on regularly scheduled routes where the driver has essentially the same schedule every day.

Differences by area type (table G-6) are not marked. Doubles have higher fatality rates in rural areas than urban, 1.04 compared with 0.70. Speeds are typically higher in rural areas, increasing the chance of a fatality, given an accident. The rates for singles and doubles are virtually identical in rural areas. The accident rate of doubles is slightly lower in urban areas.

Table G-6. Travel, fatal involvements, and involvement rates by area type, singles and doubles, NTTIS and 1980–86 TIFA data

Area Type	*Miles (10^8)*	*Percent*	*Fatal Involvement*	*Percent*	*Involvement Rate*
			Singles		
Urban	106.27	30.2	6,094	27.6	0.91
Rural	226.01	64.3	14,861	67.4	1.05
Single subtotal	332.28	94.5	20,955	95.0	1.01
			Doubles		
Urban	7.37	2.1	325	1.5	0.70
Rural	11.98	3.4	783	3.5	1.04
Double subtotal	19.35	5.5	1,108	5.0	0.91
Grand Total	351.63	100.0	22,063	100.0	1.00

When accidents more clearly related to stability and control issues are considered, the differences between singles and doubles become sharper. Table G-7, for example, shows rates by road type for fatal involvements where the truck rolled over. Overall, the rollover rate for doubles is significantly higher than that for singles, 1.20 compared to 0.99. Clearly, doubles as currently configured have greater propensity to roll over than singles. On limited access roads their rollover rates are more equal—0.70 for doubles compared to 0.61 for singles. On other types of roads, doubles exhibit the much higher rollover involvement rate, 2.49 compared with 1.52.

Interestingly, rollover involvement rates for doubles at night are lower than that for singles at night. About 75 percent of doubles nighttime travel is on limited access roads. During the day, when traffic densities are higher, the doubles rollover involvement rate is

Table G-7. Travel, rollover fatal involvements, and involvement rates by road type, singles and doubles, NTTIS and 1980–86 TIFA data

Road Type	*Miles*		*Fatal*		*Involvement*
	(10^8)	*Percent*	*Involvement*	*Percent*	*Rate*
Singles					
Limited access	193.97	55.2	1,239	33.6	0.61
Other	138.30	39.3	2,200	59.7	1.52
Single subtotal	332.28	94.5	3,439	93.4	0.99
Doubles					
Limited access	13.96	4.0	103	2.8	0.70
Other	5.40	1.5	141	3.8	2.49
Double subtotal	19.35	5.5	244	6.6	1.20
Grand Total	351.63	100.0	3,683	100.0	1.00

Table G-8. Travel, rollover fatal involvements, and involvement rates by time of day, singles and doubles, NTTIS and 1980–86 TIFA data

Time of Day	*Miles*		*Fatal*		*Involvement*
	(10^8)	*Percent*	*Involvement*	*Percent*	*Rate*
Singles					
Day	270.03	76.8	2,168	58.9	0.77
Night	62.24	17.7	1,271	34.5	1.95
Single subtotal	332.28	94.5	3,439	93.4	0.99
Doubles					
Day	12.56	3.6	132	3.6	1.00
Night	6.79	1.9	112	3.0	1.57
Double subtotal	19.35	5.5	244	6.6	1.20
Grand Total	351.63	100.0	3,683	100.0	1.00

higher than that of singles. Rollover involvement rates are higher for both singles and doubles in rural areas than in urban. Higher traffic speeds are probably in large part responsible for this. Accidents or even accident-avoidance maneuvers are more likely to result in rollovers at higher operating speeds. Note also (table G-9) that the rural rollover involvement rate for doubles is significantly higher than that for singles.

Table G-9. Travel, rollover fatal involvements, and involvement rates by area type, singles and doubles, NTTIS and 1980–86 TIFA data

Area Type	*Miles* (10^8)	*Percent*	*Fatal Involvement*	*Percent*	*Involvement Rate*
			Singles		
Urban	106.27	30.2	629	17.1	0.57
Rural	226.01	64.3	2,810	76.3	1.19
Single subtotal	332.28	94.5	3,439	93.4	0.99
			Doubles		
Urban	7.37	2.1	45	1.2	0.58
Rural	11.98	3.4	199	5.4	1.59
Double subtotal	19.35	5.5	244	6.6	1.20
Grand Total	351.63	100.0	3,683	100.0	1.00

Thus far, the analysis has shown that doubles have an overall accident rate comparable to that of singles. This result seems related in large part to the relatively large fraction of doubles travel that is confined to limited access roads. When operating off limited access roads, doubles have significantly higher rates than singles. It is likely that some portion of this difference is due to stability-related differences. These differences include the propensity for rearward amplification and low rollover thresholds. Rollover accidents rates tend to distinguish between doubles and singles in a manner that matches the hypothesis arising from the study of differences in stability characteristics.

The earlier work indicated that doubles are overinvolved in single-vehicle fatal accidents. The original expectation was that, if doubles have more handling problems than singles, they should be overinvolved in single-vehicle accidents. With nine years of TIFA data, that finding no longer holds. Table G-10 shows that doubles have virtually the same proportion of single-vehicle accidents as singles. When all levels of accident severity are considered, however, (i.e., including injury and property-damage-only accidents, as well) doubles do have a higher proportion of single-vehicle accidents. Table G-11 uses data from the combined 1988–90 GES files. In that file, almost 32 percent of doubles accidents involve only one vehicle, while 24.6 percent of tractor-semitrailer accidents involve only one vehicle. Even if the relationship disappeared for fatal accidents, there still is some evidence of overinvolvement in single-vehicle accidents for doubles.

Table G-10. Tractor-trailer involvements by number of vehicles involved and number of trailers, 1980–88 TIFA data

Number of Vehicles	*Single*		*Double*	
Involved	*N*	*Percent*	*N*	*Percent*
Single Vehicle	6,077	20.3	351	20.6
Multiple Vehicle	23,838	79.7	1,353	79.4
Total	29,917	100.0	1,704	100.0
N	28,367		1,704	

Table G-11. Tractor-trailer involvements by number of vehicles involved and number of trailers, 1988–90 GES data

Number of Vehicles	*Single*		*Double*	
Involved	*N*	*Percent*	*N*	*Percent*
One vehicle	108,891	24.6	2,804	31.9
Multiple vehicles	333,485	75.4	5,994	68.1
Total	442,376	100.0	8,798	100.0
N	5,665		177	

The evidence is also somewhat mixed with respect to jackknifes, another accident type that is handling-related. In fatal accidents, doubles have an excess of both primary-event and subsequent-event jackknifes. About 6.0 percent of doubles fatal involvements have jackknife coded as the first event, compared to 4.3 percent for singles. For subsequent event jackknifes, the figures are 6.6 percent for doubles and 4.9 percent for singles. Jackknife is not broken down into primary and subsequent events in the GES file, but there doubles actually have a lower proportion of jackknife than singles, 6.1 percent to 8.6 percent.

With the A-dolly offering virtually no resistance to rollover of the full-trailer units, we note the possibility that a sudden maneuver may roll over the second trailer by itself.

Ideally, accident data files would include information on whether the trailers rolled over together or which trailer rolled over first. Unfortunately, currently available accident data do not include that information. However both the TIFA and the GES files do show that doubles have an excess of rollovers. Table G-12 shows primary and subsequent-event rollovers for singles and doubles using the 1980–88 TIFA file. Doubles have a lower proportion of primary event rollovers but a much higher proportion of subsequent event rollovers, given a fatal accident, than singles. The lower incidence of first-event rollovers that produce a fatality is probably explained by the fact that rollover of the last trailer in a doubles combination does not pose a direct threat to the life of the truck driver (whose tractor and lead trailer are still standing.) Nevertheless, with the substantially higher incidence of doubles rollovers, overall, more than 20 percent of doubles fatal involvements include rollover, compared to only about 15 percent for singles. GES does not separate rollovers into primary and subsequent event, but that file shows a similar pattern for all accident severities (table G-13). Doubles have over twice the proportion of rollovers compared to singles, 13.9 percent to 5.9 percent.

Table G-12. Tractor-trailer involvements by rollover and number of trailers, 1980–88 TIFA data

Number of Vehicles	*Single*		*Double*	
Involved	*N*	*Percent*	*N*	*Percent*
No roll	25,309	84.6	1,355	79.5
1st event	1,575	5.3	64	3.8
Subs. event	3,033	10.1	285	16.7
Total	29,917	100.0	1,704	100.0
N	28,367		1,704	

Rollover accidents tend to be more serious than nonrollovers, producing more injuries and deaths. Table G-14 shows the distribution of accidents by combination type (single or double) and rollover. Accidents are split into casualty and property-damage-only accidents. Cases with unknown accident severity are distributed proportionately among the knowns. Note that there are only 18 cases of doubles rollover. Keep in mind that these statistics are from the GES (General Estimating System), which sampled 18 actual doubles rollover cases in order to represent 1,227 cases in the full population of vehicles. More detailed splits cannot be supported in these data. Rollover accidents are more serious for both singles and doubles. The proportion of casualties in nonrollover accidents for singles is only 25.3 percent, less than half the proportion for rollover accidents. Doubles have higher casualty rates for both rollover and non-rollover accidents. There is an injury or fatality in 37.1 percent of non-rollover accidents. In cases where the vehicle rolls over, that proportion rises to 62.4 percent.

Table G-13. Tractor-trailer involvements by rollover and number of trailers, 1988–90 GES data

Number of Vehicles	*Single*		*Double*	
Involved	*N*	*Percent*	*N*	*Percent*
No roll	416,287	94.1	7,571	86.1
Rollover	26,090	5.9	1,227	13.9
Total	442,376	100.0	8,798	100.0
N	5,665		177	

Table G-14. Accident severity and rollover, singles and doubles, 1988–90 GES data

Frequency				
Accident	*Single*		*Double*	
Severity	*Roll*	*No roll*	*Roll*	*No roll*
PDO	11,972	310,655	461	4,749
Casualty	14,118	105,302	766	2,802
Total	26,090	415,957	1,227	7,551
N	438	5,227	18	159
Percent				
Accident	*Single*		*Double*	
Severity	*Roll*	*No roll*	*Roll*	*No roll*
PDO	45.9	74.7	37.6	62.9
Casualty	54.1	25.3	62.4	37.1
Total	100.0	100.0	100.0	100.0

Estimates of Benefits of Innovative Dollies

The rate calculations presented above show that there are differences in involvement between single- and twin-trailer combinations. Overall, the comparative rates are quite similar, but on roadways with more restrictive geometries, doubles tend to have higher involvement rates. We have seen that part of this difference is attributable to the tendency of doubles to rollover at higher rates than singles. The focus in this section will be on the benefits that would accrue from reducing the doubles rollover rate to a level equal to that of singles. While there may be other accident types with doubles that may be reduced by the use of advanced dollies, rollover is the clearest and most directly demonstrable.

The safety benefits to be estimated from eliminating excess rollovers come from two areas: 1) property damage and 2) injury severity reductions. In making this estimate, three separate calculations will be made. The first is the benefits to reducing doubles property-damage-only rollovers to a rate equal to that of singles. Since these accidents involve only property damage, it will be assumed that by eliminating the rollover, the accident is essentially eliminated and that all cost associated with the accident will be saved. The second benefit is reducing property damage in injury accidents. For this calculation, it will be assumed that the accident would have occurred anyway but that the property damage associated with the excess rollovers will be saved. The final area is the reduction in costs generated by the excess injuries associated with rollover accidents. If the vehicle does not rollover, injuries will be less severe, and the accompanying costs can be saved.

Table G-15 uses data from the combined 1988–90 GES file. The table is limited to PDO accidents. It shows that a higher proportion of doubles PDO accidents are rollovers than is the case with singles. Over 8 percent of doubles PDOs are rollovers, compared to 3.7 percent of singles. This would appear to implicate the rear-trailer-only rollover mechanism that is the peculiar propensity of the double.

Table G-15. Tractor-trailer involvements by rollover and number of trailers property damage only accidents, 1988–90 GES data

	Singles		*Doubles*	
No roll	306,107	96.3	4,749	91.8
Rollover	11,798	3.7	427	8.2
Total	317,905	100.0	5,176	100.0
N	2,956		93	

The frequencies in table G-15 are population totals from three years of data. As established earlier, GES underestimates the number of accidents. Table G-2 above revises GES annual estimates with the intention of more accurately representing the true number of singles and doubles accidents per year. Using the estimated number of doubles PDOs from table G-2 and the proportion of such rollovers from table G-15, it is estimated that there are 305 (.082 * 3695 = 305) PDO doubles rollovers annually. If doubles rolled over at the same rate as singles, there would be 137 PDO rollovers. Advanced dollies would thus eliminate the excess of 168 rollovers.

The OMC data is one source that can be used to investigate the cost of a property damage rollover. As part of the information reported to OMC, carriers estimate the value of total property damage in an accident. Though OMC data were found to be biased in some regards, the data on accident costs are satisfactory. The focus here is on average costs. Property damage from a rollover is expected to always exceed the reporting threshold, so underreporting with respect to other variables will not affect the validity of costs estimates. Combining the four most recent years of OMC data, 1987–1990, to achieve large and more stable sample sizes, the average property damage in a doubles rollover is $13,138. Eliminating 168 PDO rollovers would thus save $2,207,184 annually.

The estimate of $2,207,184 is conservative. Property damage of $13,138 seems low as an estimate of total property, including any cargo, damaged in a rollover accident. Instructions for the MCS-50T form indicate that all property damage in the accident is included, but it is possible that some carriers include only vehicle damage. Therefore, the true cost savings could be underestimated.

The next source of cost savings from eliminating rollovers by an advanced dolly is property damage in casualty accident rollovers. The proportion of rollovers in casualty accidents is taken from the TIFA data. Even with three years of data, sample sizes in GES are currently too small for this question. In the TIFA data (table G-12), 20.5 percent of fatalities involving doubles include rollover, while only 15.4 percent of single fatalities involve rollover. Using the annual casualty accident totals from table G-2 ((2278 + 232) x 20.5 percent = 514)), there are an estimated 514 doubles rollovers. If doubles in casualty accidents rolled over at the same rate as singles, there would be 386 rollovers, saving 128 rollovers annually.

Again, the OMC data is used to estimate the value of the extra property damage due to rollover in a casualty accident. For the period 1987–90 the average property damage in a casualty rollover was $22,560. The average property damage in a casualty accident where the doubles combination did not rollover was $17,003. Thus, eliminating the rollover is estimated to save $5,557. Eliminating the 128 excess rollovers in casualty accidents results in a savings of $711,297. Again, this estimate is almost surely conservative.

The final area to estimate is the dollar savings due to reductions in injury and death from rollovers. This analysis uses GES data to determine the overall proportion of rollovers for all accidents, split by singles and doubles. The proportion of rollovers (table G-13) for doubles is 13.9 percent; for singles, 5.9 percent. Applying these percentages to the figure for the total number of doubles accidents from table G-2, there are 862 doubles rollovers. If doubles rolled over at the same rate as singles, there would be 366 rollovers, or 496 fewer rollovers.

From table G-14, the probability of a casualty given a doubles rollover is 62.4 percent. For nonrollover doubles accidents, the probability of a casualty is 37.1 percent. Using these probabilities, the number of casualties saved if doubles roll over at the same rate as singles can be calculated. Given that the probability of a casualty is 62.4 percent, there should be 310 casualties among the 496 rollovers that can be eliminated. If none of those 496 rolled over, they would presumably have the injury severity distribution of nonrollover accidents, producing 184 casualties. Thus, the number of casualties eliminated by using innovative dollies would be 126. Note that this makes the conservative assumption of only one injury or fatality per casualty accident.

These are average casualties, not further broken down by severity. Currently, a more detailed break-down of injury severity in doubles rollovers is not possible in GES because there is not sufficient sample size. However the NASS file does have enough information for singles, so the distribution of injury severity for singles will be used to make inferences for doubles. This distribution should not be too far from the real distribution, and in any case, should be a conservative underestimate of the real accident severity distribution since doubles accidents tend to be more severe than singles accidents. The other reason for using the NASS dataset in this instance is that NASS codes injuries in terms that can be used to estimate the social costs of injury. The most current source for estimating the social cost of traffic injuries is the recent work of Miller [12]. Cost estimates for injury in Miller are presented by AIS (abbreviated injury severity) code. NASS is the only available data source that uses the AIS coding. A combined file for 1983–86 is used in the present analysis.

In table G-16, the first column shows the Maximum Abbreviated Injury Severity (MAIS) code. The next column shows the distribution of injuries by MAIS code among singles accidents in the 1983–86 NASS data. The next two columns show estimated costs (from Miller) for an injury of a given severity. Two means of estimating costs are shown. Direct costs include the costs of medical care and emergency services, lost wages and household production, costs for workplace disruption, insurance costs, and legal proceedings. Comprehensive costs include the direct costs but add costs for pain and suffering [12]. The costs of pain and suffering are determined by considering the amount people are willing to pay to avoid a given injury. In effect, including this measurement of pain and suffering estimates the social cost of a given injury. Costs per casualty are calculated by summing over all injury severities the cost of a particular injury times the proportion of that injury. In effect, this is a weighted average cost of injury, weighted by the proportion each injury is of all truck injuries. The total direct cost is $30,749 per casualty. The social costs of a casualty are estimated to be $128,024.

Table G-16. Estimated direct and comprehensive costs of casualty accidents by MAIS code

MAIS	*Percent*	*Direct Cost*	*Comprehensive Cost*	*Direct Total*	*Comprehensive Total*
1	0.72	2,788	5,581	2,011	4,025
2	0.16	21,065	97,905	3,304	15,354
3	0.08	69,896	360,794	5,380	27,769
4	0.02	133,328	917,488	2,024	13,928
5	0.01	511,438	1,906,113	4,662	17,373
fatal	0.02	643,962	2,387,879	13,369	49,575
Total cost per casualty (N = 944)				$30,749	$128,024

These estimates are conservative in that they assume only one injury per accident. Moreover, they use the distribution of injury severity from singles while there is evidence that doubles accidents are more severe. Nevertheless, they represent a reasonable estimate of the costs of injuries. The savings in direct costs of eliminating 126 casualties by eliminating 126 excess doubles rollovers is $3,874,374. If the social costs of injury and fatality are considered, the cost savings in lower injury rates from advanced dollies is $16,130,024.

In sum, the total cost savings from the use of innovative dollies is $6,792,855, considering just the direct costs of injuries and property damage. If the larger social costs are included, the total cost savings are $19,049,505. If the social costs are related to the table G-3 travel rates of 19.35 x 10^8 miles traveled annually by all doubles, the potential cost savings from eliminating doubles rollovers is $.0098 per dolly mile.

FINANCIAL ANALYSIS

During the process of conducting informal surveys for this study, an interesting amount of anecdotal information was gathered. One truck driver related a story of driving through a ditch (to avoid a car spinning on ice) then back up onto the road again with a set of double fuel oil tankers connected by a massive roll-limited A-dolly. He was sure he would have lost the whole rig had he been running a standard A-dolly. A similar situation was reported by a fleet owner where use of a C-dolly on the downhill side of an icy mountain allowed the driver to keep the rig under control while slowing. In a similar situation, this same owner experienced an accident with an A-dolly. These stories are interesting but very difficult to put hard numbers to for analysis.

One source of more concrete data is from a relatively small trucking company in the Pacific Northwest. This company regularly operates 24 C-dollies in more difficult than average service with an annual mileage of 125,000 miles (200,000 km) per rig. With A-dollies they had been experiencing an accident rate of 1 in 250,000 miles (400,000 km). With the C-dollies, their accident rate has dropped to 1 in 1,500,000 miles (2,400,00 km). If this reduction in involvement rates was applied to the national fleet data, accident involvement rates listed in table G-2 plus the accident costs indicated earlier would yield an increase in the potential savings to $0.17 per dolly mile. This is roughly 20 times the savings of $0.008 per dolly mile predicted by the rigorous national database analysis and a conservative set of assumptions. While it is not likely that the national fleet, with over 70 percent of its travel logged on limited access highways in better environmental conditions than that experienced by the mentioned fleet, these data certainly support looking at a range of accidents savings of up to $0.016 per dolly mile.

Another source of accident cost data comes from a very rough rule of thumb used by one insurance underwriter. The rule says that large trucking companies spend approximately 1.5 percent of their gross revenues on insurance and accident loss costs. When this figure is applied to the fleet of one company representative of a large trucking operation that primarily uses doubles, the insurance and accident costs are $0.063 per dolly mile. If 5.9 percent (average of the excess rollovers estimated in the database analysis) of doubles accidents were eliminated through the use of innovative dollies, a company in this class would save $0.0037 per dolly mile.

These additional analyses of accident savings provide a range of values to use in the overall economic analysis and, perhaps more significantly, show that the national accident database analysis is within a believable range and probably conservative.

Introduction

Objective

The economic analysis is designed to determine if the benefits of introducing innovative dollies into a fleet that uses conventional A-dollies outweigh the costs. To avoid dealing with too many variables, an Auto Steering C-dolly will be compared to standard A-dollies in the analysis. Most other innovative dollies fall somewhere in between the two dolly types in price, weight, performance, and other characteristics. Those characteristics that tend to control the economics will be evaluated further for the different types of dollies.

Approach

The 1986 study of innovative dollies [1] was used as a benchmark and format basis. This analysis is a condensed version of that done previously with similarities and differences described but without the background philosophy being restated. The reader is referred to the previous report to put this analysis into full perspective.

Innovative dollies remain relatively rare hardware items in the doubles segment of the trucking industry. As such, related operational information is still somewhat limited. The majority of advanced dolly usage is in Canada where federal and provincial regulations favor C-dollies and other innovative dollies in certain applications. Updated information from these fleets was used in this analysis with due consideration being given to the regulatory factor.

Method of Analysis

The financial model used previously [1] was used again with current data and costs. The sensitivity analysis involves changing the values of various parameters to determine their impact on a baseline or reference situation. Key parameters are identified by their ability to affect significantly the results of the analysis through small variations in their values. A sensitivity analysis helps to identify the important parameters and the key issues associated with the parameters.

None of the operators surveyed keeps extensive data on the operational costs and benefits of using advanced dollies. Most of the collected information involved pieces of hard numerical data mixed with anecdotal information. This information was used to modify the baseline and range values of the independent variables in the financial model to revisit operating cost sensitivities.

Data Gathering

Users and manufacturers of innovative dollies were contacted and requested to fill out an informal questionnaire relative to this study. Questionnaires were mailed to 24 manufacturers and 31 users of innovative dollies. Only 5 of the total of 55 organizations responded by mail. In order to amass a reasonable amount of data for this analysis, a telephone survey was begun. The number of responses grew to 16 viable manufacturers and 14 users. The phone survey had the advantage of getting to the right person but the disadvantage of limiting the quantity and quality of data collected to the attention span of a telephone conversation, typically about one-half hour.

Financial Model

Type of Analysis

The model determines the financial effects of using an innovative dolly as an alternative to the conventional A-dolly. The cash flows (where costs are negative cash flows or an outflow of cash and benefits are positive cash flows or an inflow of cash) are defined as an increase or decrease in the operating cost due to the use of an innovative dolly instead of an A-dolly. For example, the model projects higher annual preventive maintenance costs (see "Assumptions Concerning Economic Issues") for every innovative dolly added to the fleet. There is also an additional investment due to the extra cost incurred in buying an innovative dolly instead of an A-dolly. In other words, the model analyzes the future *incremental* cash flows resulting from an *additional* investment made today.

Life of the Project

The life of the project (over which cost increments due to the change in dolly types is to be computed) is assumed to be ten years to keep it comparable to the previous study.

Assumptions Concerning Economic Issues

The following parameters, which are assumed to increase or decrease the cost of operation, are used in the financial model. The background of the parameters is discussed in the previous study [1]. Differences between values used in that study and those presently used are described.

- Initial cost of the dolly—A base C-dolly is assumed to cost $5,500 more than a conventional A-dolly. This assumption is based on the fact that a typical single-axle A-dolly (with wheels and tires) costs $5,500 and the latest design C-dolly (with wheels and tires) costs $11,000. Volume discounts could reduce these prices by 5 to 20 percent. Options and special features could increase the cost a like amount. Other advanced dollies, such as linked-articulation A-dollies and solid axle (non-steering) C-dollies fall in between the standard A-dolly and C-dollies in cost and performance. The controlled-steer C-dolly, previously referred to as the CSB-dolly (1) was not included in this analysis due to its prototype nature.
- Converting existing equipment—At least one semitrailer must be modified for every C-dolly purchased. Many owners that have both A- and C-dollies in their fleet modify all their trailers and have three pintle hooks for using either type of dolly. The average cost of installing two additional pintle hooks (which cost about $700), and frame-stiffening the semitrailer's chassis costs approximately $600. A combination of certain trailer types requiring additional reworking of the frame and shops unfamiliar with doing this type of work could drive the cost of installation to $1,500. The total cost is likely to be between $1,300 and $2,200.

The financial model retains the feature that analyzes the elimination of yard tractors for over 60 trailer moves (30 doubles combinations) a day. This effect only comes into play if 60 or more advanced dollies are purchased or entered into a fleet.

- Major overhauls—Canadian operators of both A- and C-dollies believe that C-dollies must undergo a major overhaul twice as often as A-dollies. A U.S.

manufacturer keeps tabs on a number of its operators and believes 400,000 miles (640,000 km) is a reasonable figure for major overhauls. The industry standard used in the previous study was to overhaul an A-dolly every 500,000 miles (800,000 km) and a C-dolly every 250,000 miles (400,000 km). With an improving reliability record for C-dollies, the overhaul point used in this study is 350,000 miles (560,000 km) with a possible variable range of 50,000 miles (80,000 km). As an overhaul includes, among other things, fifth wheels, drawbar eyelets, steering systems, brakes, and springs, the cost of a major overhaul is kept as a variable and is defined as a percentage of the initial cost of the dolly. This cost is assumed to include factors related to both the time and materials for maintenance and the service time lost during maintenance.

- Preventive maintenance—The cost of regular maintenance such as inspection and lubrication depends upon the size of the fleet and the frequency at which maintenance is done. In previous studies, the general opinion was that maintenance costs of the CSB-dolly was twice that of A-dollies. For the more common C-dollies, that difference is reduced by half.
- Tire wear—During normal operation, the tires on conventional dollies last for 120,000-130,000 miles (190,000-208,000 km). Tire scrubbing on C-dollies used more often in local operations tends to wear tires 10-15 percent faster. The analysis looks at range of tire wear criteria to determine costs from excess tire wear. Tire costs were assumed to average $1,100 for a set of radials to a fleet operator.
- Scheduling costs—Scheduling varies across truck fleets, and practices are dependent on the size of the operation. Some large operations have delegated most of the scheduling exercise to computer programs that route tractors, semitrailers, and dollies according to variables such as trip length and freight being hauled. On the other hand, fleets with fewer units are more comfortable maintaining scheduling as part of the day-to-day administration of the trucking operation.

Since many owners modify all or most their trailers with three pintle hooks for using either type of dolly, scheduling is not a major problem. Moreover, present versions of the linked-articulation dolly involve permanently married trailers, changes in scheduling costs are assumed to be negligible. CSB-dollies, however, introduce another variable into the scheduling problem, where dollies and semitrailers stop being completely interchangeable. Thus, there is bound to be an increase in scheduling costs. It is assumed, however, that there is a learning curve associated with the scheduling process, and the increase in cost will disappear over time. In addition, CSB-dollies are not a significant portion of the innovative dolly fleet, so consideration of that type of scheduling cost is not significant.

A complete changeover from A- to C-dollies would not affect the process of scheduling. If, however, half of the total number of dollies are C-dollies, then the increase in scheduling costs is assumed to be at its maximum, but for a short period. To account for this trend, the model assumes a triangular distribution in which scheduling cost varies as a percentage of the C-dollies in the fleet. The model assumes a single expense to update computer programs and any scheduling-related data bases.

- Training/loss of productivity—To address the fact that drivers and yard personnel must deal with a new piece of equipment, the model accounts for training and a cost associated with a temporary loss of productivity. The increase in time required to hitch a C-dolly is a specific example of a loss of productivity. Operators of C-dollies believe that, with some relatively rare exceptions (such as hitching on uneven yard surfaces), hitching C-dollies could become as routine as hitching A-dollies. Furthermore, new C-dolly designs with swiveling hitches are reported to be easier to hitch than A-dollies. The model uses a short learning curve to account for the temporary nature of this cost.
- Backing up—Assembling and disassembling double-trailer combinations is a time-consuming task. Since it is difficult to back up A-dolly-equipped doubles, drivers of such vehicles require an intermediate staging area to drop and maneuver both trailers into their loading docks. Depending upon the distance from the loading dock to the staging area, the entire process of assembling and disassembling a set of double trailers could take up to an hour of the driver's time. A more realistic estimate of the extra time required to maneuver an A-dolly-connected set of doubles is fifteen minutes.

Assuming that the driver has enough space to maneuver both trailers, the C-dolly, by eliminating an articulation joint, gives the driver the ability to back up both trailers to their loading docks without using the intermediate staging area. One variation in model parameters assumes that the driver saves the fifteen minutes by not having to make two trips to and from the staging area. Assuming an internal labor rate of $30 per hour (including benefits) a fleet operator could save $7.50 for each double-trailer combination that is assembled and disassembled. This assumes that both the vehicle and the driver are idle for the period.

However, if the time saved were accumulated and put to productive use, such as hauling freight, then the benefits might help recover the increased costs of operating a C-dolly. For example, the additional benefits produced from fifteen minutes of extra hauling time can be calculated in the following manner. Assuming an average transportation speed of 20 mph (including stops, delays, etc.) and a freight hauling charge of $0.000116 per lb (0.45 kg) per mile (1.6 km), then a fully loaded vehicle would earn an additional $64 per fifteen minute period. In other words, the fleet operator could earn $30 for each double-trailer combination (with an innovative dolly that can be backed up) that is assembled and disassembled.

LA or similar type dollies, by the very nature of their hitching arrangements, are most suited to operations where the two trailers are permanently married. Transportation of bulk products, such as fuel oil and grain, are examples of such operations. Since the loading and unloading of bulk products are performed in a drive-through operation, the advantage of being able to backup twin-trailers is less significant.

- Loss of revenue from hauling less weight—Due to the steerable axle and related hardware, current versions of the C-dolly weigh 460 lbs (210 kg) more than a conventional A-dolly. The two additional hitches for the C-dolly weigh 60 lbs (27 Kg) each but may (depending on whether the operator runs with two or three hitches on their trailers) replace one of the A-dolly hitches, resulting in only one additional hitch, for a total weight penalty associated with the C-dolly of 520 lbs.

Under conditions where vehicles are operated at maximum gross weight, the extra weight of the dolly displaces an equivalent amount of freight. The loss of revenue depends upon a number of factors—type of freight (freight class), trip length, etc. For example, the revenue from shipping 10,000 lb (4,535 kg) of freight from Ann Arbor, Michigan, to San Diego, California (a distance of 2,373 miles (3,818 km)), is $2,752. If a vehicle is forced to forego carrying 1,000 lb (454 kg) of freight, then the loss of revenue for the trip is $275.20.

- Savings from fewer accidents—The analysis in the original study (1) predicted that the improved safety characteristics of the CSB-dolly (now CSC) over the standard A-dolly would save the fleet operator $0.008 per mile. The analysis done for this study, detailed in the preceding section, with more recent data and a different view of accidents, predicts very similar savings of $0.0098 per mile from the use of the better performing C-dollies. This analysis was slanted towards the conservative, so higher costs could be expected.

The two other sources of accident cost data, although not as rigorously developed as the analysis using national accident databases, support examining a range of savings from fewer accidents with better performing dollies of from $0.002 to $0.016 per dolly mile.

- Ability to operate on secondary roads—A number of states limit the operation of double-trailer combinations on their supplemental highways. Considering a situation where both trailers in a doubles combination are headed for the same destination off the designated highway system, the combination must be disassembled, and each trailer must be transported to the site independently. If such limitations were to be removed because of the improved dynamic performance of doubles with innovative dollies, there would be a cost savings associated with the elimination of two trips to and from the local drop-off site. (This is allowed by permit in Saskatchewan, Canada.)

- Permit to increase axle loads—As the loss of revenue from operating overweight dollies is so great, some provinces in Canada have allowed truck fleets to increase their gross vehicle weights on a permit basis. This assumption, very similar to the one discussed above, addresses current highway regulation and has been included to describe a possible situation in the U.S.

The Investment Rule

The Net Present Value (NPV) rule is used as a basis for analyzing the investment decision. The NPV rule reduces all forecasted cash flows to current dollars (based on a given discount rate) and is reliable in ranking projects that offer different patterns of cash flow. Other investment rules such as Payback and Average Return on Book are inadequate when analyzing incremental cash flows.

Application of the Financial Model

The Independent Variables

The variables follow the form of those given in the previous study (1) modified to current values.

Influences of the excess weight of the C-dolly

- Percent of trips at maximum gross vehicle weight (GVW). Though it is desirable to operate vehicles cube-full and at maximum axle loads, the actual loading situation is determined by the density of the freight being shipped. The reference condition assumes a hypothetical fleet operating its vehicles at maximum GVW 60 percent of the time. (This value of 60 percent corresponds to the experience of large LTL (less than truck load) fleets in the U.S.).
- Excess weight of the C-dolly. As discussed above, the total likely weight penalty imposed by C-dollies is 520 lbs (237 kg).
- Miles per year per dolly. In addition to predicting the frequency of preventive maintenance, this variable helps estimate the loss of revenue from having to carry less freight. The average used for annual dolly-miles is 100,000 miles (160,000 km) to compare to the previous study (1), even though many fleets report an average mileage of 125,000 miles (200,000 km) per year.
- Freight charges. The freight charge has a direct bearing on the loss of revenue due to displaced cargo. Among other factors, the charge is dependent upon the distance the freight is to be shipped. For the reference condition, it is assumed that the charges are $27.50 per 100 lb (45 kg) of freight shipped from Ann Arbor, Michigan, to San Diego, California. (However, the charges from Ann Arbor to Toledo, Ohio are $5.00 per 100 lbs (45 kg). On a per mile basis, the San Diego rate is $0.01159 per 100 lb (45 kg) per mile (1.6 km), and the Toledo rate is $0.10 per 100 lb (45 kg) per mile (1.6 km).)

Size of the fleet

The size of the operation and the proportion of innovative dollies being added to the fleet determines the scheduling and training costs a company might incur. The pertinent variables are:

- Number of innovative dollies added to the fleet.
- Total number of dollies owned by the fleet.

For comparison to the previous study, the reference fleet has 15 dollies with 6 of them being C-dollies.

Maintenance

- Increase in tire wear. More experience with C-dollies shows that increased tire wear is related to proper maintenance and the amount of use in local operations. The reference fleet is assumed to have 7.5 percent more tire wear in general with sensitivities ranging from 0–15 percent.
- Cost of a major overhaul. The cost of a major overhaul is defined as a percentage of the original cost of the dolly. The model assumes that a C-dolly undergoes a major overhaul every three years while an A-dolly has a major overhaul once every four years. The cost of a major overhaul for the hypothetical fleet is assumed to be 20 percent of the cost of the dolly, that is, $2,200 for a C-dolly and $1,100 for an A-dolly.
- Cost of preventive maintenance. From trip and maintenance records, A-dollies have been known to cost the fleet operator $500 per year. Since the innovative dollies would be twice as expensive with respect to preventive maintenance (that is, they are brought in more often for routine maintenance and have additional steering and hitching linkages to keep up), the difference in the annual cost of preventive maintenance is estimated to be $500.

Number of backups per day

If a fleet operates over short distances where double-trailer combinations must be assembled and disassembled more than once every day, then the ability to back up two trailers could have an impact on the profitability of the operation. The reference fleet does not directly consider backing up to be a cost-saving alternative but examines the sensitivities of up to two backups per day.

Accident savings

As the C-dolly's improved dynamic ability reduces the possibility of accidents, it is assumed to save the fleet operator $0.008 per dolly per mile (1.6 km), with the value possibly ranging from $0.002 to $0.016 per dolly per mile (1.6 km). This rate, instead of the $0.0098 per dolly per mile (1.6 km) developed in the accident analysis section, was used to allow a more direct comparison to the previous study. The higher developed accident rate gives credibility to the higher end of the range.

Discount rate

The discount rate is used to reduce future cash flows to current amounts and is assumed to be 10 percent (after taxes) for the shipping and transportation industry. A range of 8–12 percent for the discount rate was analyzed

Scheduling and training

- Scheduling programs and data bases. This variable attempts to address the single expense incurred by large fleets when scheduling-related computer programs and data bases are updated. A large fleet is assumed to operate at least 30 dollies.
- Administrative training. The training of managers and administrative personnel is associated with a learning curve and is defined as the training cost per C-dolly during the first year of its introduction.
- Driver/yard personnel training. The training of drivers and yard personnel is defined in a fashion similar to administrative training.

Local deliveries

The local deliveries variable analyzes the ability to operate on secondary roads. Assuming variations in local regulations, a double-trailer vehicle saves the fleet operator $30 for every local (off the federal highway system) trip it is allowed to make. This $30 represents the cost of the extra trip needed for individually towing each trailer to the local delivery site.

Permit to increase gross vehicle weight

Assuming a change in regulation, a permit to allow an increase in maximum gross vehicle weight is used to offset the additional weight of the innovative dollies. An arbitrary range of 1,000 lbs (450 kg) to 4,000 lbs (1800 kg) was used.

The variables and their reference values are listed in table G-17.

DISCUSSION OF THE RESULTS

The analysis model spreadsheet results are laid out in the three sections of table G-18. The first column in table G-18 is used to label the economic issues outlined previously in this section. The following columns, titled Year 0 (the current year) through Year 19 (the tenth year), contain the annual cash flows resulting from each of the items mentioned in the first column. Negative cash flows, or expenses, are shown in parentheses.

Table G-17. Variations used in analyzing operating cost sensitivities for the C-dolly

		Sensitivity Variations	
Variables	*Reference Values*	*Minimum*	*Maximum*
Percentage of trips at max. GVW	60%	30%	90%
Additional dolly weight	500 lbs	300 lb	1,000 lbs
Miles per year per dolly	100,000 mi	50,000 mi	150,000 mi
Charge/lb/mile for freight hauled	$0.0001159	$0.0000386	$0.00057
Size of the fleet (No. of C:A + C)	6 15	3 15	30 40
Tire wear, % over normal	7.50%	0.00%	15.00%
Overhaul cost (% of initial dolly cost)	20%	10%	30%
Overhaul frequency	350000 mi	300000 mi	400000 mi
Preventive maintenance, per year	$500	$250	$750
Double assembly & disassembly (C-dolly backup)	0 per day	0.5 per day	2 per day
Accident savings per mile per C-dolly	$0.008	$0.002	$0.016
Annual discount rate	10%	8.00%	12.0%
Local deliveries	0 per year	130 per year	260 per year
Overweight hauling allowance	0 lbs	1,000 lbs	4,000 lbs
Conversion cost	$1,300	$1,000	$4,000
Initial cost	$5,500	$4,000	$7,000

Net Present Value

In the model, cash flows occurring in Year 0 result from operational costs and one-time expenses such as purchasing, scheduling, and equipment conversions. Cash flows in the following years result from changes in operational costs only. The reference example in table G-18 shows that a fleet of 9 doubles adding six C-dollies versus one adding six A-dollies would have to spend an additional $33,000 to cover the initial cost of the dollies. This cost, plus other initial investments and operational costs, results in a loss of $67,157.00 in the first year of the project. During the second year, the fleet operator would lose $22,058.58 due to increases in operational costs alone. The Net Present Value (NPV) of the sum of the incremental cash flows over the life of the project (using the baseline values for valuables) results in a total negative cash flow of $205,894.

Change in Shipping Charges

Assuming that the reference fleet were to raise its shipping charges to cover its incremental loss, the freight charges would have to be increased by $0.0000858 per 100 lb (45 kg) per mile (1.6 km), as indicated in table G-18. The rate increase was determined for six C-dollies, observed over the ten-year period, traveling 100,000 miles per year and carrying 40,000 lb of cargo per trip.

Change in Operating Cost

The increased operating cost of a C-dolly—that is, the NPV of the investment less the one-time costs of scheduling, purchasing, and converting equipment—is computed (per dolly per mile (1.6 km)) in the last row of the column of Year 0. It is this value (0.0293 dollars per dolly per mile (1.6 km)) that is used as the reference value in the sensitivity analyses.

To study the influence of the economic issues discussed earlier, results for the surrogate dollies, the standard A-dolly and the C-dolly, are presented here.

Current Operating Environment

Starting with a situation that tries to approximate the current U.S. operating environment, the financial model is used to analyze the decision by a fleet operator to purchase six innovative dollies. In the case of the C-dolly, the Net Present Value (the NPV is defined as the sum of the incremental cash flows over the life of the project reduced to current dollars) of such a decision results in a total negative cash flow (a loss) of $205,894. The incremental cash flows projected over 19 years are as shown in table G-18.

It is important to emphasize that this loss is an *incremental loss* due to a decision to buy a C-dolly instead of an A-dolly. For example, if there were an underlying decision (with an NPV of at least $205,000) to use twin-trailer combinations instead of tractor-semitrailers, then the decision to use C-dollies would only reduce the profitability of the original decision. The purchase of conventional dollies, however, would not affect the original NPV of at least $205,000.

Assuming that the reference fleet were to raise its shipping charges to cover its incremental loss, the freight charges would have to be increased by $0.0000858 per 100 lb (45 kg) per mile (1.6 km), as indicated in table G-18. The rate increase was determined for six C-dollies, observed over a ten-year period, traveling 100,000 miles (160,934 km) per year and carrying 40,000 lb (22,500 kg) of cargo per trip. The increase in freight charges translates into an increase of $203.60 for 100,000 lb (45,359 kg) of cargo, shipped in small lots over a period of time, from Ann Arbor to San Diego—an increase of 7.4 percent.

Table G-18. Analysis model spreadsheet results

Δ costs/benefits between A and ASC-dollies	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Initial cost of dollies	($33,000.00)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Converting existing equipment	($7,800.00)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Major overhauls	$0.00	$0.00	$0.00	($13,200.00)	$6,600.00	$0.00	($13,200.00)	$0.00
Tire wear	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)
Preventive maintenance	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)
Scheduling	($800.00)	($294.30)	($108.27)	($39.83)	($14.65)	($5.39)	($1.98)	($0.73)
Training	($6,000.00)	($2,207.28)	($812.01)	($298.72)	($109.89)	($40.43)	($14.87)	($5.47)
Ability to back up	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Less weight hauled	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)
Fewer accidents	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00
Ability to operate on secondary roads	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Allow higher GVW	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Total	($67,157.00)	($22,058.58)	($20,477.28)	($33,095.55)	($13,081.55)	($19,602.82)	($32,773.86)	($19,563.20)
Net Present Value	($205,894)							
Cost increase to cover loss/100lb/mi	$8.58E-05							
Change in operating cost / dolly / mile	$0.0293							

Δ costs/benefits between A and ASC-dollies	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19
Initial cost of dollies	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Converting existing equipment	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Major overhauls	$0.00	$6,600.00	($13,200.00)	$0.00	$0.00	($13,200.00)	$6,600.00	$0.00	$0.00	($13,200.00)	$0.00	$6,600.00
Tire wear	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)	($495.00)
Preventive maintenance	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)	($3,000.00)
Scheduling	($0.27)	($0.10)	($0.04)	($0.01)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Training	($2.01)	($0.74)	($0.27)	($0.10)	($0.04)	($0.01)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Ability to back up	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Less weight hauled	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)	($20,862.00)
Fewer accidents	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00	$4,800.00
Ability to operate on secondary roads	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Allow higher GVW	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Total	($19,559.28)	($12,957.84)	($32,757.31)	($19,557.11)	($19,557.04)	($32,757.02)	($12,957.01)	($19,557.00)	($19,557.00)	($32,757.00)	($19,557.00)	($12,957.00)

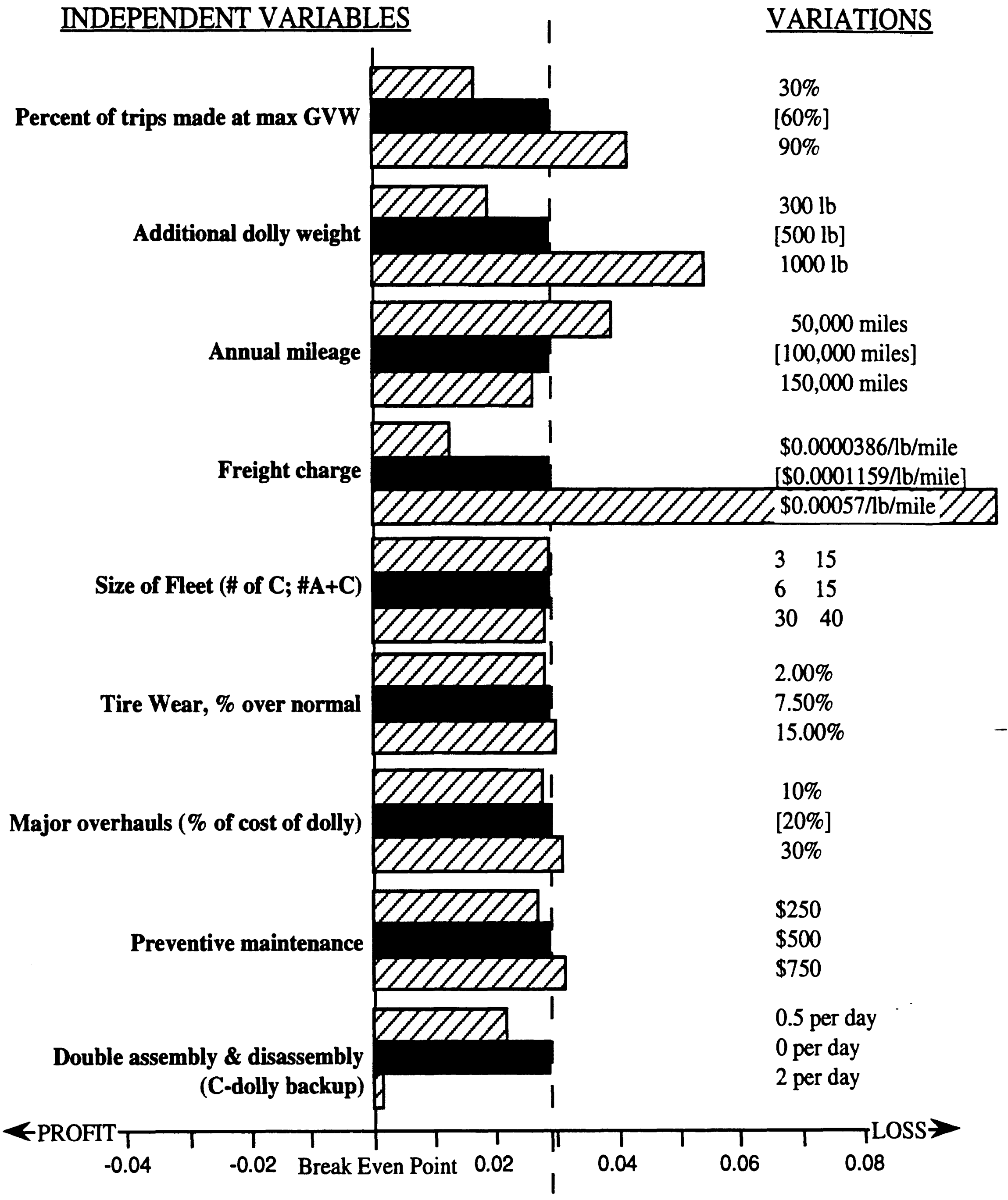


Figure G-1. Operating cost sensitivities for a C-dolly

It is often helpful to see how a project fares under various scenarios. A sensitivity analysis is helpful in determining the key variables that determine whether a project fails or succeeds. Table G-19 contains a list of the reference values and the variations used in the analysis of the C-dolly. The influences of the variations listed in table G-19 are displayed in figures G-1 and G-2. The figures show that reasonable increases or decreases in some

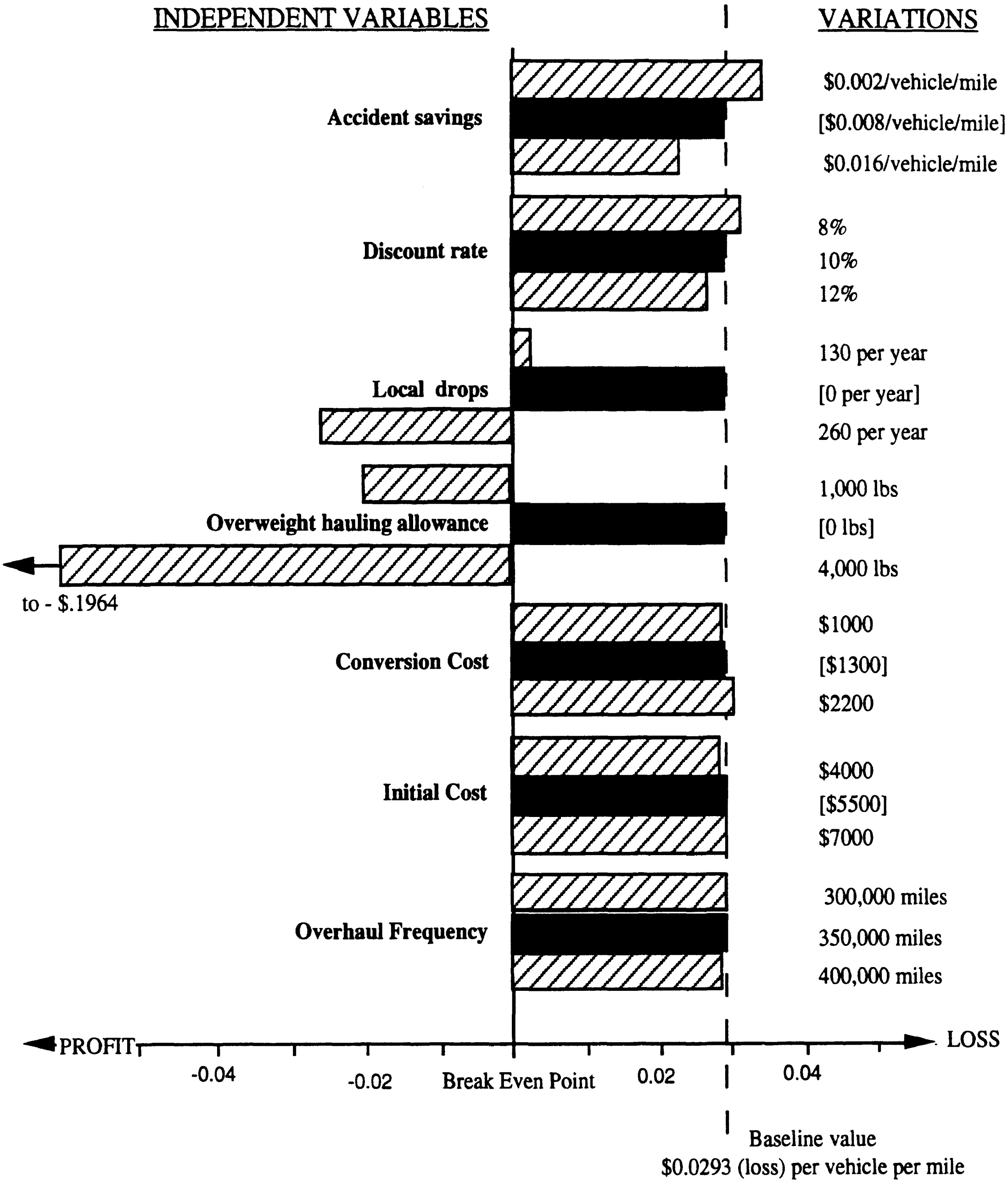


Figure G-2. Operating cost sensitivities for a C-dolly

of the independent variables have little influence on the operating cost. (The reference values are enclosed in square brackets for easy identification in the figures. The baseline value, indicated by a vertical dashed line, is obtained by exercising the financial model using the reference values of the independent parameters.) The "Break Even Point" (the 0.0 value on the horizontal scale in the figures) is the point where the costs associated with purchasing and operating an A-dolly are equal to the costs associated with purchasing and operating a C-dolly. Examination of figures G-1 and G-2 indicates that increases in (1) freight charges, (2) percentage of trips made at GVW, (3) dolly weight, (4) local drops, and (5) double assembly and disassembly have significant influences on the changes in operating cost associated with acquiring C-dollies. With regard to accident costs, the results show that accident costs have only a moderate influence on the financial picture. The profit side of the bar chart is reached if the owners of C-dollies assemble and disassemble their double-trailers twice a day and apply the time saved to productive use.

Other reasonable variations in certain parameters, with the rest of the reference values remaining constant, were tried to investigate alternative approaches to reaching the break even point. If the weight of a C-dolly were reduced to that of a standard A-dolly at a cost increase of $1,500 over the base price of $11,000 ($7,000 over the cost of the A-dolly) and the operator was able to make 36-37 local drops per year, the operation would break even. Alternatively, an operation could break even at reference dolly costs and weights if it could achieve 160 local deliveries and manage a 690 lb (313 kg) overweight hauling allowance. Many other variations are possible.

Figures G-1 and G-2 present an overall message that could be considered more significant than the details. The message comes in two parts: out-of-pocket cost does not matter much and *weight is what does matter* — which is certainly not a surprise to most people familiar with the trucking business.

Each of the elements of out-of-pocket cost (initial and conversion costs, tire wear, overhauls, and maintenance cost) are shown to have little influence according to figures G-1 and G-2. Of the other elements of the figures directly attributable to the dolly (as opposed to the operating environment), we see that the reduced accident costs have a modest influence, but the penalty for increased weight is the most significant. (Improved operating efficiencies that might be brought about by the C-dolly could be substantial but are more speculative.)

In fact, of the $0.0293 per mile incremental loss of the baseline condition, 85 percent ($0.0248) is attributable directly to the additional dolly weight. (When evaluated on the basis of net present value rather than cost per mile, the weight penalty accounts for about 72 percent of the loss.) The net of all the other baseline influences is a loss of $0.0045 per mile. That is, the model yields an operating loss of $0.0045 per vehicle mile with the baseline assumptions modified by (1) zero additional dolly weight, *or* (2) zero percent of trips at maximum GVW, *or* (3) an overweight hauling allowance equal to the additional dolly weight.

Figure G-2 further emphasizes the importance of weight by showing how powerful an influence an overweight allowance has on the change in operating costs. The figure shows the large profit influences of allowance of 1,000 and 4,000 pounds. The model also shows that, under the other baseline assumption, an allowance of 90 pounds more than the additional dolly weight (590 pounds in this case) would bring the incremental cost

Table G-19. Variations used in analyzing operating COST sensitivities for the C-dolly (Numbers in parentheses indicate profit values.)

Variables	*Reference Values*	*Sensitivity Variations*	
		Minimum	*Maximum*
Percentage of trips at max GVW	60%	30 %	90 %
	$205,894	$131,369	$280,419
	$0.0293	$0.0169	$0.0417
Additional dolly weight	500 lbs	300 lb	1,000 lbs
		$146,274	$354,944
		$0.0194	$0.0542
Miles per year per dolly	100,000 mi	50,000 mi	150,000 mi
		$146,747	$265,040
		$0.0389	$0.0261
Charge/lb/mile for freight hauled	$0.0001159	$0.0000386	$0.00057
		$106,484	$789,876
		$0.0127	$0.1266
Size of the Fleet (No. of C:A + C)	6 15	3 15	30 40
		$102,947	$1,024,210
		$0.0293	$0.0291
Tire Wear, % over normal	7.50%	2.00%	15.00%
		$203,300	$209,430
		$0.0289	$0.0299
Overhaul cost (% of initial dolly cost)	20 %	10%	30%
		$198,318	$213,469
		$0.0281	$0.0306
Preventive maintenance - per year	$500	$250	$750
		$195,177	$216,611
		$0.0275	$0.0311

Table G-19 (Cont.). Variations used in analyzing operating COST sensitivities for the C-dolly (Numbers in parentheses indicate profit values.)

Variables	*Reference Values*	*Sensitivity Variations*	
		Minimum	*Maximum*
Double assembly & disassembly (C-dolly backup)	0 per day	0.5 per day	2 per day
		$164,098	$38,711
		$0.0223	$0.0015
Accident savings per mile per C-dolly	$0.008	$0.002	$0.016
		$231,614	$171,600
		$0.0336	$0.0236
Annual discount rate	10%	8.00%	12.0%
		$218,657	$194,743
		$0.0314	$0.0275
Local deliveries	0 per year	130 per year	260 per year
		$38,711	($128,472)
		$0.0015	($0.0264)
Overweight hauling allowance	0 lbs	1,000 lbs	4,000 lbs
		($92,206)	($986,506)
		($0.0204)	($0.1694)
Conversion cost	$1,300	$1,000	$2,200
		$204,094	$211,294
		$0.0290	$0.0302
Initial cost	$5,500	$4,000	$7,000
		$193,831	$217,756
		$0.0288	$0.0298
Overhaul frequency	350,000 mi	300,000 mi	400,000 mi
		$208,699	$200,127
		$0.0298	$0.0284

per mile to the break-even point. An allowance of 191 pounds more than the additional dolly weight (691 pounds in this case) is needed to bring the net-present-value computation to zero, making the decision to buy C-dollies rather than A-dollies a break-even proposition. Given that we are dealing with a vehicle system of nominally 80,000 pounds, it becomes quite clear that the economics are very sensitive to weight penalties or rewards.

In summary, the economic analyses presented here suggest that the broad application of C-dollies across the doubles fleet may not be a profitable investment decision under current operating rules. Purchase costs and other changes in out-of-pocket cost are not the major reason for this. Rather, the increased weight of the C-dolly and the commensurate loss of payload is the issue. The economics are so sensitive to weight that an increase in the legal weight allowance of as little as a few hundred pounds over and above the weight penalty imposed by the use of the heavier dolly could make the C-dolly financially attractive.

APPENDIX H

RESOLUTION OF THE DIFFERENCES IN REARWARD AMPLIFICATION DETERMINED BY TWO DIFFERENT CALCULATION METHODS

INTRODUCTION

Fancher used the UMTRI *Simplified Model* to determine rearward amplification (RA) while studying potential "Turner vehicles."[13] In his report, he presented RA results for five double-trailer vehicles as calculated using the *Simplified Models*. (Fancher studied seven vehicles in total; two were single-trailer combinations.) Based on a few additional calculations using *Yaw/Roll*, he also indicated that RAs determined for "moderate lane change maneuvers" (i.e., 0.15 g at the tractor) would produce noticeably higher values for all the vehicles. It is this discrepancy that we wish to resolve here.

Rearward amplification refers to the vehicle property wherein *rearward* elements (trailers) of the combination exhibit *amplified* lateral motions relative to the lateral motions of the tractor during transient maneuvers. Rearward amplification is "frequency dependent" so that it tends to be more severe in quick, evasive maneuvers than it is during "normal" lane changes. The phenomenon is illustrated in figure H-1. The figure illustrates the behavior of a double-trailer vehicle in a rapid evasive maneuver. The maneuver is like a lane change (but may or may not be a full lane). An important characteristic of this maneuver is that both the steering input, and the acceleration time history of the tractor (also considered as input in determining RA) have the form of a single-cycle sine wave. The most generally accepted quantitative definition of rearward amplification is shown in the figure. That is, the rearward amplification for the vehicle, operating at the *frequency* and implied by the period of the tractor maneuver, and at the specified *velocity*, is:

$$RA \equiv {}^{A_{y(\text{last})}}\!/_{A_{y1}} \qquad (1)$$

Further, when RA is quoted as a single number for a vehicle, it is generally the worst-case RA, i.e., at the particular maneuvering frequency that generates the largest RA, at the specific test velocity.

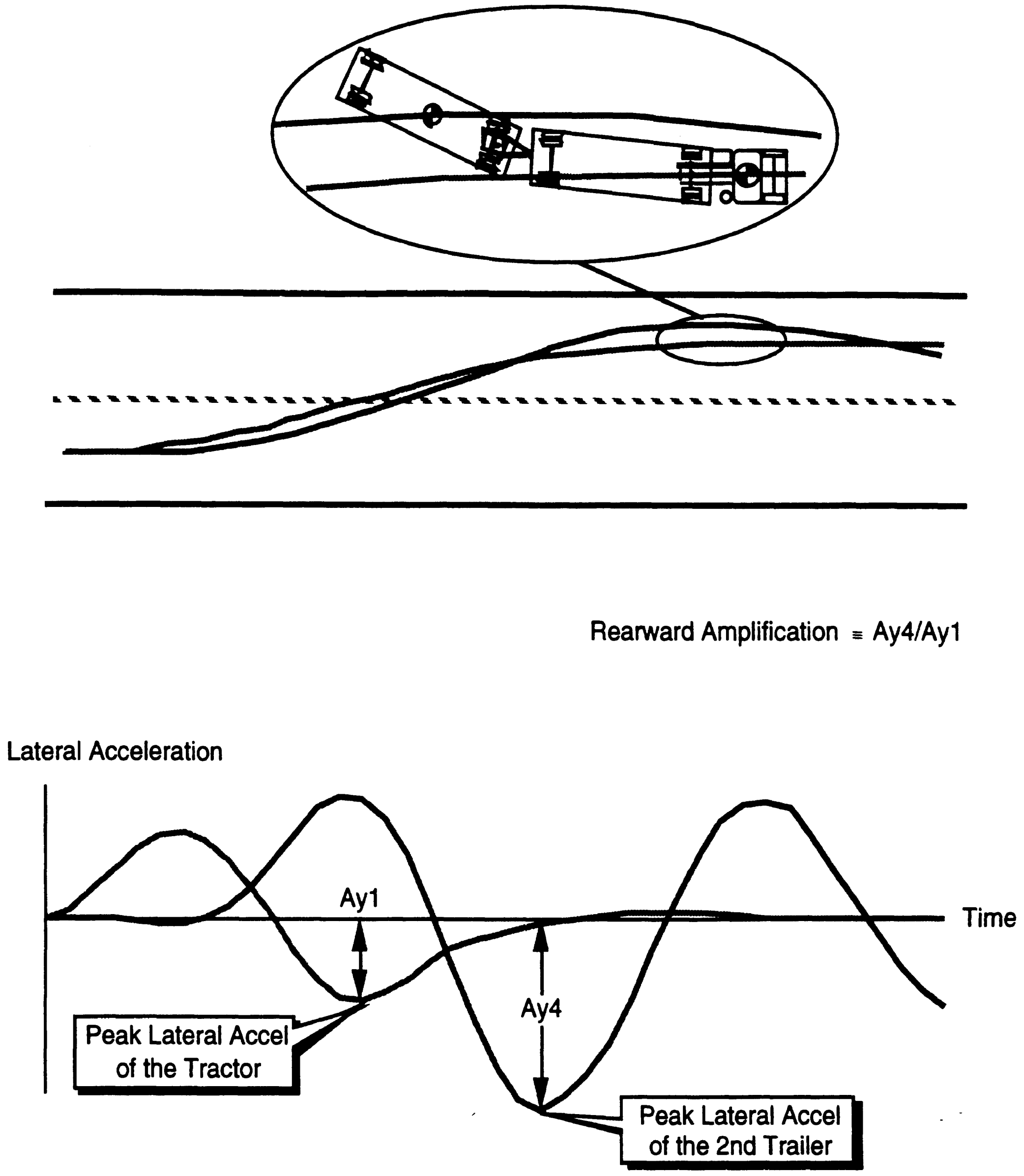


Figure H-1. Illustration of the Rearward Amplification Phenomenon

In addition to the sensitivity to frequency and velocity, the rearward amplification of *real* vehicles is sensitive to the magnitude of the tractor maneuver. If vehicles were linear this would not be so; rearward amplification would be the same for (and could be measured at) any magnitude of input. But real vehicles have nonlinear tires (tire *lateral* force capability eventually saturates, and tires lift off the ground and change their *vertical* properties) and nonlinear suspensions (suspensions have lash and friction and non-constant spring rates). Due largely to the establishment of the "standard RTAC maneuvers," rearward amplification is usually measured using a tractor maneuvering level of 0.15 g. For vehicles with relatively high rearward amplification (say, 2.5), this level of maneuver will produce severe, but not ridiculous levels of lateral acceleration (0.38 g) at the pup trailer (although it will produce rollover for some of the less stable trailers).

To determine rearward amplification using large-scale simulation programs (e.g., *Yaw/Roll*), UMTRI will typically conduct three 0.15 g lane change maneuvers, one each with periods of 2.0, 2.5, and 3.0 sec. at highway speeds (usually 55 mph or 100 kph, depending on the venue of interest). Rearward amplification is calculated for each (as per equation (1)) and the highest value of the three is reported as the rearward amplification of the vehicle at the specified speed.

If a large number of vehicles are studied, the procedure is relatively expensive, as *Yaw/Roll* is a large-scale simulation requiring complete and complicated vehicle descriptive data as input, and a substantial amount of computer time to complete the calculation.

When scanning rearward amplification for a large number of vehicles, it is more economical to determine rearward amplification through simpler calculation methods. The UMTRI *Simplified Model* for rearward amplification[1] embodies such a method. This mathematical model is significantly different when compared to the *Yaw/Roll* model, as follows:

i) The *Simplified Model* is a closed form solution for rearward amplification. Simulations calculate the actual vehicle motions, and then rearward amplification is determined just as shown in figure H-1. The *Simplified Model* for rearward amplification, is a specialized, theoretical calculation to determine rearward amplification directly from vehicle properties without actually calculating the motions of the vehicle. The solution is determined for all frequencies (i.e., the solution is continuous over a specified frequency range), not just a few discrete frequencies. The peak rearward amplification is determined from this continuous solution.

ii) To make a closed-form solution possible, a number of simplifying assumptions were required. The more important of these are:

- Only yaw plane dynamics are considered, i.e., the vehicle does not roll.
- The vehicle is linear, i.e., tire lateral properties are represented by a constant cornering stiffness coefficient (in addition to ignoring roll motions and associated nonlinearities). Thus, the calculated rearward amplification is not sensitive to the magnitude of the input.
- The local rearward amplification from the tractor c.g. to the semitrailer c.g. is assumed to be unity. (This has been observed to be nearly true for many vehicles, and, further, the closed-form solution for this portion of the vehicle proved to be extremely complicated.) Thus the rearward amplification calculated is from the

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[1] The UMTRI *Simplified Models* are copyrighted software of the University of Michigan Transportation Research Institute.

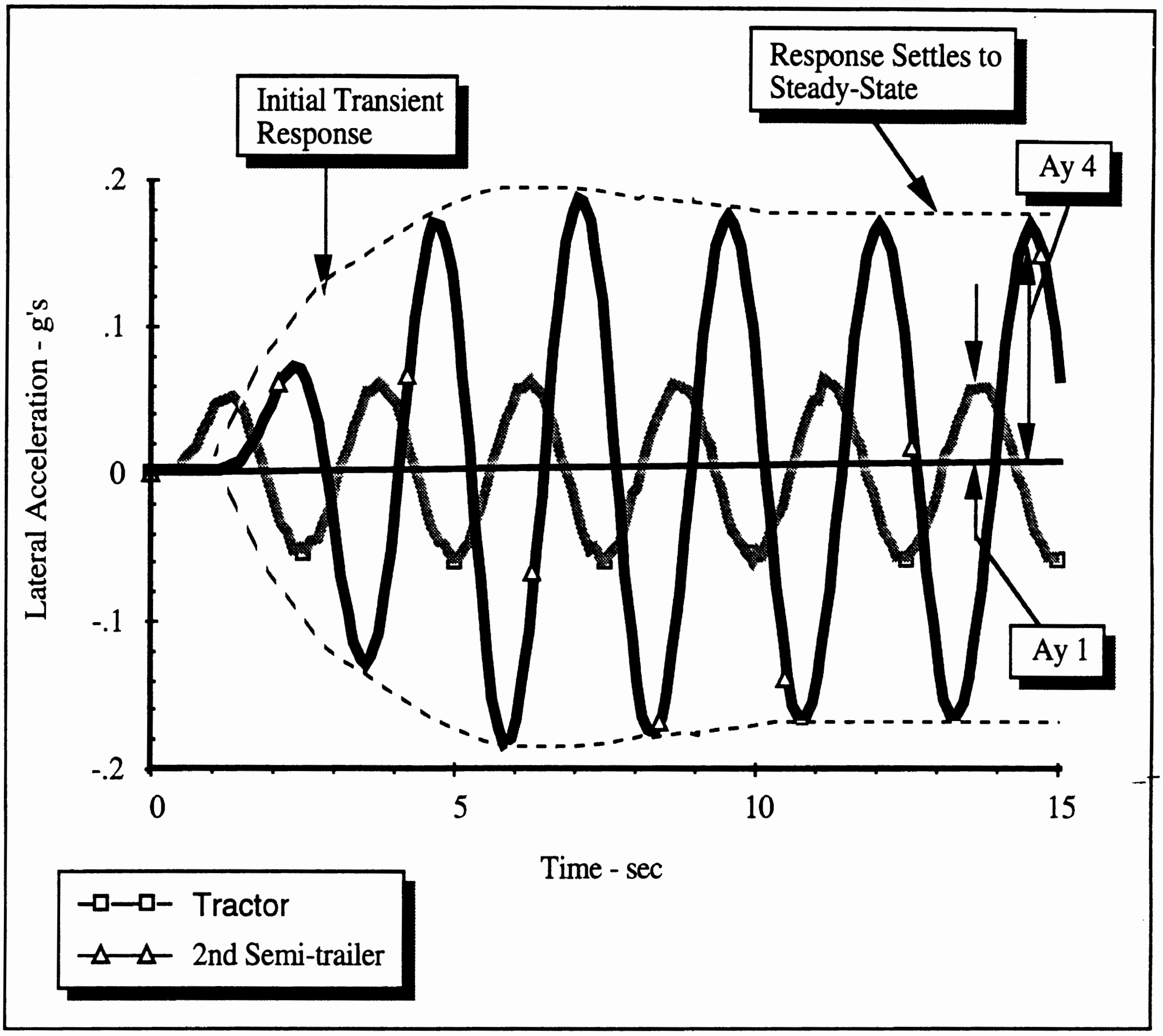

Figure H-2. Rearward Amplification determined in the "continuous" sine wave maneuver.

semi-trailer to the last trailer, not from the tractor to the last trailer (although this would be identical if the assumption of unity were exactly true.)

- The solution is for the steady-state response to sinusoidal input. That is, rather than looking at the response to a single sine wave of input, the input is considered to be a continuous sine wave, and the solution is for the steady-state response after many cycles have occurred and the start-up transients have died out. (See figure H-2.)

METHOD

To review, the primary maneuver and vehicle differences between Yaw/Roll and the *Simplified Model* are:

Table H-1. Significant Differences Between the Models

Model	*Maneuver*	*Roll Behavior*	*Tire Properties*	*Rear Amp Measured*
Simplified Model	continuous cycling (steady state)	not included	linear	from Semi-trailer to last trailer
Yaw/Roll	Single cycle (transient)	included	nonlinear	from tractor to last trailer

The approach in this study task was to isolate and evaluate the individual influences of maneuver, roll behavior, tire properties, and the specific rearward amplification measurement. Fancher's seven *Turner vehicles* were used as test vehicles.

Each of the seven vehicles was examined under the Model-Maneuver-Vehicle-Measurement conditions indicated in the table H-2.

The relationships existing between the categories in table H-1 and table H-2 are obvious, with perhaps the exception of the relationship between *Roll Behavior* in table H-1 and *C.G. Height* in table H-2. In order to isolate the influence of roll behavior, the performance of the test vehicles was examined with two different c.g. heights. With the sprung mass c.g. located at its normal height (94 inches in this case), *Yaw/Roll* calculated the normal roll behavior roll. To remove the influence of roll from the *Yaw/Roll* calculations, the sprung mass c.g. was also located unusually low (at the same height as the suspension roll centers; 29 inches). With the c.g. at this position, the sprung mass inertial forces do not produce any moment about the roll axis of the vehicle, and the sprung mass, therefore, does not roll on the suspension. Some vehicle roll does occur due to tire deflection, but even this is small since the absolute height of the c.g. is so low.

Then in table H.2, rearward amplification from the semi to the last trailer, calculated under the "condition" of the second line, is the *Yaw/Roll* equivalent of the *Simplified Model* result.

The condition of line 3 adds the influence of roll behavior. In this case, the added influence is the roll motion *only*, and not the additional influences that roll usually begets. That is, i) all suspensions of the test vehicles are assigned zero roll steer, and ii) the tires are simple linear tires with no load influence. Therefore, in this condition roll does not influence tire performance or wheel-steer angle. Its influence is restrained to simply the additional source of lateral motion of the sprung mass c.g. and the additional lateral motion of hitch points.

Table H-2. Matrix of Study Conditions

Test Condition	*Maneuver*	*Model*	*C.G. Ht.*	*Tires*	*Rear Amp Measured*	
					Tractor to Last trailer	*Semi to Last trailer*
1	Continuous -cycling	Simple Model	NA	Linear		x
2		Yaw/Roll	Low	Linear	x	x
3		Yaw/Roll	Normal	Linear	x	x
4		Yaw/Roll	Normal	Non-lin.	x	x
5	Single-cycle	Yaw/Roll	Low	Linear	x	x
6		Yaw/Roll	Normal	Linear	x	x
7		Yaw/Roll	Normal	Non-lin.	x	x

The influence of nonlinear tire properties is added in the fourth line of the table. Now the lateral load transfer which takes place with roll produces realistic changes in tire properties.

The "conditions" of lines 5, 6, and 7 reproduce those of 2, 3, and 4, but with a single sine-wave (lane change) maneuver rather than a continuous wave maneuver.

All of the calculations using *Yaw/Roll* allow for determining rearward amplification including or exclude the contribution from the tractor c.g. to the first trailer c.g.

RESULTS

Figure H-3 shows results which are rather typical for all of the calculations performed. The figure shows the rearward amplification values which were calculated for Fancher's 'Prototype, 9-axle, A-double.'[2] Results from all seven of the test conditions indicated in table H-2 are included. The rearward amplification values measured i) from the tractor c.g. to the first trailer c.g., ii) from the first trailer c.g. to the last trailer c.g., and iii) from the tractor to the last trailer c.g. are all displayed for calculations performed by *Yaw/Roll.*

Figure H-3 shows that:

- *Simplified Model* and *Yaw/Roll* results are quite similar when the *Yaw/Roll* vehicle and maneuver are similar to the *Simplified Model* vehicle and maneuver (compare conditions 1 and 2).

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[2] The results for this vehicle are quite typical of the 4 A-train doubles in the set. The B-train displays less rearward amplification in general and less severe differences between conditions. The same is true of the two tractor-semitrailer combinations. Further, these later two can not be examined using the *Simplified Model.*

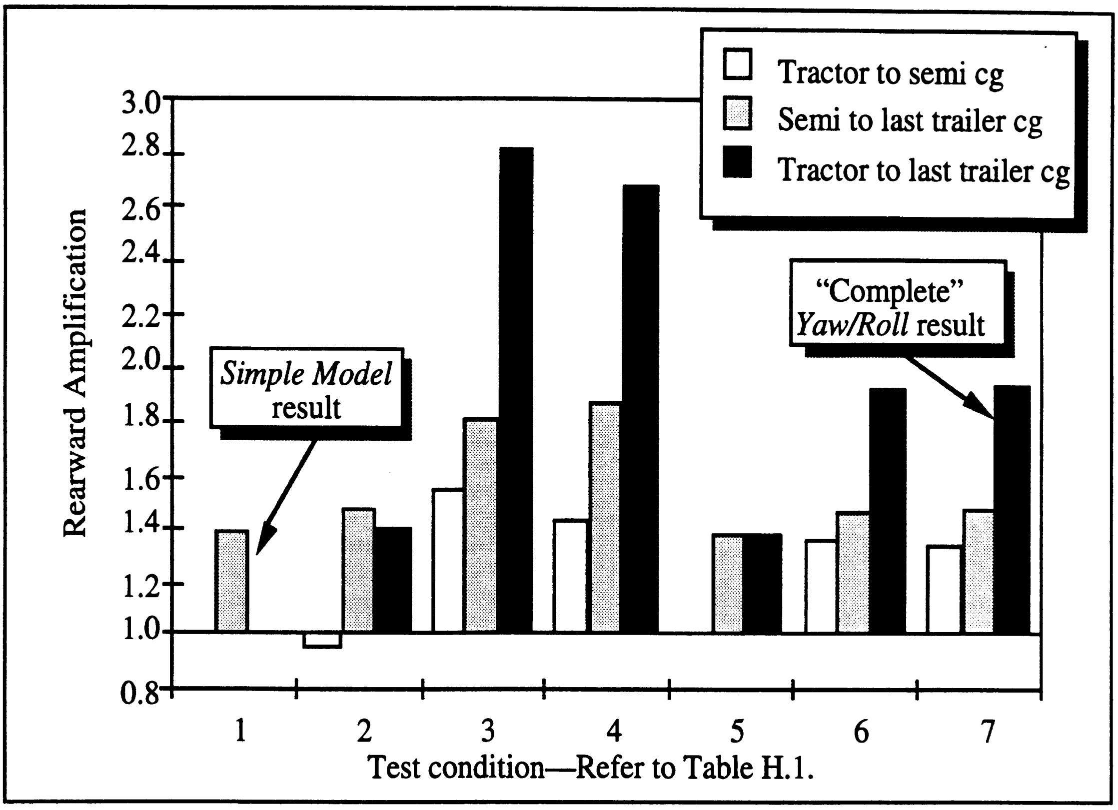


Figure H-3. Rearward Amplification

- The *Simplified Model* assumption that the tractor-to-semitrailer rearward amplification is near unity holds well, *given the assumption of a nonrolling vehicle* (see conditions 2 and 5).
- Roll motion, *per se*, has a major influence on rearward amplification. It elevates the tractor-to-semitrailer rearward amplification significantly above unity (compare conditions 2 and 3, or conditions 5 and 6). In this case, the influence of roll on the semi-to-last-trailer component of rearward amplification is mixed. For the continuous maneuver, it appears significant (compare conditions 2 and 3), but not particularly so for the lane-change maneuver (compare conditions 5 and 6).
- The influence of the nonlinear properties of the tires is quite small (compare conditions 3 and 4, and conditions 6 and 7).
- The influence of the different maneuvers ("continuous" and "lane change") depends on the assumption concerning roll. Without roll, the difference between maneuvers is minimal (compare conditions 2 and 5). With roll, the difference is major (compare conditions 3 and 6 or conditions 4 and 7). This suggests a resonant response of the roll motion that requires a few cycles to build up full response.

The findings here regarding the influence of roll and the nonlinear properties of tires are rather startling. Previously, most researchers have assumed that the primary influence of roll on rearward amplification was not roll motion per se, but rather the side-to-side transfer of vertical tire load and the resulting degradation of the effective total cornering stiffness of the tires on a given axle. (This mechanism has been thoroughly documented to be of major importance in other measures of vehicle-handling performance, both for cars and trucks.)

Additional calculations were made to gain a clearer understanding of the part that roll motion plays in generating rearward amplification. The simplest possible hypothesis to explain the influence of roll would seem to be that the roll motion of the sprung mass simply adds an additional component to the lateral displacement of the c.g. during the maneuver, and that this additional lateral displacement results directly in additional lateral acceleration at the c.g. That is to say, we would hypothesize that the lateral motion of the point on the roll axis at the longitudinal position of the c.g. (nominally beneath the c.g.) of the rolling vehicle, would be similar to the lateral motion of the c.g. of the nonrolling vehicle in similar maneuvers. (See figure H-4.) If this were the case, and if roll motion of the vehicle were in phase with lateral acceleration, then the hypothesis would hold.

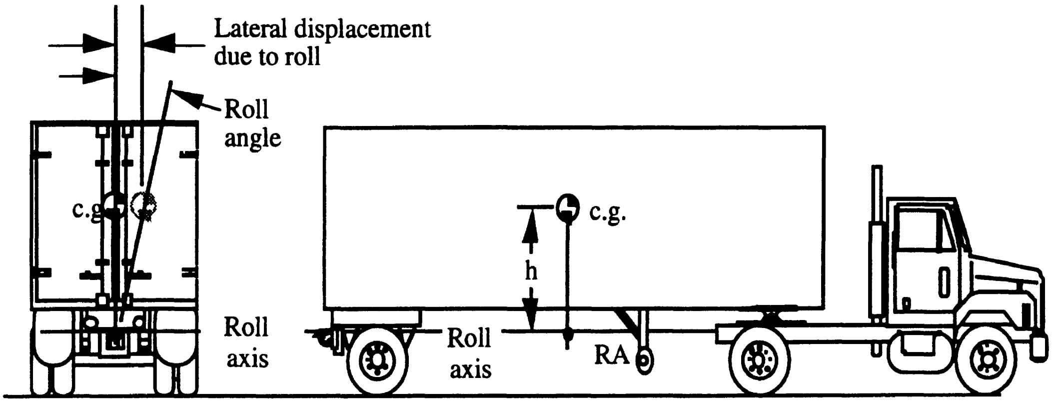


Figure H-4. Location of the roll axis reference point

Examination of simulation time histories showed that, indeed, the necessary phase relationship between lateral acceleration and roll existed in the simulation runs. It is not convenient, however, to obtain a "print out" of the path of an arbitrary point from *Yaw/Roll* (in this case, the reference point on the roll axis beneath the c.g., RA). Rather, we deduced the effective peak lateral displacements of all the points of interest by calculation based on peak lateral acceleration and peak roll angle. The equations of interest are:

$$Y_{cg} = a_y \bullet \frac{P^2}{4\pi^2} \bullet 386 \qquad (2)$$

$$Y_{RA} = Y_{cg} - \frac{(\phi \bullet h)}{57.3} \qquad (3)$$

where: a_y is the peak lateral acceleration of the c.g., inches/sec^2

h is the vertical distance between the c.g. and the roll axis, inches

P is the period of the maneuver, sec

Y_{cg} is the peak lateral displacement of the c.g., inches
Y_{RA} is the peak lateral displacement of the point RA, inches
ϕ is the peak roll angle of the sprung mass, degrees,

In all cases, the peaks used were those from which rearward amplification had been obtained, and the absolute value of the peak readings were used.

The calculations represented by equations (2) and (3) were performed for test conditions 2 and 3 and for test conditions 5 and 6, for all seven of the test vehicles. The results for the prototype 9-axle double are shown in figures H-5 and H-6. (Similar graphs for the other study vehicles are appended. Figure H-5 shows the results for conditions 2 and 3 ("continuous" maneuvers) and figure H-6 was derived from the results for conditions 5 and 6 ("lane change" maneuvers). The qualities of the two figures are virtually identical, so this discussion will refer only to figure H-5.

The upper portion of the figure presents data related to the tractor and the first trailer; the lower portion is for the tractor and last trailer. Each section is a plot of peak displacements as a function of the time period of the maneuver. Each contains four individually plotted lines, viz.:

i) one line for the tractor c.g. path, which is virtually identical for the two test conditions (conditions 2 and 3),

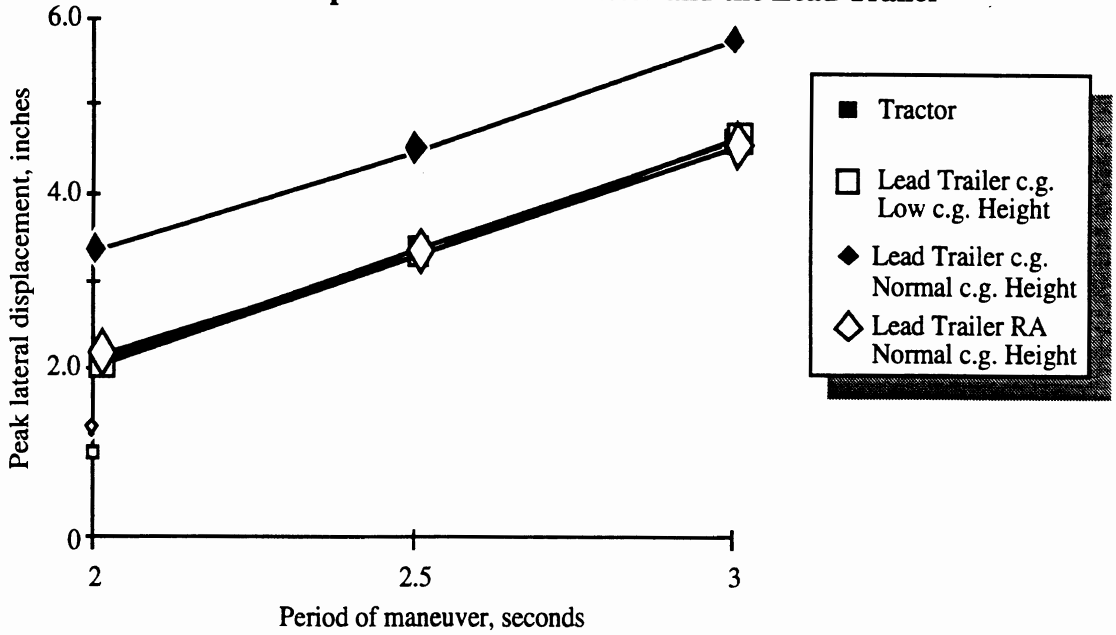
ii) one line for the path of the c.g. of the nonrolling trailer, that is, the trailer with the low c.g. height (condition 2),

iii) one line for the path of the c.g. of the rolling trailer, that is, the trailer with the normal c.g. height (condition 3), and

iv) one line for the path of the point RA of the rolling trailer, that is, the trailer with the normal c.g. height (condition 2).

The hypothesis suggests that, for the *lead* trailer, lines (ii) and (iv) should be identical and line (iii) should exceed lines 2 and 3. The upper portion of the figure confirms this expectation. The fact that line (i) also falls with lines (ii) and (iv) simply relates to the fact that the tractor-to-semitrailer rearward amplification of the nonrolling vehicle was unity.

Peak Lateral Displacement at the Tractor and the Lead Trailer



Peak Lateral Displacement at the Tractor and the Pup Trailer

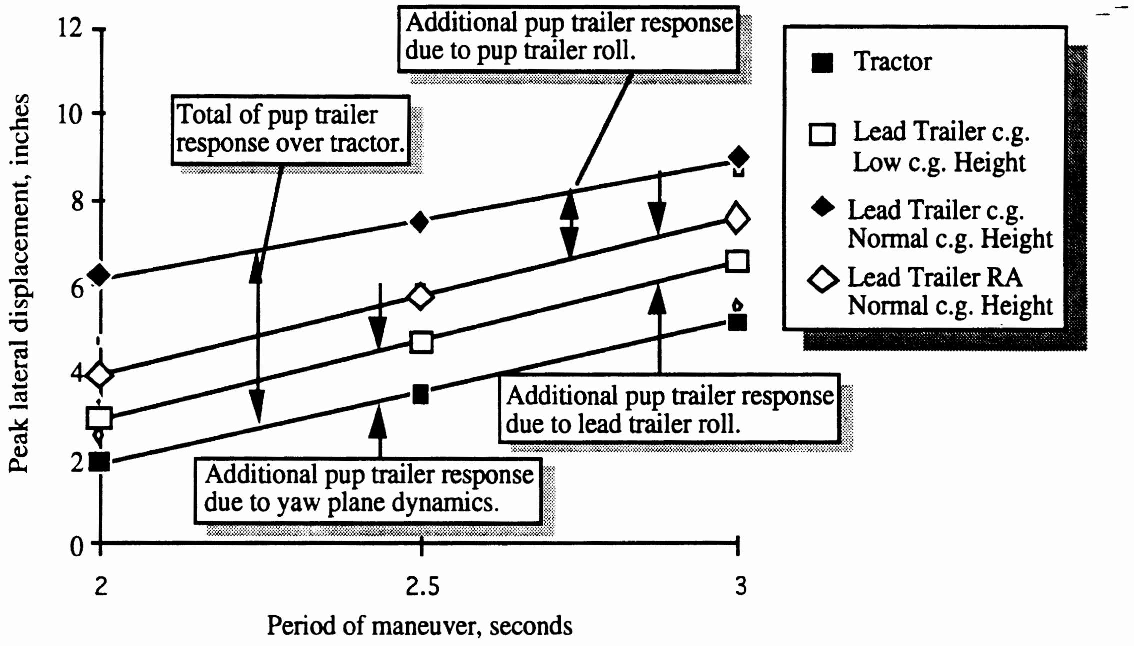
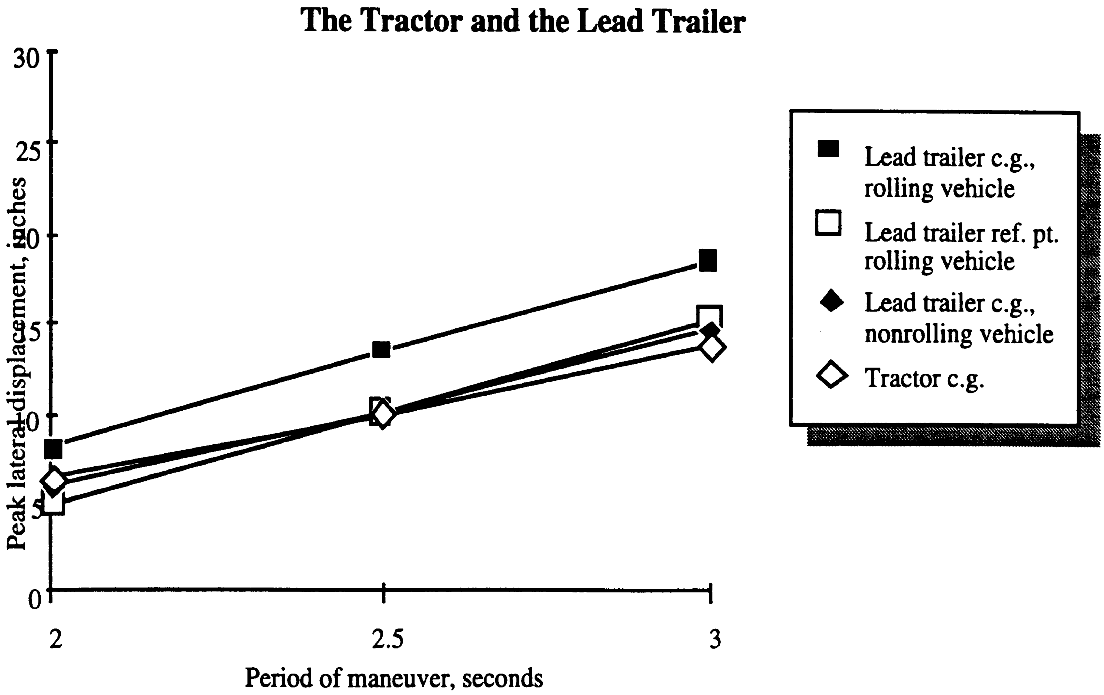


Figure H-5. Peak lateral displacements for the prototype 9-axle double in the lane-change maneuvers (conditions 5 and 6).



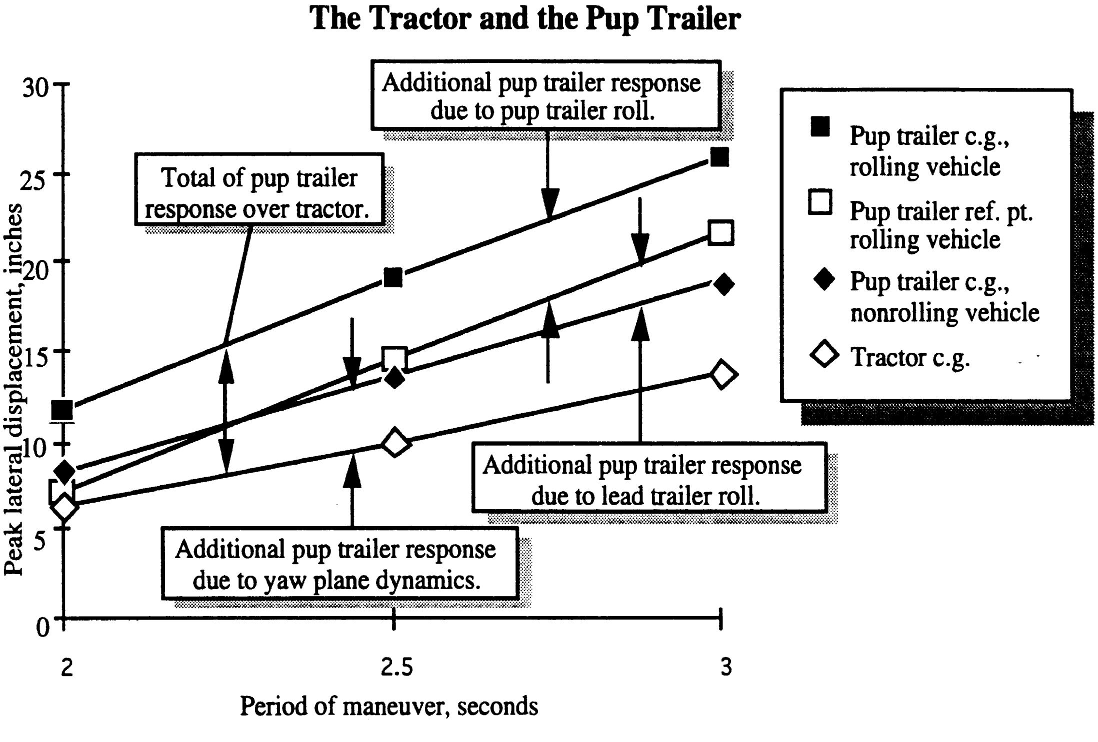


Figure H-6. Peak lateral displacements for the prototype 9-axle double in the lane-change maneuvers (conditions 5 and 6).

The lower portion of the graph rather clearly indicates the various contributions of roll motion to overall rearward amplification. Total rearward amplification is represented by the vertical spacing between lines of the tractor (i) and of the c.g. of the normal trailer (iii). This total is composed of:

- The contribution of the pure, yaw plane dynamics without roll, represented by the vertical spacing between the tractor line (i) and the line for the c.g. of nonrolling trailer (ii).
- The additional *second* trailer motion, which occurs because of the roll motion of the *first* trailer. The first trailer roll motion produces a larger motion of the pintle hitch, and therefore a larger "input" to the second trailer. This is represented by the spacing between the line for the nonrolling trailer (ii) and the RA point of the rolling trailer (iv).
- Finally, the additional contribution of the roll motion of the second trailer. This contribution was the straightforward addition to lateral motion of the trailer c.g. due to roll and the position of the c.g. above the roll axis.

There is one more very interesting, but somewhat more subtle, implication of roll motion. We have observed that the path of the RA reference point was generally not influenced by the trailer spring mass roll motion. Further, trailer roll motion did produce increased peak lateral accelerations at the trailer c.g. simply by increasing the lateral displacement peaks. Carrying the logic further, we can hypothesize that:

- The increased lateral acceleration implies that the motivating lateral forces must also have increased. Since tire forces are, ultimately, *the* motivating forces, then the level of tire forces must have increased.
- Tire forces derive from slip angles that derive from the motion of the vehicle. However, we have observed that the motion of RA was *not* influenced by roll. Therefore, since the path of the *tires* must have been different, we conclude that the *yaw* displacement of the trailers (i.e., rotation of the trailer about the point RA in the overhead view) must have been influenced by roll motion. The yaw motions of the rolling trailer must have been exaggerated relative to the yaw motion of the nonrolling trailer.

The data presented in figure H-7 confirms this reasoning. Figure H-7 shows the plots of the yaw angle time history of the prototype 9-axle double in the simulation runs of conditions 2 and 3, 2.5 second period. The yaw motion of the rolling trailer (condition 3) is notably larger than the yaw motions of the nonrolling trailer (condition 2)[3].

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[3] Others of the test vehicles showed larger differences than what is shown for this vehicle.

The same is true for the yaw motions of the second trailer and, indeed, for the tractor. We chose to display the results for the first trailer to emphasize the following. The additional yaw motion not only adds to the slip angle of the trailer tires, but it also serves to add to the lateral displacement of the pintle hitch at the rear of the trailer. The additional yaw apparent in the figure adds approximately 0.34 inch of lateral displacement to the hitch over a baseline of about 5 inches. So, a portion of the additional pintle hitch motion referred to in point (2) of the discussion of figures H-5 and H-6 derives from this mechanism. In this particular case, this portion is certainly not major, but it is significant.

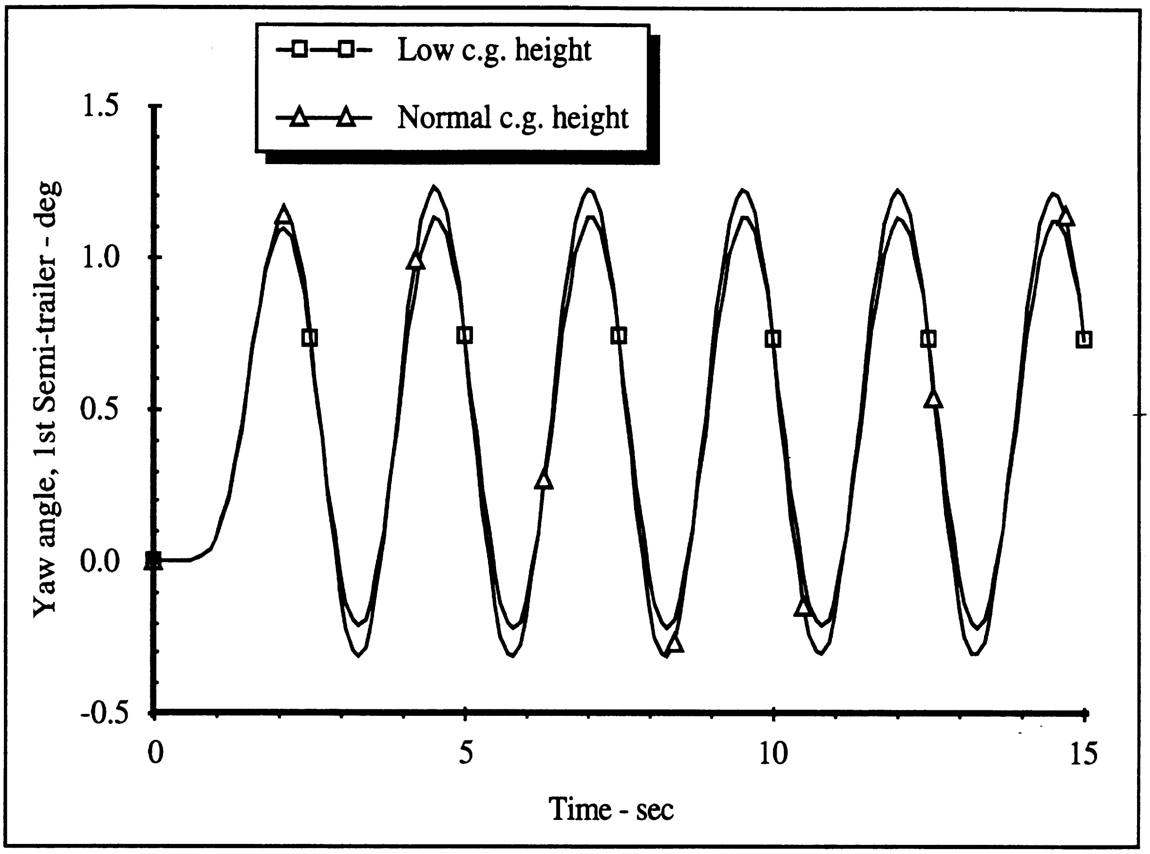

Figure H-7. Yaw Angle of the first semi-trailer of the prototype 9-axle double in the continuous maneuvers (conditions 2 and 3).

CONCLUSION

The mechanisms that cause the calculation procedures of the *Simplified Model* to produce different values of rearward amplification than those which are obtained using *Yaw/Roll* simulations have been clearly explained. The largest part of the difference derives from the fact that the *Simplified Model* does not include roll motion and that roll motion influences rearward amplification in a manner heretofore not recognized. The difference in the types of maneuvers is not terribly important. This is mostly a matter of luck since there is a strong synergistic relation between the maneuver response and roll motion. If the Simplified Model had included roll motion, then the difference in maneuvers would have been very important.

It should be explicitly noted that *Simplified Model* results accurately reflect the influence of the vehicle elements that the model includes. That is, this model is useful for investigating the relative influence of those vehicle parameters that it includes. On the other hand, the *Simplified Model* can not be expected to produce accurate "absolute" results because it does not include some important elements of the vehicle. (In varying degrees, the later statement holds for all simulations, indeed, for all analyses.)