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Applied Research in Statistics - Mathematics - Operations Research

RESEARCH ON THE DEVELOPMENT OF A STATISTICAL IMPACT ACCELERATION INJURY PREDICTION MODEL FROM $-G_x$ ACCELERATOR RUNS

by

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and
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I. INTRODUCTION

This report discusses research on the development of a statistically based model for predicting human head/neck impact acceleration injury. Model development is focused on those situations in which the torso is well-restrained, but the head and neck are unrestrained. One example, of course, is the Navy pilot in the cockpit of his plane.

The objective of the research discussed here is the development of a model that can adequately predict the probability of head/neck injury based on head dynamic response data. Once this objective is met, the model, and the information it provides, should be a major component in development of improved restraint systems and other protection methods.

In order to provide a basis for comparison, three classes of prediction models are considered in this report. One class is based on head dynamic response variables only, another is based on sled acceleration profile terms only, and the third class is based on the combined set of independent variables. All of the prediction models are of the same functional type as those considered in previous Desmatics technical reports [6], [7], [8]:

$$P(\underline{x}) = \{1 + \exp[-(\beta_0 + \sum_{1}^{k} \beta_i x_i)]\}^{-1}$$

where:

$\underline{x} = (x_1, \ldots, x_k)$ denotes the set of independent variables considered,

$(\beta_0, \beta_1, \ldots, \beta_k)$ denotes a set of parameter values,

and $P(\underline{x})$ denotes the true probability of injury corresponding to $\underline{x}$.

This type of model was previously applied to observed data from a set of 28 $-G_x$ accelerator runs involving subhuman primates (Rhesus monkeys) with securely restrained torso and unrestrained head [7]. The data was collected by the Naval Biodynamics Laboratory (NBDL) as part of its research effort on impact acceleration injury prevention. The NBDL data base now consists of 68 $-G_x$ accelerator runs. (The 28 runs that were analyzed previously constitute a subset of the existing data.) In addition to examining this larger data set, this report considers additional independent variables. The variables comprising the former data set and the additions to the new one are listed in Table 1.

The data base is used to develop the "best" one-variable, two-variable and three-variable models for each of the three classes. In the context here, the "best" model is the one which maximizes the log likelihood function at each stage [4]. (In all cases, the contribution of additional terms beyond the three-variable models was negligible.) The predictions from the "best" models are compared with the observed results to evaluate performance.

Sled Profile Variables

*1. Peak acceleration (G)

*2. Rate of acceleration onset (G/sec)

3. Duration of peak acceleration (msec)

Head Dynamic Response Variables

*1. Peak resultant angular acceleration (rad/sec^2)

*2. Peak resultant linear acceleration (m/sec^2)

*3. Peak resultant angular velocity (rad/sec)

4. Peak x-component of angular acceleration (rad/sec^2)

5. Peak y-component of angular acceleration (rad/sec^2)

6. Peak z-component of angular acceleration (rad/sec^2)

7. Peak x-component of linear acceleration (m/sec^2)

8. Peak y-component of linear acceleration (m/sec^2)

9. Peak z-component of linear acceleration (m/sec^2)

10. Peak x-component of angular velocity (rad/sec)

11. Peak y-component of angular velocity (rad/sec)

12. Peak z-component of angular velocity (rad/sec)

*Denotes a variable in the former data set.

Table 1: Independent Variables Available for Model Building

II. MODEL CONSTRUCTION

As mentioned in the previous section, the current NBDL data base consists of 68 observations. However, because of missing data on five of these runs, only 63 observations were used in model construction. Since some of the monkeys were run more than once, dependence exists in the data. However, in model development the assumption is made that any resulting bias in the parameter estimates is small. In fact, if there is a bias, it should result in a model that overpredicts probabilities. This is, of course, the best direction for model bias, since it provides an extra margin of safety.

Since the occurrence or nonoccurrence of injury is difficult to determine, the criterion of fatality is used in the model building process. The models are thus fatality prediction models. The data for all 63 observations is presented in Table 2. In this table, the observed probability of fatality for a given accelerator run is denoted by 1 for a fatal run and 0 for a nonfatal run.

A. DETERMINATION OF APPROPRIATE MODELS

A forward selection method [1,2] was used to determine the inclusion of important variables. Importance of each of the variables was determined by likelihood-ratio tests [3] that are used in conjuction with nested models. This involved computing the following quantities:

$L_1 = -2$ log likelihood for model containing $(x_1,\dots,x_k)$.

and $L_2 = -2$ log likelihood for model containing $(x_1,\dots,x_{k+1})$.

Under the null hypothesis that the additional variable x_{k+1} provides no improvement in the model, the statistic $L_1 - L_2$ has an approximate Chi-square

Run Number	Subject Number	Observed Probability	Peak Sled Acceleration	Rate of Acceleration Onset	Duration of Peak	Head Angular Acceleration			
						Peak x-Component	Peak y-Component	Peak z-Component	Peak Resultant
LX3710	ARNA02	0	9.9	641	55.6	700	-640	-700	1120
LX3713	ARNA02	0	10.0	753	51.0	570	1550	-1260	2050
LX3714	ARNA02	0	61.1	3381	17.6	-2800	3700	8000	9500
LX3715	ARNA02	0	61.1	3677	18.3	-3200	6700	11000	12700
LX3695	ARNA28	0	10.0	664	54.9	-700	1050	2300	2800
LX3696	ARNA28	0	5.6	2138	53.0	240	650	-310	650
LX3697	ARNA28	0	45.0	2423	26.4	-7000	2750	15000	16800
LX3698	ARNA28	0	44.5	2449	27.3	-7400	2750	16600	18500
LX3691	AR0012	0	10.1	1470	61.2	1010	320	-1650	1850
LX3692	AR0012	0	5.3	986	56.0	-560	325	920	1100
LX3693	AR0012	0	74.2	4398	16.3	-9000	6200	14000	16500
LX3694	AR0012	0	78.3	5111	16.1	-16000	4900	27500	32000
LX3025	AR3923	0	9.8	599	51.9	-970	1190	2550	2825
LX3024	AR4107	0	10.0	950	54.4	-1060	1300	2020	2300
LX3027	AR4114	0	10.4	4630	49.6	1210	2250	-3300	4100
LX3028	AR4114	0	41.6	1804	24.0	3200	3400	-12500	13200
LX3707	AR8790	0	10.0	726	47.0	520	805	-600	1050
LX3708	AR8790	0	5.2	1805	73.5	310	620	-750	1020
LX3709	AR8790	1	87.9	5660	15.3	16500	13500	-28000	34000
LX3703	AR8802	0	10.1	661	53.3	-1600	1450	3000	3700
LX3704	AR8802	0	5.3	1739	76.7	380	350	-450	660
LX3705	AR8802	0	64.3	3672	17.6	8100	14100	-16300	23000
LX3706	AR8802	0	63.7	3786	18.7	10000	12500	-19000	24000
LX3183	AR8824	0	10.5	558	48.9	-910	1100	700	1400
LX3184	AR8824	0	62.4	4111	21.5	10000	8200	-13000	16000
LX3186	AR8857	0	82.7	6287	15.7	12100	10800	-34000	29000
LX3187	AR8863	0	10.2	612	52.2	-975	1125	1150	1470
LX3188	AR8863	1	104.5	8180	13.7	-13500	16000	23500	29000
LX3189	AR8866	0	10.3	1578	56.6	-1350	1150	2200	2600
LX3191	AR8866	0	10.2	671	55.0	-670	1000	1000	1240
LX3192	AR8866	1	105.3	8769	13.6	12000	6000	-19000	22500
LX3699	AR8872	0	4.3	352	1.0	1600	900	-2500	3200
LX3700	AR8872	0	5.2	1453	59.6	370	520	-700	880
LX3701	AR8872	0	44.5	2154	25.5	10000	5250	-14200	17600
LX3702	AR8872	0	44.3	2201	26.3	12000	6000	-14000	18800
LX1897	A03896	1	192.9	29126	9.3	-20000	19000	6500	21000
LX1081	A03921	0	10.3	1533	49.6	-300	800	1000	1190
LX1083	A03921	0	38.3	3512	27.2	-1600	1250	800	2005
LX1084	A03921	0	38.5	3832	27.3	-2200	3750	5700	6800
LX1085	A03921	0	38.2	3478	26.9	-1725	2150	2600	3200
LX1086	A03921	0	39.4	3829	27.3	-2100	1500	2750	3450
LX1087	A03921	0	39.6	3775	26.6	-2700	4500	-4500	5700
LX1364	A03921	0	36.9	1612	26.5	-2200	4300	4400	5650
LX1365	A03921	1	108.7	13398	18.5	-37000	22600	-57000	52000
LX1893	A03924	0	110.4	9306	14.2	9200	21000	-24000	31000
LX1894	A03933	0	108.6	9303	14.6	-11000	15000	24000	27600
LX1362	A03935	0	105.5	17949	21.0	16500	31000	15000	38000
LX1363	A03935	1	123.0	20762	18.7	-18000	-12000	10000	23000
LX1891	A03943	0	83.8	6334	15.8	-9000	15500	26000	30000
LX1896	A03946	1	131.4	14980	13.6	-6000	23000	12100	26800
LX1892	A03948	0	83.7	7342	17.1	-4200	10000	20000	20700
LX1895	A03951	1	130.7	12698	12.9	-10000	16500	35000	38000
LX1359	A04099	0	106.9	16586	19.2	-11000	14500	14000	18000
LX1360	A04099	1	128.2	21421	17.2	20000	18500	-45000	52000
LX1889	A04101	0	34.8	1614	27.5	-6500	7500	-6500	9700
LX1890	A04101	0	33.3	1561	28.1	-1870	2700	5300	5700
LX1898	A04101	0	32.5	1585	28.9	750	3800	-1600	4000
LX1899	A04101	0	32.5	1413	27.9	1100	2750	-3200	3450
LX1900	A04101	0	74.8	5690	16.8	3600	10000	-11000	14500
LX1901	A04101	0	74.7	5418	16.9	1800	10000	-6000	13500
LX1902	A04101	0	75.6	6232	17.1	1100	-5000	-2900	5750
LX1903	A04101	0	75.3	6308	17.2	2900	-5600	-4900	7000
LX1905	A04101	1	126.4	13814	13.6	7000	-8300	-11800	16700

Table 2: The Data Set

Run Number	Subject Number	Observed Probability	Head Angular Velocity				Head Linear Acceleration			
			Peak x-Component	Peak y-Component	Peak z-Component	Peak Resultant	Peak x-Component	Peak y-Component	Peak z-Component	Peak Resultant
LX3710	ARNA02	0	9.0	-8.9	-10.2	13.9	-195	59	-117	220
LX3713	ARNA02	0	6.8	21.0	-20.5	29.5	-192	73	-20	205
LX3714	ARNA02	0	-16.0	17.0	50.0	55.0	-1460	290	-770	1660
LX3715	ARNA02	0	-21.5	36.5	80.0	89.0	-1220	350	-720	1340
LX3695	ARNA28	0	-8.5	12.0	35.0	40.0	-100	-130	-60	200
LX3696	ARNA28	0	4.1	14.0	-5.3	15.0	-88	22	12	90
LX3697	ARNA28	0	-44.0	31.0	100.0	110.0	-770	-610	-350	900
LX3698	ARNA28	0	-45.0	32.0	103.0	114.0	-840	-650	-355	1010
LX3691	AR0012	0	19.5	8.4	-32.0	37.5	-130	92	-67	143
LX3692	AR0012	0	-12.2	9.0	20.7	24.6	-61	-46	-26	72
LX3693	AR0012	C	-50.0	45.0	78.0	92.0	-1400	-480	-700	1500
LX3694	AR0012	0	-75.0	31.0	135.0	158.0	-1140	-850	-800	1500
LX3025	AR3923	0	-13.0	18.4	38.0	44.0	-120	-165	42	148
LX3024	AR4107	0	-12.6	12.2	26.2	30.0	-176	-114	-45	168
LX3027	AR4114	0	11.2	21.4	-35.5	42.5	-125	175	87	335
LX3028	AR4114	0	37.0	15.0	-102.0	110.0	-810	-570	-365	1010
LX3707	AR8790	0	5.1	7.4	-7.0	11.0	-190	41	-105	210
LX3708	AR8790	0	7.7	13.0	-19.3	23.8	-55	48	33	88
LX3709	AR8790	1	60.0	51.0	-122.0	145.0	-1750	1200	-1040	2200
LX3703	AR8802	0	-20.0	25.0	40.0	51.0	-110	-136	-13	170
LX3704	AR8802	0	13.3	10.7	-16.7	23.0	-28	50	27	56
LX3705	AR8802	0	37.5	87.0	-82.0	123.0	-1165	690	-950	1390
LX3706	AR8802	0	42.0	73.0	-90.0	122.0	-1210.	830	-910	1460
LX3183	AR8824	0	-6.5	8.0	-7.2	11.3	-184	-52	-90	95
LX3184	AR8824	0	44.0	50.0	-60.0	76.0	-1425	850	-550	1475
LX3186	AR8857	0	62.0	60.0	-200.0	120.0	-1460	-1900	-1060	2600
LX3187	AR8863	0	-12.7	14.2	11.3	19.5	-170	-73	-63	175
LX3188	AR8863	1	-45.0	135.0	90.0	120.0	-2500	-1200	-850	2600
LX3189	AR8866	0	-15.0	9.0	28.0	35.0	-155	-108	-88	182
LX3191	AR8866	0	-10.0	4.0	14.0	17.0	-216	-47	-108	228
LX3192	AR8866	1	49.0	17.0	-75.0	95.0	-2100	980	-775	2380
LX3699	AR8872	0	22.5	17.0	-30.0	44.0	-140	128	-102	188
LX3700	AR8872	0	8.2	17.5	-13.0	19.8	-88	40	-30	98
LX3701	AR8872	0	69.0	37.5	-108.0	130.0	-665	-620	-720	1130
LX3702	AR8872	0	70.0	48.0	-135.0	140.0	-700	-500	-680	1060
LX1897	A03896	1	-52.0	100.0	20.0	100.0	-2500	1000	-1700	3050
LX1081	A03921	0	-5.8	8.3	12.5	15.2	-142	-65	-27	147
LX1083	A03921	0	-10.0	8.7	5.2	12.8	-630	-50	-195	650
LX1084	A03921	0	-18.0	24.0	46.0	54.0	-550	-390	-290	625
LX1085	A03921	0	-12.0	15.0	19.0	25.6	-630	-145	-280	635
LX1086	A03921	0	-15.0	10.8	24.0	28.9	-620	-205	-235	640
LX1087	A03921	0	8.0	28.0	-19.0	44.0	-720	320	-290	730
LX1364	A03921	0	-27.0	32.5	43.0	55.5	-640	-400	-300	680
LX1365	A03921	1	-193.0	160.0	-350.0	350.0	9200	1500	-1550	9200
LX1893	A03924	0	37.5	100.0	-110.0	140.0	-2150	1350	-1350	2400
LX1894	A03933	0	-53.0	62.0	120.0	133.0	-1550	-1300	-1350	2550
LX1362	A03935	0	82.0	145.0	110.0	120.0	-4000	1700	-860	4100
LX1363	A03935	1	-60.0	-80.0	36.0	105.0	-1800	-400	-840	2000
LX1891	A03943	0	-46.0	75.0	130.0	148.0	-1300	1410	-700	1950
LX1896	A03946	1	-31.5	80.0	62.0	105.0	-2400	-615	-1700	2490
LX1892	A03948	0	-25.0	82.0	124.0	137.0	-1260	950	-560	1630
LX1895	A03951	1	-56.0	88.0	200.0	220.0	-1400	1900	-1650	2880
LX1359	A04099	0	-63.0	51.5	60.0	89.0	-2630	-900	-820	2760
LX1360	A04099	1	85.0	45.0	-233.0	250.0	-2400	-4200	-2440	5200
LX1889	A04101	0	-50.0	55.0	-125.0	132.0	-1200	1200	-400	1460
LX1890	A04101	0	-17.6	12.5	45.0	8.0	-535	-285	-275	615
LX1898	A04101	0	5.3	41.5	-20.0	43.0	-660	90	-190	670
LX1899	A04101	0	14.3	26.5	-32.0	40.0	-560	255	-165	580
LX1900	A04101	0	22.0	66.0	-68.0	90.0	-1430	720	-590	1540
LX1901	A04101	0	9.0	68.0	-28.0	78.0	-1640	370	-680	1680
LX1902	A04101	0	5.0	-30.0	-10.6	32.0	-1605	-440	-880	1770
LX1903	A04101	0	9.0	-27.0	-19.0	40.0	-1950	310	-940	1990
LX1905	A04101	1	23.0	-35.0	-38.0	53.0	-2710	710	-1500	2810

Table 2: The Data Set (continued)

distribution with one degree of freedom. The hypothesis may be tested by comparing the value of $L_1 - L_2$ with the upper percentage points of the Chi-square distribution.

B. HEAD DYNAMIC REPSONSE VARIABLES

As previously mentioned, up to three head dynamic response variables were considered in model development. As a consequence of the forward selection procedure used, (i.e., at each stage the variable that maximized the log likelihood function was entered next) the variables in the "best" one-variable and two-variable models constituted a subset of the variables chosen for the "best" three-variable model. A statistical analysis of the data indicated that the best one-variable, two-variable, and three-variable models are those based on, respectively, the three sets

(1) x_1

(2) x_1, x_2

(3) x_1, x_2, x_3

where

x_1 denotes the peak z-component of head linear acceleration measured in meters/sec^2,

x_2 denotes the peak head resultant linear acceleration measured in meters/sec^2,

and x_3 denotes the peak y-component of head angular acceleration measured in radians/sec^2.

Because of the nesting in these models, the relative contribution of each of the variables may be tested. The log likelihoods, the Chi-square values and associated p-values presented in Table 3 contain the relevant information. In the first stage, x_1 was tested to determine whether it significantly improved a model which assumed constant probability over all the values of the three head

Variable Set	-2 Log Likelihood	Chi-Square	p-value
Constant Only	55.13		
x_1	25.58	29.55	0.00
x_1, x_2	24.06	1.52	0.22
x_1, x_2, x_3	20.64	3.42	0.06

y_1 denotes peak z-component of head linear acceleration

y_2 denotes peak head linear resultant acceleration

y_3 denotes peak y-component of head angular acceleration

Table 3: Head Dynamic Response Variable Sets with -2 Log Likelihood and Chi-Square Values

dynamic response variables. The observed Chi-square value of 29.55, which is statistically significant at the 0.001 level, indicated that this variable did result in an improved model.

The second stage of testing involved consideration of the addition of another variable to the model which included only variable x_1. Variable x_2 was the next to enter the model. The addition of x_2, which resulted in an observed Chi-square value of 1.52 and an associated p-value of 0.22, did little to improve the model. However, when x_3 was added to the model containing x_1 and x_2, the Chi-square value of 3.42 and its corresponding p-value of 0.06 indicated that there was an enhancement to the model.

Thus, based on the data available, the best one-variable, two-variable and three-variable head dynamic response models are:

$$\hat{P}(x_1) = \{1 + \exp[-(-5.7852 - .0048099x_1)]\}^{-1} \tag{1}$$

$$\hat{P}(x_1,x_2) = \{1 + \exp[-(-6.4795 - .0035446x_1 + .0008661x_2)]\}^{-1} \tag{2}$$

$$\hat{P}(x_1,x_2,x_3) = \{1 + \exp[-(-8.1485 - .004019x_1 + .001901x_2 + .000117x_3)]\}^{-1} \tag{3}$$

where $\hat{P}(x)$ denotes the predicted probability. The discussion of the contribution supplied by each of the variables to the model indicates that either model (1) or (3) could be chosen for prediction purposes. Table 4 presents, for both models, a comparison of observed (i.e., 0 or 1) and predicted probability, where the observations are arranged in order of increasing predicted probability for model (1).

Run Number	Subject Number	Observed Probability	Predicted Probability Model (1)	Predicted Probability Model (3)	Peak z-Component of Head Linear Acceleration (x_1)	Peak Head Linear Resultant Acceleration (x_2)	Peak y-Component of Head Angular Acceleration (x_3)
LX3027	AR4114	0	0.0020	0.0003	87.0	335.0	2250.0
LX3025	AR3923	0	0.0025	0.0003	42.0	148.0	1190.0
LX3708	AR8790	0	0.0026	0.0003	33.0	88.0	620.0
LX3704	AR8802	0	0.0027	0.0003	27.0	56.0	350.0
LX3696	ARNA28	0	0.0029	0.0003	12.0	90.0	650.0
LX3703	AR8802	0	0.0033	0.0004	-13.0	170.0	1450.0
LX3713	ARNA02	0	0.0034	0.0004	-20.0	205.0	1550.0
LX1081	A03921	0	0.0035	0.0004	-27.0	147.0	800.0
LX3692	AR0012	0	0.0035	0.0004	-26.0	72.0	325.0
LX3700	AR8872	0	0.0035	0.0004	-30.0	98.0	520.0
LX3024	AR4107	0	0.0038	0.0004	-45.0	168.0	1300.0
LX3187	AR8863	0	0.0041	0.0005	-63.0	175.0	1125.0
LX3695	ARNA28	0	0.0041	0.0005	-60.0	200.0	1050.0
LX3691	AR0012	0	0.0042	0.0005	-67.0	143.0	320.0
LX3183	AR8824	0	0.0047	0.0004	-90.0	95.0	1100.0
LX3189	AR8866	0	0.0047	0.0005	-88.0	182.0	1150.0
LX3699	AR8872	0	0.0050	0.0006	-102.0	188.0	900.0
LX3191	AR8866	0	0.0051	0.0006	-108.0	228.0	1000.0
LX3707	AR8790	0	0.0051	0.0006	-105.0	210.0	805.0
LX3710	ARNA02	0	0.0054	0.0008	-117.0	220.0	-640.0
LX1899	A04101	0	0.0067	0.0012	-165.0	580.0	2750.0
LX1898	A04101	0	0.0076	0.0014	-190.0	670.0	3800.0
LX1083	A03921	0	0.0078	0.0019	-195.0	650.0	1250.0
LX1086	A03921	0	0.0094	0.0021	-235.0	640.0	1500.0
LX1890	A04101	0	0.0114	0.0020	-275.0	615.0	2700.0
LX1085	A03921	0	0.0117	0.0023	-280.0	635.0	2150.0
LX1084	A03921	0	0.0122	0.0020	-290.0	625.0	3750.0
LX1087	A03921	0	0.0122	0.0022	-290.0	730.0	4500.0
LX1364	A03921	0	0.0128	0.0021	-300.0	680.0	4300.0
LX3697	ARNA28	0	0.0163	0.0047	-350.0	900.0	2750.0
LX3698	ARNA28	0	0.0167	0.0059	-355.0	1010.0	2750.0
LX3028	AR4114	0	0.0175	0.0057	-365.0	1010.0	3400.0
LX1889	A04101	0	0.0206	0.0096	-400.0	1460.0	7500.0
LX3184	AR8824	0	0.0415	0.0165	-550.0	1475.0	8200.0
LX1892	A03948	0	0.0434	0.0186	-560.0	1630.0	10000.0
LX1900	A04101	0	0.0499	0.0177	-590.0	1540.0	10000.0
LX1901	A04101	0	0.0748	0.0327	-680.0	1680.0	10000.0
LX3702	AR8872	0	0.0748	0.0163	-680.0	1060.0	6000.0
LX1891	A03943	0	0.0818	0.0312	-700.0	1950.0	15500.0
LX3693	AR0012	0	0.0818	0.0390	-700.0	1500.0	6200.0
LX3701	AR8872	0	0.0893	0.0237	-720.0	1130.0	5250.0
LX3715	ARNA02	0	0.0893	0.0297	-720.0	1340.0	6700.0
LX3714	ARNA02	0	0.1109	0.0888	-770.0	1660.0	3700.0
LX3192	AR8866	1	0.1133	0.2301	-775.0	2380.0	6000.0
LX3694	AR0012	0	0.1259	0.0659	-800.0	1500.0	4900.0
LX1359	A04099	0	0.1369	0.2149	-820.0	2760.0	14500.0
LX1363	A03935	1	0.1487	0.6059	-840.0	2000.0	-12000.0
LX3188	AR8863	1	0.1549	0.1606	-850.0	2600.0	16000.0
LX1362	A03935	0	0.1613	0.3750	-860.0	4100.0	31000.0
LX1902	A04101	0	0.1747	0.3401	-880.0	1770.0	-5000.0
LX3706	AR8802	0	0.1965	0.0402	-910.0	1460.0	12500.0
LX1903	A04101	0	0.2203	0.5167	-940.0	1990.0	-5600.0
LX3705	AR8802	0	0.2287	0.0345	-950.0	1390.0	14100.0
LX3709	AR8790	1	0.3137	0.2043	-1040.0	2200.0	13500.0
LX3186	AR8857	0	0.3347	0.4493	-1060.0	2600.0	10800.0
LX1893	A03924	0	0.6700	0.3525	-1350.0	2400.0	21000.0
LX1894	A03933	0	0.6700	0.5932	-1350.0	2550.0	15000.0
LX1905	A04101	1	0.8068	0.9851	-1500.0	2810.0	-8300.0
LX1365	A03921	1	0.8416	1.0000	-1550.0	9200.0	22600.0
LX1895	A03951	1	0.8958	0.8845	-1650.0	2880.0	16500.0
LX1896	A03946	1	0.9162	0.6763	-1700.0	2490.0	23000.0
LX1897	A03896	1	0.9162	0.9062	-1700.0	3050.0	19000.0
LX1360	A04099	1	0.9974	0.9999	-2440.0	5200.0	18500.0

Table 4: A Comparison of Observed and Predicted Probabilities for Head Dynamic Response Models (1) x_1 and (3) x_1, x_2, x_3.

C. SLED PROFILE VARIABLES

The same technique used in the previous section was also employed for choosing the "best" one-variable, two-variable, and three-variable sled profile models. The sled profile variables under consideration here are denoted by z_1, z_2, and z_3, where:

z_1 is the peak sled acceleration measured in G's,

z_2 is the duration of peak measured in milliseconds,

and z_3 is the rate of sled acceleration onset measured in G/sec.

As Table 5 indicates, the "best" one-variable model is based on z_1. The Chi-square value of 38.43 for z_1 and its corresponding p-value of 0.001 reveals that peak sled acceleration is essential to the sled profile model. The resulting model is given by:

$$\hat{P}(z_1) = \{1 + \exp[-(-12.10 + .11462z_1)]\}^{-1} \tag{4}$$

The second stage of testing provided the following "best" two-variable model:

$$\hat{P}(z_1,z_2) = \{1 + \exp[-(-6.8859 + .11239z_1 - .30402z_2)]\}^{-1} \tag{5}$$

However, the addition of z_2, duration of peak, did little for the betterment of the model, with a Chi-square value of 1.37 and a p-value of 0.24.

Subsequently, in the third stage, z_3 was added to the model containing z_1 and z_2. The resulting three-variable model is:

$$\hat{P}(z_1,z_2,z_3) = \{1 + \exp[-(-5.6780 + .10391z_1 - .34906z_2 + .00003557z_3)]\}^{-1} \tag{6}$$

The Chi-square value of 0.01 for z_3 is evidence that this variable is not an important addition to the model.

As indicated by these results, the "best" sled profile model is the one-variable model (4) containing only peak sled acceleration. Table 6 presents,

Variable Set	-2 Log Likelihood	Chi-Square	p-value
Constant Only	55.13		
z_1	16.70	38.43	0.00
z_1, z_2	15.33	1.37	0.24
z_1, z_2, z_3	15.32	0.01	0.93

z_1 denotes peak sled acceleration

z_2 denotes duration of peak

z_3 denotes rate of onset

Table 5: Sled Acceleration Profile Variable Sets with -2 Log Likelihood and Chi-Square Values

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Sled Acceleration (z_1)
LX3699	AR8872	0	0.0000	4.3
LX3700	AR8872	0	0.0000	5.2
LX3708	AR8790	0	0.0000	5.2
LX3692	AR0012	0	0.0000	5.3
LX3704	AR8802	0	0.0000	5.3
LX3696	ARNA28	0	0.0000	5.6
LX3025	AR3923	0	0.0000	9.8
LX3710	ARNA02	0	0.0000	9.9
LX3024	AR4107	0	0.0000	10.0
LX3707	AR8790	0	0.0000	10.0
LX3713	ARNA02	0	0.0000	10.0
LX3695	ARNA28	0	0.0000	10.0
LX3691	AR0012	0	0.0000	10.1
LX3703	AR8802	0	0.0000	10.1
LX3187	AR8863	0	0.0000	10.2
LX3191	AR8866	0	0.0000	10.2
LX3189	AR8866	0	0.0000	10.3
LX1081	A03921	0	0.0000	10.3
LX3027	AR4114	0	0.0000	10.4
LX3183	AR8824	0	0.0000	10.5
LX1899	A04101	0	0.0002	32.5
LX1898	A04101	0	0.0002	32.5
LX1890	A04101	0	0.0003	33.3
LX1889	A04101	0	0.0003	34.8
LX1364	A03921	0	0.0004	36.9
LX1085	A03921	0	0.0004	38.2
LX1083	A03921	0	0.0004	38.3
LX1084	A03921	0	0.0005	38.5
LX1086	A03921	0	0.0005	39.4
LX1087	A03921	0	0.0005	39.6
LX3028	AR4114	0	0.0007	41.6
LX3702	AR8872	0	0.0009	44.3
LX3698	ARNA28	0	0.0009	44.5
LX3701	AR8872	0	0.0009	44.5
LX3697	ARNA28	0	0.0010	45.0
LX3714	ARNA02	0	0.0061	61.1
LX3715	ARNA02	0	0.0061	61.1
LX3184	AR8824	0	0.0070	62.4
LX3706	AR8802	0	0.0082	63.7
LX3705	AR8802	0	0.0087	64.3
LX3693	AR0012	0	0.0267	74.2
LX1901	A04101	0	0.0283	74.7
LX1900	A04101	0	0.0286	74.8
LX1903	A04101	0	0.0302	75.3
LX1902	A04101	0	0.0312	75.6
LX3694	AR0012	0	0.0421	78.3
LX3186	AR8857	0	0.0678	82.7
LX1892	A03948	0	0.0754	83.7
LX1891	A03943	0	0.0762	83.8
LX3709	AR8790	1	0.1166	87.9
LX3188	AR8863	1	0.4695	104.5
LX3192	AR8866	1	0.4924	105.3
LX1362	A03935	0	0.4981	105.5
LX1359	A04099	0	0.5381	106.9
LX1894	A03933	0	0.5861	108.6
LX1365	A03921	1	0.5888	108.7
LX1893	A03924	0	0.6351	110.4
LX1363	A03935	1	0.8806	123.0
LX1905	A04101	1	0.9159	126.4
LX1360	A04099	1	0.9305	128.2
LX1895	A03951	1	0.9469	130.7
LX1896	A03946	1	0.9508	131.4
LX1897	A03896	1	1.0000	192.9

Table 6: A Comparison of Observed and Predicted Probability for Model Based on Peak Sled Acceleration

for this model, a comparison of observed (i.e., 0 or 1) and predicted probability, where the observations are arranged in order of increasing predicted probability.

D. COMBINED HEAD AND SLED VARIABLES

The complete set of head dynamic response and sled profile variables was also used in the development of a prediction model. As Table 7 indicates, $y_1 \equiv z_1$ (peak sled acceleration) provided the best fitting one-variable model, which is given by (4). The next term to enter the model was y_2 (the peak z-component of head angular velocity). This variable had a Chi-square value of 2.42 with an associated p-value of 0.12. The resulting model is:

$$\hat{P}(y_1,y_2) = \{1+\exp[-(-13.582+.12863y_1-.0082432y_2)]\}^{-1} \qquad (7)$$

The "best" three-variable model was obtained by introducing $y_3 \equiv z_2$ (duration of peak sled acceleration) into the model containing y_1 and y_2. The resulting model is:

$$\hat{P}(y_1,y_2,y_3) = \{1+\exp[-(-6.9958+.12234y_1-.008002y_2-.37337y_3)]\}^{-1} \qquad (8)$$

However, the Chi-square value of 1.51 and its corresponding p-value of 0.22 indicate that duration of peak did not improve much on the "best" two-variable model.

Thus, the "best" combined (head dynamic response and sled profile) model appears to be the two-variable model containing peak sled acceleration and the peak z-component of head angular velocity. Table 8 shows the agreement between predictions and observations that is obtained for this model.

Variable Set	-2 Log Likelihood	Chi-Square	p-value
Constant Only	55.13		
y_1	16.70	38.43	0.00
y_1, y_2	14.28	2.42	0.12
y_1, y_2, y_3	12.77	1.51	0.22

y_1 denotes peak sled acceleration

y_2 denotes peak z-component of head angular velocity

y_3 denotes duration of peak sled acceleration

Table 7: Combined Variable Sets with -2 Log Likelihood and Chi-Square Values

Run Number	Subject Number	Observed Probability	Predicted Probability	Peak Sled Acceleration (y_1)	Peak z-Component of Head Angular Velocity (y_2)
LX3692	AR0012	0	0.0000	5.3	20.7
LX3696	ARNA28	0	0.0000	5.6	-5.3
LX3700	AR8872	0	0.0000	5.2	-13.0
LX3699	AR8872	0	0.0000	4.3	-30.0
LX3704	AR8802	0	0.0000	5.3	-16.7
LX3708	AR8790	0	0.0000	5.2	-19.3
LX3025	AR3923	0	0.0000	9.8	38.0
LX3703	AR8802	0	0.0000	10.1	40.0
LX3695	ARNA28	0	0.0000	10.0	35.0
LX3024	AR4107	0	0.0000	10.0	26.2
LX3189	AR8866	0	0.0000	10.3	28.0
LX3191	AR8866	0	0.0000	10.2	14.0
LX3187	AR8863	0	0.0000	10.2	11.3
LX1081	AO3921	0	0.0000	10.3	12.5
LX3707	AR8790	0	0.0000	10.0	-7.0
LX3710	ARNA02	0	0.0000	9.9	-10.2
LX3183	AR8824	0	0.0000	10.5	-7.2
LX3713	ARNA02	0	0.0000	10.0	-20.5
LX3691	AR0012	0	0.0000	10.1	-32.0
LX3027	AR4114	0	0.0000	10.4	-35.5
LX1890	AO4101	0	0.0001	33.3	45.0
LX1898	AO4101	0	0.0001	32.5	-20.0
LX1364	AO3921	0	0.0001	36.9	43.0
LX1899	AO4101	0	0.0001	32.5	-32.0
LX1084	AO3921	0	0.0001	38.5	46.0
LX1085	AO3921	0	0.0001	38.2	19.0
LX1086	AO3921	0	0.0002	39.4	24.0
LX3698	ARNA28	0	0.0002	44.5	103.0
LX1083	AO3921	0	0.0002	38.3	5.2
LX3697	ARNA28	0	0.0002	45.0	100.0
LX1087	AO3921	0	0.0002	39.6	-19.0
LX1889	AO4101	0	0.0003	34.8	-125.0
LX3028	AR4114	0	0.0006	41.6	-102.0
LX3701	AR8872	0	0.0009	44.5	-108.0
LX3702	AR8872	0	0.0011	44.3	-135.0
LX3715	ARNA02	0	0.0017	61.1	80.0
LX3714	ARNA02	0	0.0022	61.1	50.0
LX3184	AR8824	0	0.0063	62.4	-60.0
LX3693	AR0012	0	0.0092	74.2	78.0
LX3706	AR8802	0	0.0095	63.7	-90.0
LX3705	AR8802	0	0.0096	64.3	-92.0
LX3694	AR0012	0	0.0097	78.3	135.0
LX1891	AO3943	0	0.0204	83.8	130.0
LX1892	AO3948	0	0.0211	83.7	124.0
LX1902	AO4101	0	0.0225	75.6	-10.6
LX1901	AO4101	0	0.0232	74.7	-28.0
LX1903	AO4101	0	0.0232	75.3	-19.0
LX1900	AO4101	0	0.0323	74.8	-68.0
LX3186	AR8857	0	0.2150	82.7	-200.0
LX3709	AR8790	1	0.2194	87.9	-122.0
LX1362	AO3935	0	0.2854	105.5	110.0
LX3188	AR8863	1	0.2929	104.5	90.0
LX1894	AO3933	0	0.3540	108.6	120.0
LX1359	AO4099	0	0.4194	106.9	60.0
LX3192	AR8866	1	0.6414	105.3	-75.0
LX1893	AO3924	0	0.8214	110.4	-110.0
LX1895	AO3951	1	0.8295	130.7	200.0
LX1363	AO3935	1	0.8747	123.0	36.0
LX1896	AO3946	1	0.9432	131.4	62.0
LX1905	AO4101	1	0.9522	126.4	-38.0
LX1365	AO3921	1	0.9639	109.7	-350.0
LX1360	AO4099	1	0.9921	128.2	-233.0
LX1897	AO3896	1	1.0000	192.9	20.0

Table 8: A Comparison of Observed and Predicted Probability for Model Based on Peak Sled Acceleration and Peak z-Component of Head Angular Velocity

E. CLASSIFICATION OF OBSERVATIONS

The predicted probabilities from the "best" models developed in the previous sections can be used to classify observations into groups. In other words, an observation can be classified as nonfatal if the predicted probability is less than or equal to some specified cut-off value. In particular, each such value yields a classification matrix of the form given in Figure 1. From this figure, the following probabilities can be defined:

$$P_1 = \text{Prob(observe fatality} \mid \text{predict nonfatality)} = B/(B+D)$$

and

$$P_2 = \text{Prob(observe fatality} \mid \text{predict fatality)} = A/(A+C).$$

Ideally, it is desired to have $P_1 = 0$ and $P_2 = 1$. Of course, P_1 is the more critical probability of the two.

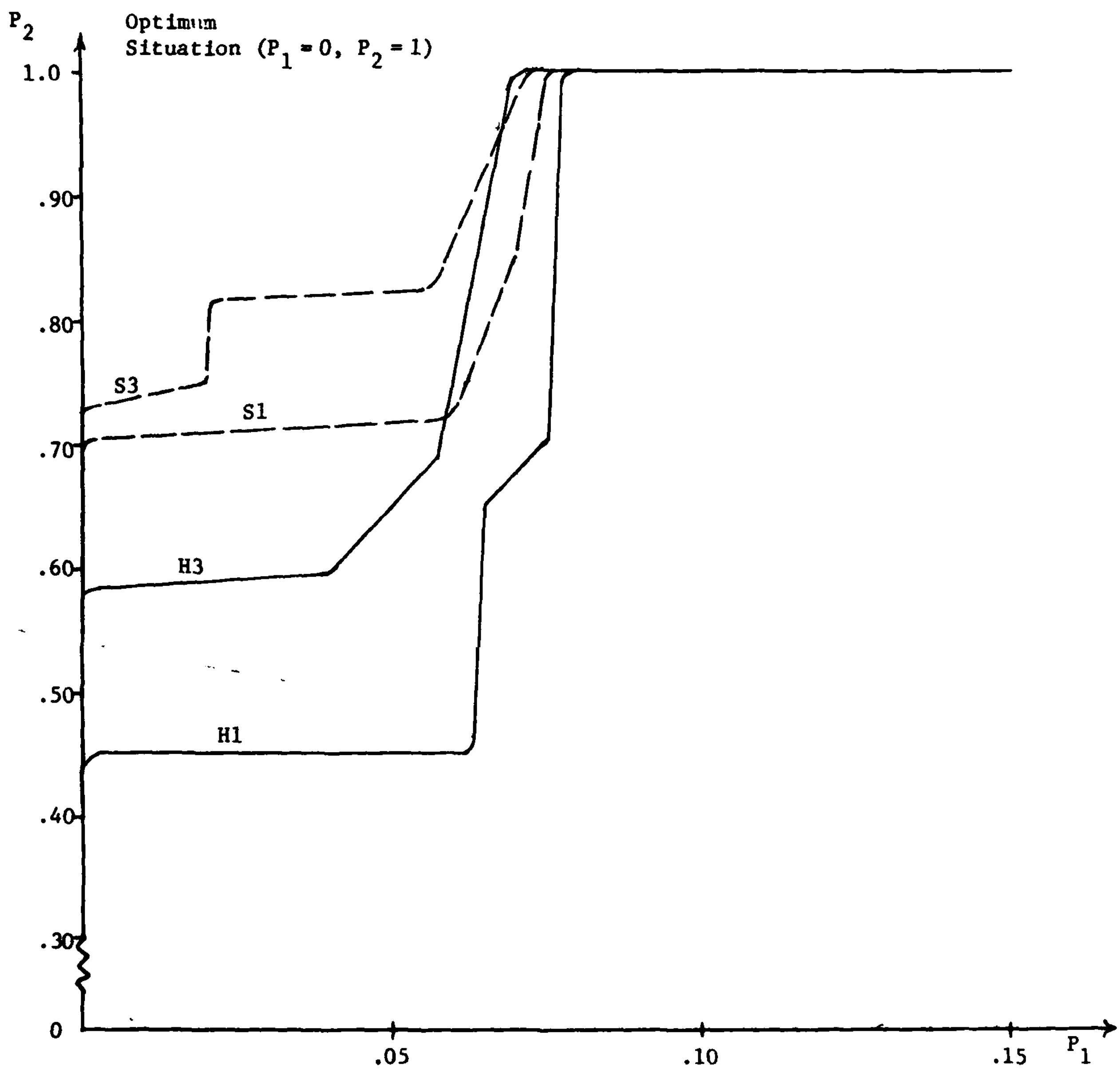
Graphs of P_1 versus P_2 (as a function of the cut-off value) compare the performance of the "best" one-variable, two-variable, and three-variable models. For example, Figure 2 compares the models based on the head dynamic response variables with those based on sled acceleration variables. The improvement that is obtained by going from the "best" one-variable to the "best" three-variable model (in terms of approaching the ideal situation, i.e., $P_1 = 0$ and $P_2 = 1$) can be seen graphically within each variable set.

Observed \ Predicted	Fatality	Nonfatality
Fatality	A	B
Nonfatality	C	D

$$P_1 = B/(B+D)$$

$$P_2 = A/(A+C)$$

Figure 1: Classification Matrix



H1 denotes best one-variable head model

H3 denotes best three-variable head model

S1 denotes best one-variable sled model

S3 denotes best three-variable sled model

Figure 2: Comparison of Models

III. SUMMARY

Using an identical data base, three different models were constructed, one based on sled profile variables, another based on head dynamic response variables, and the last one comprised of the combined set of independent variables. The "best" head dynamic response model appeared to be the three-variable model containing the peak z-component of head linear acceleration, peak head linear resultant acceleration, and the peak y-component of head angular acceleration. The "best" sled acceleration profile model was the one-variable model consisting of peak sled acceleration alone. The "best" combined (head dynamic and sled profile) model was the two-variable model consisting of peak sled acceleration and the peak z-component of head angular velocity.

The statistical technique of testing the contribution of successive terms in nested models [3] cannot be employed for models involving different variables (i.e., no formal test exists for determining whether or not one model provides a significant improvement over another). However, a relative assessment of the various models can be made on the basis of the log likelihood values. In particular, for models containing the same number of variables, the one which maximizes the log likelihood value would be favored. In this regard, it can be seen from Table 9 that the three-variable head dynamic response model does not do any better than the one-variable model based on peak sled acceleration alone. Similarly, it appears that the combined two-variable model does better than the three-variable head dynamic response model. In addition, graphs of the probability of correct classification (i.e., observing fatality given that fatality is predicted) indicate that this probability is maximized sooner for the combined two-variable model.

There still remains the question as to why the head dynamic response models

Best Models \ Variable Type	Head Dynamic Response	Sled Acceleration Profile	Combined Variable Set
One-Variable	-12.79	-8.35	-8.35
Two-Variable	-12.03	-7.66	-7.14
Three-Variable	-10.32	-7.66	-6.38

Table 9: Log Likelihood Values for Best Models

did not perform as well as the models involving sled profile variables. It was speculated in [7] that this result may be due to any or all of the following: (a) the wrong variables were being extracted from the head dynamic response time traces, (b) inaccurate measurements were being made on the correct variables, and (c) the small sample size had produced a spurious result.

Since the sample size appears to be sufficiently large here, it is believed that (c) can be ruled out. In addition, (b) also appears to be an unlikely explanation, since the effect of minor measurement inaccuracies would most likely be negligible in larger samples. However, it is still possible that there exists more valuable information that can be extracted (via the method of principal components [5], for example) from the head dynamic response time traces.

This latter contention is borne out by the fact that the head dynamic variable found to be most important was the peak z-component of head linear acceleration, which was not available for consideration as a variable in the original report on model development [7]. This indicates that, in some sense, the current set of twelve head dynamic response variables provides better information than the original set of three variables.

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Statistical Prediction Model

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Statistical impact acceleration injury prediction models are developed for the head/neck segment from data obtained during 68 $-G_x$ accelerator runs. These runs involved subhuman primates (Rhesus monkeys) with securely restrained torso and unrestrained head. The data was collected by the Naval Biodynamics Laboratory (NBDL) as part of its research effort on acceleration impact injury prevention. Three classes of prediction models are constructed, one based on sled profile variables, another based on head dynamic response variables only, and the third comprised of the combined set of independent vari-

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ables. The model predictions are compared with the observed results to evaluate performance.

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