TRANSLATIONAL ENERGY CRITERIA AND ITS CORRELATION WITH HEAD INJURY IN THE SUB-HUMAN PRIMATE

Richard L. Stalnaker
Tah C. Low
Department of Mechanical Engineering
The Ohio State University
Columbus, Ohio 43210

Alex C. Lin
Department of Industrial Engineering
University of California
Berkeley, California 94709

ABSTRACT

In recent years, the "Mean Strain Criterion" (MSC) for head impacts has been re-evaluated and an improved version formulated. The old MSC models were upgraded and reported at a previous IRCOBI conference. Based on these models, now called "Translational Head Injury Models" (THIM) and 37 lateral head impacts to three species of primates, a new head injury criteria is presented.

In this study, it was assumed that the THIM are lumped parameter models of the head and that the elements of the models, in a broad sense have a physical counterpart in the head. It was also assumed that energy going into the head (model) is one of the major parameters that cause head injury in an impact situation. Furthermore, it was postulated that the higher the impact energy level, the greater the potential for head injury.

The energy stored or dissipated by each model element is plotted with respect to time. The peak energy or power values were correlated with the Abbreviated Injury Scale (AIS) or skull fracture. The result of this effort is the Translational Energy Criteria (TEC) in the form of injury predictive functions for both skull fracture or brain contusion.

The acceleration response of the large mass of the lateral THIM was used to compute the Head Injury Criteria (HIC) for each primate head impact and correlated with the AIS injury number. It was concluded that the Translational Energy Criteria from the THIM and the HIC values from the THIM, both correlated very well with head injury. But, the TEC was more comprehensive and revealed more injury detail than the HIC.

INTRODUCTION

The mathematical lumped-parameter model to simulate head impact response and to relate model output to head injury has been proposed for many years [1,2,3,4]. All of these models, but one, were founded on the

Numbers in [] designate references at end of paper.

Wayne State Tolerance Curve (WSTC) [5]. That one model is a one dimensional, two-degree-of-freedom model introduced by Stalnaker 18 years ago [6]. This model was composed of two masses, one spring, and one damper. The values for the model parameters were determined by fitting the calculated driving-point mechanical impedance of the head model to the experimentally determined impedance of living sub-human primates or cadavers for various directions of loading. These models were then used to generate the "Mean Strain Criterion" (MSC) for head injury [7]. The MSC related model output mean strain to primate or cadaver head injuries ranked in terms of an injury code call Estimated Severity of Injury (ESI).

Due to poor fit of the original models to the head impedance data, a reanalysis of the models was undertaken in 1984 and the results for cadavers were reported in 1985 [8]. This update consisted of adding a second damper in series with the spring in the model. The new cadaver models were standardized in four directions, Anterior-Posterios (A-P), Posterior-Anterior (P-A), Superior-Inferior (S-I), and Left-Right (L-R) and to a common head mass of 4.545 Kg (10 lb). The new model now called the Translational Head Injury Models (THIM) were studied to determine what physical means, if any, the model elements have with respect to the human head. The THIM and the governing equations are shown in Figure 1.

The physical meaning of the model elements for the cadaver is listed below:

1. Summation of masses (M_1 and M_2) will always add up to total head mass.

2. Mass M_1 is the mass of the skull which was moving directly under a rigid impact.

3. The stiffness K and the damper C_1 form the nonlinear skull stiffness in a given direction.

4. The damper C_2 was found to be a constant for all directions and was believed to be primarily the damping of the brain.

A more detailed discussion of the cadaver THIM is given by Stalnaker [9] and in this study the observations made from the cadaver THIM are assumed to apply to the sub-human primate THIM.

TRANSLATIONAL ENERGY CRITERIA (TEC)

Data Selection: A large series of primate lateral head impact tests was carried out in the early to mid seventies at the Highway Safety Research Institute (HSRI) of the University of Michigan.* These tests were reevaluated for use in this study. Thirty-seven of the tests were judged to be suitable, based on the following criteria:

1. Only lateral tests.
2. No padding.

*Now called the University of Michigan Transportation Research Institute (UMTRI).

3. Must be from a large sample size.
4. Force-time curve must be clear and complete.
5. Injury information must be clear and complete.

A complete description of the test protocol is given in References 10 and 11.

Three different species were selected for study, Saimir sciurius squirrel, Macaca facicularis cynomologus, and Macaca mulatta rhesus. The old MSC models for each of these species were up-dated so that the model mechanical impedance response would give the best fit to the experimentally measured impedance response. This was accomplished in the same manner as was reported for the cadaver THIM by Stalnaker [8].

The experiemental and model driving point mechanical impedance curves along with the model parameter values for each of the species studied are given in Figures 2 through 4.

Normalization: The force time curves from each test were electronically hand digitized, smoothed, and stored in the computer. The injury information was analyzed and assigned an AIS number. Since the force-time function for each test will be used as an input to the appropriate species THIM, each force-time function had to be normalized to its own model mass. This normalization was achieved by the following scaling relatioships:

$$\lambda = (M_m/M_i)^{1/3}$$

$$F_n = \lambda^2 F_a$$

$$t_n = \lambda t_a$$

Where: λ = scaling factor

M_m = model mass for the species (Kg)

M_i = head mass of individual animal in species (Kg)

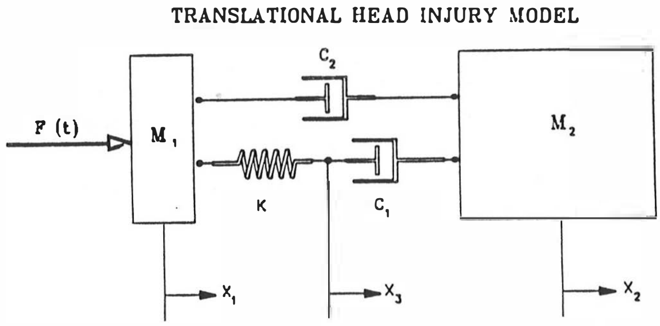
F = Force, (N)

t = time, (msec)

n = normalized

and a = measured

A summary of the head impact test data used in this study is given in Table 1.

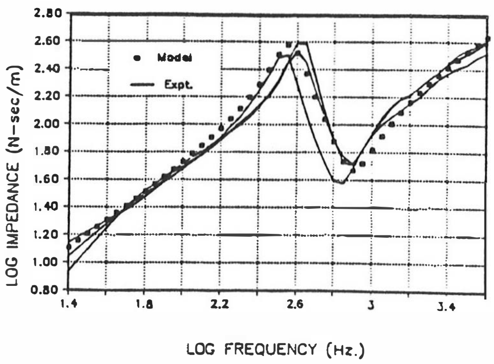


$$F = M_1 \ddot{X}_1 + K(X_1 - X_3) + C_2(\dot{X}_1 - \dot{X}_2)$$

$$M_2 \ddot{X}_2 = C_1(\dot{X}_3 - \dot{X}_2) + C_2(\dot{X}_1 - \dot{X}_2)$$

$$K(X_1 - X_3) = C_1(\dot{X}_3 - \dot{X}_2)$$

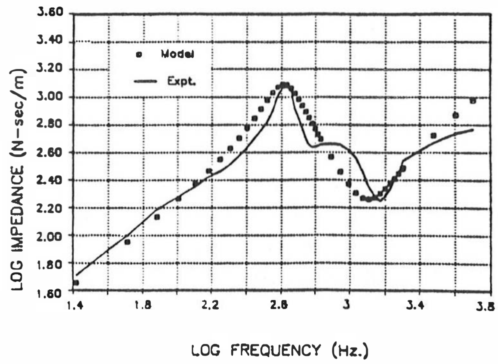
Fig 1. Translational Head Injury Model (THIM) and Governing Equations



M_1 (kg)	K (N/m)	C_1 (N-sec/m)	C_2 (N-sec/m)	M_2 (kg)
0.018	323,976	569.1	29.9	0.064

SQUIRREL - LR DIRECTION

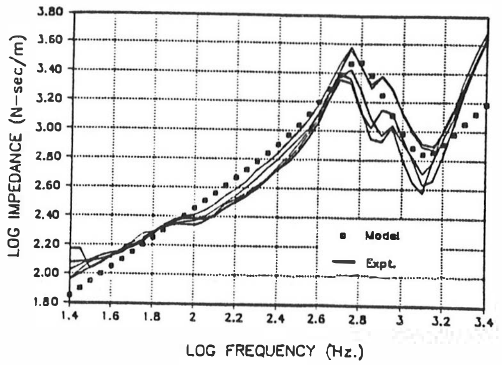
Fig 2. Squirrel Monkey Mechanical Impedance With Model Parameters



M_1 (kg)	K (N/m)	C_1 (N-sec/m)	C_2 (N-sec/m)	M_2 (kg)
0.032	1,576,100	1751.2	122.6	0.250

CYNOMOLGUS - LR DIRECTION

Fig 3. Cynomolgus Monkey Mechanical Impedance With Model Parameters



M_1 (kg)	K (N/m)	C_1 (N-sec/m)	C_2 (N-sec/m)	M_2 (kg)
0.114	4,815,861	6129.3	350.2	0.341

RHESUS - LR DIRECTION

Fig 4. Rhesus Monkey Mechanical Impedance With Model parameters

TABLE 1: SUMMARY OF PRIMATE TEST

SPECIES	TEST NUMBER	IMPACT VELOCITY (Km/hr)	TOTAL BODY WEIGHT (KG)	HEAD WEIGHT (KG)	LAMBDA *	PEAK FORCE (N)	NORMALIZED PEAK FORCE (N)	AIS	SKULL FRACTURE
SQUIRREL	SM/70- 3	30.09	0.776	0.099	.940	687.72	605.20	0	No
"	SM/70- 5	40.39	0.899	0.112	.900	707.44	573.03	0	No
"	SM/70- 8	49.56	0.849	0.108	.911	2708.30	2247.80	5	Yes
"	SM/70- 9	50.84	0.599	0.076	1.023	2379.00	2490.80	4	Yes
"	SM/70-10	47.47	0.599	0.076	1.020	2918.50	3036.40	6	Yes
"	SM/70-11	43.12	0.599	0.076	1.023	2169.40	2271.40	4	Yes
"	SM/70-12	43.28	0.799	0.102	.930	1629.10	1417.30	3	Yes
"	SM/70-13	43.28	0.599	0.076	1.023	1710.60	1791.00	3	Yes
"	SM/70-14	39.26	0.799	0.079	1.009	1678.80	1709.10	2	Yes
"	SM/70-15	33.95	0.680	0.082	.998	1276.90	1271.80	2	Yes
"	SM/70-16	30.41	0.527	0.074	1.032	937.34	998.27	1	Yes
"	SM/71-81	35.08	0.622	0.079	1.009	392.25	399.31	1	No
"	SM/71-82	35.88	0.676	0.087	.980	588.17	564.64	0	Yes
"	SM/71-83	35.08	0.499	0.064	1.085	391.68	461.01	0	No
"	SM/71-84	40.06	0.599	0.077	1.021	1570.60	1635.70	3	Yes
CYNOMOLGUS	CY/70-55	41.83	2.451	0.297	.986	2131.10	2071.90	0	No
"	CY/70-56	33.47	2.406	0.291	.992	2235.40	2199.80	0	No
"	CY/70-57	37.01	2.601	0.315	.966	2908.50	2714.20	1	No
"	CY/70-58	37.01	2.746	0.332	.950	3549.00	3203.00	2	No
"	CY/71-85	46.5	3.200	0.384	.905	3578.20	2930.60	1	No
"	CY/71-86	47.79	3.246	0.390	.900	5669.30	4592.10	3	Yes
"	CY/75-82	25.98	3.994	0.404	.890	2958.70	2343.60	0	No
"	CY/75-89	26.37	4.893	0.631	.767	9392.20	5525.50	4	Yes
"	CY/75-90	28.96	4.094	0.522	.817	4668.60	3116.30	1	No
"	CY/75-93	27.64	3.795	0.463	.850	7209.80	5209.10	4	Yes
RHESUS	RH/70-17	44.57	4.194	0.449	1.003	4812.20	4841.10	2	No
"	RH/70-18	46.18	5.184	0.481	.981	3592.80	3449.10	0	No
"	RH/70-23	54.87	9.169	0.892	.798	11830.00	7571.10	3	No
"	RH/70-24	50.04	9.373	0.828	.818	10665.00	7134.60	5	Yes
"	RH/70-25	38.94	10.576	0.994	.770	7411.00	4394.70	2	No
"	RH/70-26	45.05	10.803	1.003	.768	8351.70	5002.60	3	Yes
"	RH/70-27	57.12	10.667	0.990	.771	9499.40	5642.70	2	Yes
"	RH/70-28	48.43	11.575	1.076	.750	9946.40	5599.80	2	No
"	RH/70-29	41.67	5.402	0.481	.981	3447.60	3309.60	0	No
"	RH/71-87	loss	5.810	0.536	.946	6282.80	5623.10	3	Yes
"	RH/71-88	loss	6.673	0.622	.900	3697.20	2994.80	0	No
"	RH/71-90	loss	6.945	0.645	.890	6294.00	4984.80	3	No

* Squirrel Scaling Head Mass = 0.082 Kg
Cynomolgus Scaling Head Mass = 0.282 Kg
Rhesus Scaling Head Mass = 0.455 Kg

Each of the normalized force-time functions was used to excite the appropriate species head models. The impact energy will go into dissipated energy from the two dampers, and stored energy from the spring and the two masses. The measured force-time and normalized force-time functions, as well as the energy-time functions for each of the model elements for two representative types of model responses are given in Figures 5 and 6.

<u>Brain Contusion</u>: It is assumed that in the model, the damping element C_2, essentially represents the neural properties of the head, and the spring element K with the damping element C_1 essentially represent the non-linear stiffness of the skull.

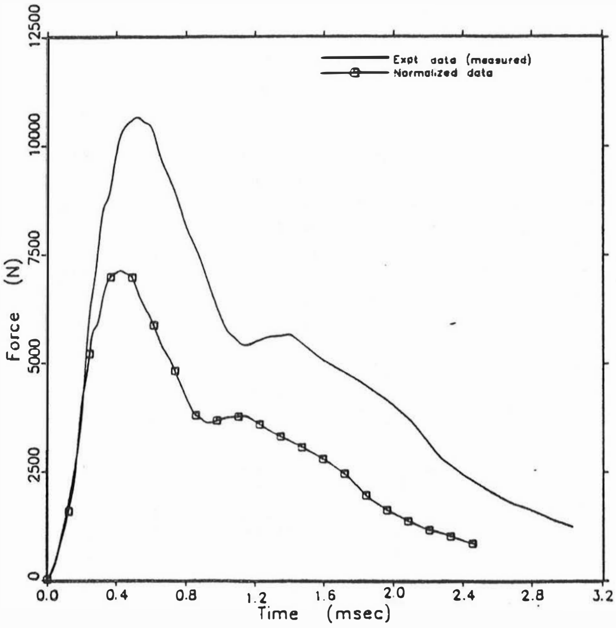


Fig 5a. Model Input (Test: RH/70-24)

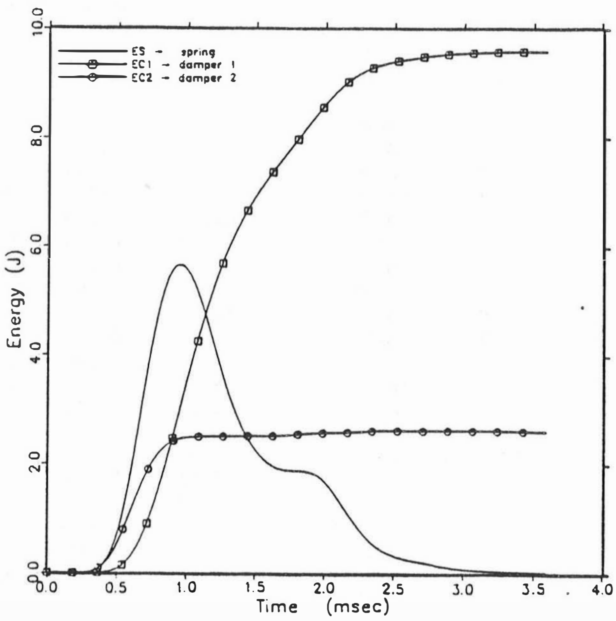


Fig 5c. Model Output - Energy in Damping and Spring Element (Under Driven - Test : RH/70-24)

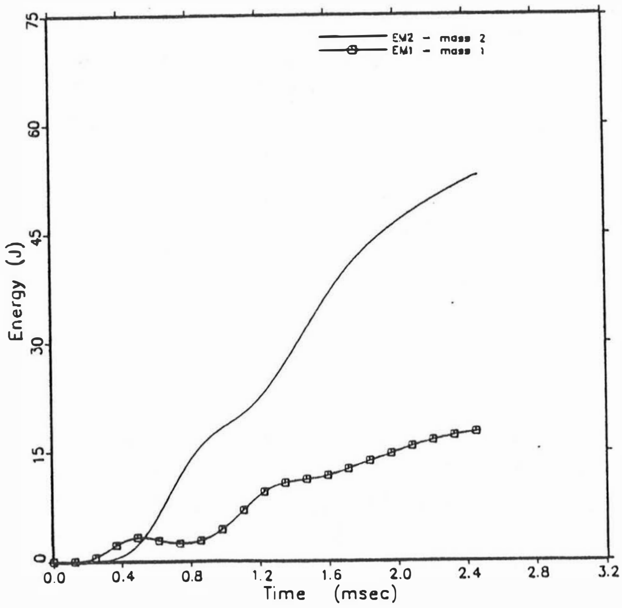


Fig 5b. Model Output - Energy in M_1 & M_2 (Test: RH/70-24)

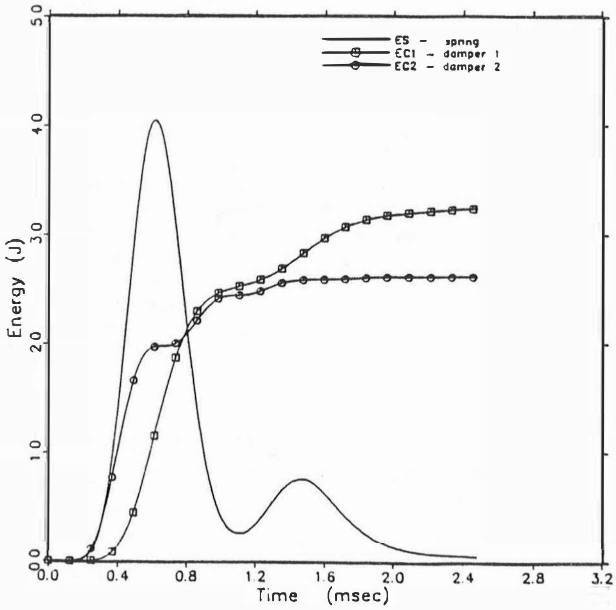


Fig 6. Model Output - Energy in Damping and Spring Element (Over Driven - Test: CY/71-86)

There are two possible modes by which energy can be transmitted to the individual components of the THIM for any given impact. They are classified for this study as: "Over Driven Impact" (Figure 5c) and "Under Driven Impact" (Figure 6).

For cases where the head is subjected to an "Under Driven Impact" (such as padded impact), the damper connected in series to the spring is capable of dissipating most of the energy released by the spring. For an "Over Driven Impact," the amount of energy stored and then released from the spring element can be significantly higher (such as rigid impact) this was found for the "Under Driven Impact." In this case, the damper connected in series to the spring is incapable of dissipating most of the energy released by the spring. The remaining energy will be transferred to the second damper via the masses in the form of kinetic energy. The severity of head injury was found to be directly proportional to the amount of "ENERGY" released by the second damper C_2.

The model maximum response is of interest for injury evaluation. This is achieved when the model reaches its terminal velocity, that is when both masses have the same constant velocity. At this time, the model has self adjusted to include all additional energy transmitted to the second damper from an "Over Driven Impact". Hence, the amount of energy dissipated by the second damper can be correlated directly to the severity of the head injury for either case.

Skull Fracture: The localized stress on the skull at the impact site must reach a critical value for the skull to fracture. Such a critical stress is a function of both maximum load and the rate at which the load is applied. Such stresses will result in strains and the skull will be deformed. Therefore, the load-deformation (energy) and the rate at which this load-deformation occurs will be related to the "POWER" stored in the model spring K.

Computation of the HIC: No accurate head acceleration data were available for these primate tests. The acceleration of the second mass (M_2) was utilized for computing the HIC number for each impact test. Since M_2 carries at least 75% of the total head mass, the acceleration of the second mass (M_2) for a rigid impact can be a good indicator, for comparison purposes, of the actual head acceleration . This is illustrated for a cadaver in Figure 7. It can be assumed that a similar observation can be seen for the primate data, since both the cadaver and sub-human primates models share the same analogy.

The definition of the HIC expressed as follows:

$$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} A_2(t)dt\right]^{2.5}\Bigg|_{max}$$

Where: $A_2(t)$ = the acceleration of the second mass.

t_2-t_1 = the computation interval

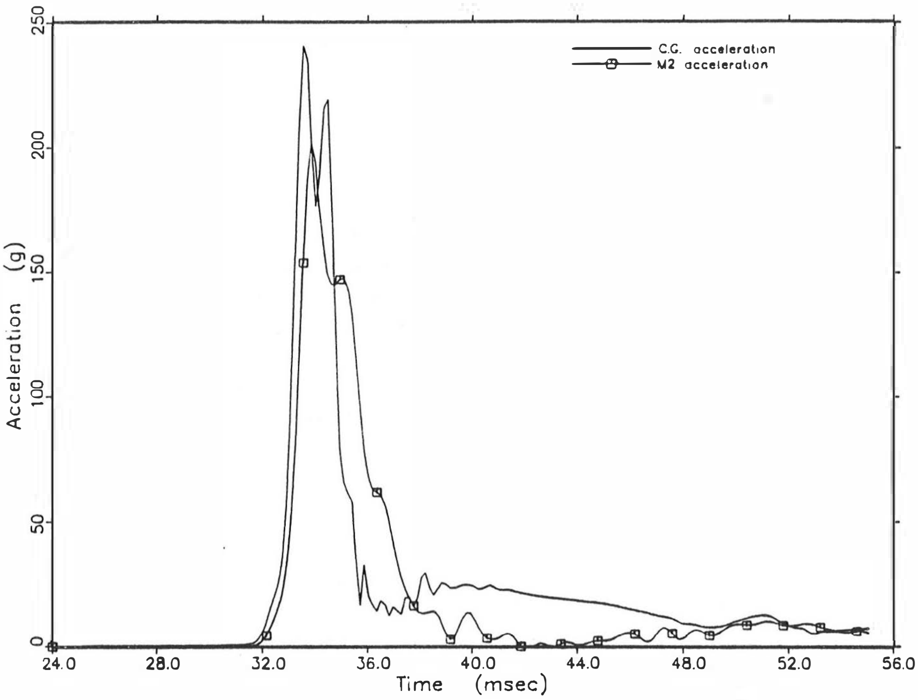


Figure 7. Center of Gravity (Cadaver) and M_2 (Model) Response

As all of the primate tests were impacted in the L-R direction, the computed HIC number will only reflect the possibility of head injury in that direction.

For the primate test, the impact is generally short in duration but high in amplitude therefore , large HIC numbers are expected. The programs used for computing the HIC number were adjusted accordingly in order to make such computation possible. It should be noted that such high HIC number should not be compared to those values in cadaver or dummy crash test with an injury threshold of 1,000. The primate HIC number is in a class by itself, and are consistent only within the same species.

RESULTS

Translational Energy Criteria: The maximum value of the energy dissipated in damper number 1 (EC_1) and damper number 2 (EC_2) the maximum energy stored in the spring (ES), mass number 1 (EM_1) and mass number 2 (EM_2), along with maximum power stored in the spring (ESDOT) are given in Table 2. All the above parameters are shown with respect to AIS and skull fracture. A linear regression was run for each species between the maximum energy dissipated by damper number 2 (EC_2) and the AIS number. The results of this regression are given in Table 3. A graph of the regression equation and the measured data for each species is shown in Figures 8 through 10.

TABLE 2: ENERGY INJURY PARAMETERS

SPECIES	TEST #	ES (J)	EC1 (J)	EC2 (J)	EM1 (J)	EM2 (J)	ESDOT (Watt)	AIS	COMPUTED AIS	SKULL FRACTURE
SQUIRREL	SM/70- 3	0.4279	0.2088	0.302	0.3295	0.7711	1524	0	0.56	No
"	SM/70- 5	0.5527	0.321	0.3034	0.4702	1.381	1662	0	0.56	No
"	SM/70- 8	8.3974	4.7056	4.6246	6.3427	19.713	26456	5	4.65	Yes
"	SM/70- 9	9.2146	5.331	4.9634	6.2126	23.11	29176	4	4.85	Yes
"	SM/70-10	14.978	9.8316	6.3746	13.891	51.095	41992	6	5.60	Yes
"	SM/70-11	6.8671	3.3459	3.0565	5.0084	13.008	22717	4	3.62	Yes
"	SM/70-12	3.1785	1.5414	1.2148	2.1484	5.8198	10039	3	1.97	Yes
"	SM/70-13	5.122	3.2204	2.6171	3.19	15.187	13795	3	3.29	Yes
"	SM/70-14	4.2317	2.4848	2.1413	2.8076	11.244	12623	2	2.89	Yes
"	SM/70-15	2.454	1.5591	1.3131	2.4511	7.2687	6829	2	2.08	Yes
"	SM/70-16	1.5253	0.9765	0.7858	1.5032	4.6226	4242	1	1.42	Yes
"	SM/71-81	0.2266	0.1511	0.1038	0.1468	0.7716	567	1	0.00	No
"	SM/71-82	0.4871	0.3482	0.1803	0.6287	2.2888	1407	0	0.24	Yes
"	SM/71-83	0.3158	0.1823	0.1595	0.338	0.8725	930	0	0.18	No
"	SM/71-84	3.9303	2.7427	1.345	2.4947	14.382	9477	3	2.12	Yes
CYNOMOLGUS	CY/70-55	1.3717	1.3497	0.7419	0.7644	6.3055	5001	0	0.29	No
"	CY/70-56	1.3592	1.9706	0.6432	1.5471	13.583	4034	0	0.08	No
"	CY/70-57	2.151	2.3374	1.1868	2.5749	20.336	7253	1	1.08	No
"	CY/70-58	3.1754	2.8199	1.8138	1.3842	11.083	11127	2	1.98	No
"	CY/71-85	2.4609	2.7708	1.1127	2.1108	16.535	7589	1	0.96	No
"	CY/71-86	5.6522	9.5935	2.6021	10.971	86.217	15880	3	2.91	Yes
"	CY/75-82	1.2437	2.6324	0.4573	4.4069	34.66	1995	0	0.00	No
"	CY/75-89	8.3443	11.951	3.6786	13.311	105.73	22703	4	3.97	Yes
"	CY/75-90	2.6243	3.2785	1.1643	2.8651	23.382	7024	1	1.05	No
"	CY/75-93	7.4533	7.847	3.7489	4.255	36.416	20691	4	4.03	Yes
RHESUS	RH/70-17	1.8188	1.8175	0.9108	10.091	29.618	6790	2	2.20	No
"	RH/70-18	0.8496	0.6851	0.4201	2.7234	8.6005	2775	0	0.82	No
"	RH/70-23	3.1554	3.2072	1.6093	14.029	41.554	5836	3	3.61	No
"	RH/70-24	4.0546	3.2403	2.6143	17.641	52.976	17317	5	5.18	Yes
"	RH/70-25	1.3622	1.2928	0.5916	6.6194	20.244	4481	2	1.36	No
"	RH/70-26	1.8604	1.6685	1.2646	9.8302	29.494	8602	3	2.96	Yes
"	RH/70-27	1.9626	2.581	0.8102	16.846	51.232	4835	2	1.95	Yes
"	RH/70-28	1.7917	1.8504	0.7953	7.8996	24.393	3534	2	1.92	No
"	RH/70-29	0.7134	0.668	0.3227	2.6227	7.686	1854	0	0.46	No
"	RH/71-87	2.3619	2.1075	1.0829	10.892	33.302	8180	3	2.59	Yes
"	RH/71-88	0.6287	0.5735	0.2782	2.3841	7.3199	1972	0	0.28	No
"	RH/71-90	1.316	1.9911	0.7029	9.843	29.683	2601	3	1.68	No

TABLE 3. LINEAR REGRESSION ANALYSIS RESULTS FOR EC2

SPECIES	CORRELATION COEFFICIENT	LINEAR REGRESSION
SQUIRREL	0.944	AIS = -0.845 + 2.55 * EC2^.5
CYNOMOLGUS	0.995	AIS = -2.706 + 3.48 * EC2^.5
RHESUS	0.922	AIS = -2.096 + 4.50 * EC2^.5

The maximum power stored in the THIM spring is plotted for each species in Figures 11 through 13. The skull fracture data together with these power ratings were analyzed to determine the Weibull cumulative risk function using maximum likelihood approach [12]. The power levels necessary to have a fifty-fifty chance of a skull fracture is given by species in Table 4.

TABLE 4 -- FIFTY PERCENT PROBABILITY OF SKULL FRACTURE

Species	Power (Watt)
Squirrel	1,918
Cynomolens	13,173
Rhesus	6,502

Head Injury Criteria: The calculated HIC based on the model M_2 mass acceleration is given in Table 5. The HIC Average Acceleration and the HIC Pulse Duration are shown in this table with respect to AIS and skull fracture.

A linear regression was run for each species between the HIC value and the AIS number. The results of these regressions are given in Table 6. A plot of the regression equation and the measured data for each species is shown in Figures 14 through 16.

The probability of skull fracture for each species as a function of HIC is shown in Figures 17 through 19. No meaningful probability of skull fracture could be generated for the Rhesus monkey (Figure 19).

DISCUSSION

The THIM developed from the mechanical impedance studies are lumped-parameter models and as such are limited in their detail of the head. But, it is also true that the model masses are by design equal to the head mass and the model responses are at least in some instances head-like. Likewise, there can be little doubt that the spring and its series damper are for the most part the skull stiffness and damping. Both static and dynamic test in various direction in human skulls show this to be true. Finally the single damper connecting the two model masses is for the most part the damping of the brain. Again, mechanical impedance studies on primate heads with the brain removed indicate that the primary damping in this damper C_2 is from the brain, also the THIM model for human heads for various directions show no change in this damper's value indicating again that this damper mostly represents the brain damping.

Because these models are of the lumped parameter type no one physical characteristic of the head can be assigned to any one element of the model. All of the head's properties have to be shared by the model elements. But, this does not say that each of the model elements cannot primarily be specified by one head property, such as, head mass, skull stiffness, brain damping, etc.

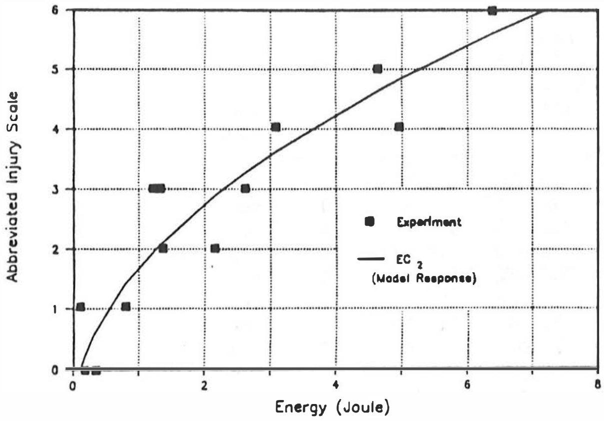


Fig 8. Regression of Energy Dissipated - C_2 (Rhesus Monkey)

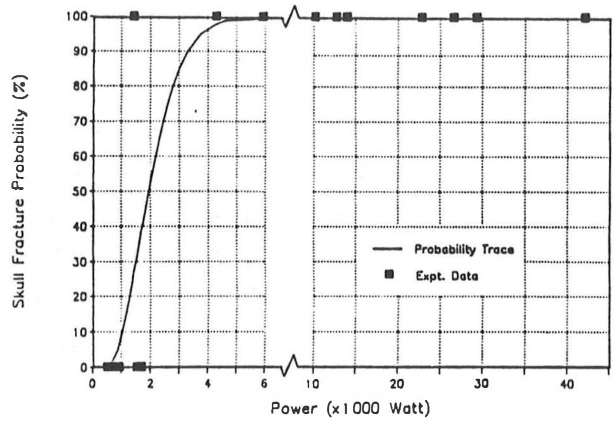


Fig 11. Power Level for Skull Fracture (Squirrel Monkey)

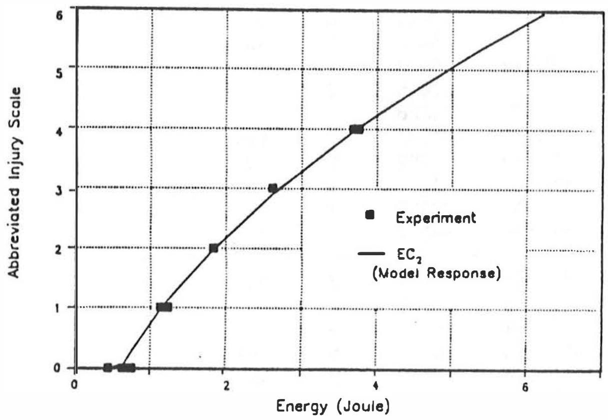


Fig 9. Regression of Energy Dissipated - C_2 (Cynomolgus Monkey)

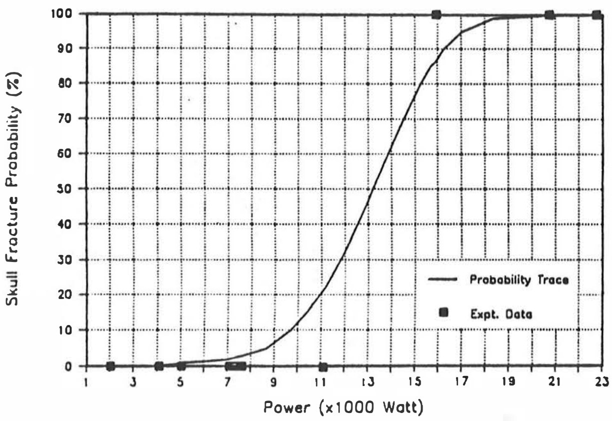


Fig 12. Power Level for Skull Fracture (Cynomolgus Monkey)

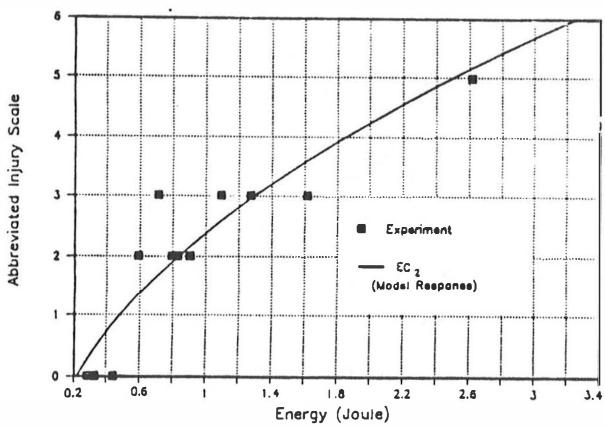


Fig 10. Regression of Energy Dissipated - C_2 (Rhesus Monkey)

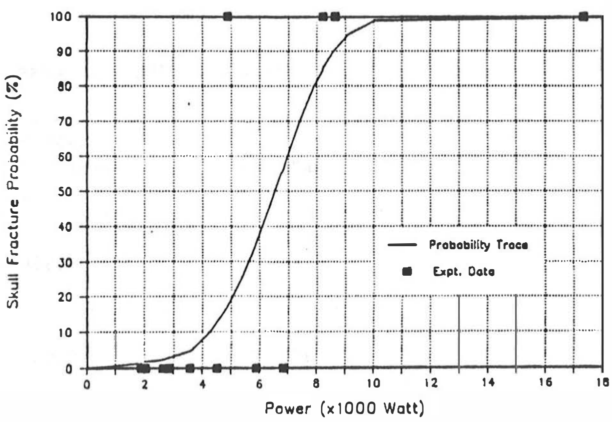


Fig 13. Power Level for Skull Fracture (Rhesus Monkey)

TABLE 5: HIC INJURY PARAMETERS

SPECIES	TEST NUMBER	HIC COMPUTATION INTERVAL (msec)	AVERAGE ACCELERATION FOR HIC COMPUTATION (G)	HIC	AIS	SKULL FRACTURE
SQUIRREL	SM/70- 3	0.555	46.182	8044	0	No
"	SM/70- 5	0.666	52.222	13125	0	No
"	SM/70- 8	0.657	202.418	382989	5	Yes
"	SM/70- 9	0.675	212.800	445897	4	Yes
"	SM/70-10	0.765	268.872	906832	6	Yes
"	SM/70-11	0.584	184.028	268302	4	Yes
"	SM/70-12	0.613	125.433	108016	3	Yes
"	SM/70-13	0.726	158.655	230182	3	Yes
"	SM/70-14	0.686	143.481	169165	2	Yes
"	SM/70-15	0.729	109.156	90749	2	Yes
"	SM/70-16	0.743	85.824	50700	1	Yes
"	SM/71-81	0.787	32.986	4918	1	No
"	SM/71-82	0.833	47.530	12974	0	Yes
"	SM/71-83	0.673	39.047	6412	0	No
"	SM/71-84	0.837	138.128	187685	3	Yes
CYNOMOLGUS	CY/70-55	0.700	47.684	10991	0	No
"	CY/70-56	1.339	42.121	15418	0	No
"	CY/70-57	0.607	59.272	16418	1	No
"	CY/70-58	0.645	72.679	29046	2	No
"	CY/71-85	0.842	60.355	23828	1	No
"	CY/71-86	1.647	82.909	103087	3	Yes
"	CY/75-82	1.326	45.275	18289	0	No
"	CY/75-89	1.151	108.676	141712	4	Yes
"	CY/75-90	0.890	64.165	29352	1	No
"	CY/75-93	0.782	109.519	98159	4	Yes
RHESUS	RH/70-17	1.324	54.323	28797	2	No
"	RH/70-18	0.648	47.283	9962	0	No
"	RH/70-23	0.878	90.649	68691	3	No
"	RH/70-24	0.515	104.933	58088	5	Yes
"	RH/70-25	1.148	48.214	18530	2	No
"	RH/70-26	1.305	51.781	25179	3	Yes
"	RH/70-27	1.040	70.338	43152	2	Yes
"	RH/70-28	0.952	65.859	33510	2	No
"	RH/70-29	0.804	42.627	9538	0	No
"	RH/71-87	0.710	76.891	36809	3	Yes
"	RH/71-88	0.810	38.040	7229	0	No
"	RH/71-90	1.219	61.388	35993	3	No

TABLE 6. LINEAR REGRESSION ANALYSIS RESULTS FOR HIC

SPECIES	CORRELATION COEFFICIENT	LINEAR REGRESSION
SQUIRREL	0.960	AIS = -0.863 + 0.029 * HIC^.4
CYNOMOLGUS	0.949	AIS = -2.251 + 0.056 * HIC^.4
RHESUS	0.859	AIS = -2.684 + 0.080 * HIC^.4

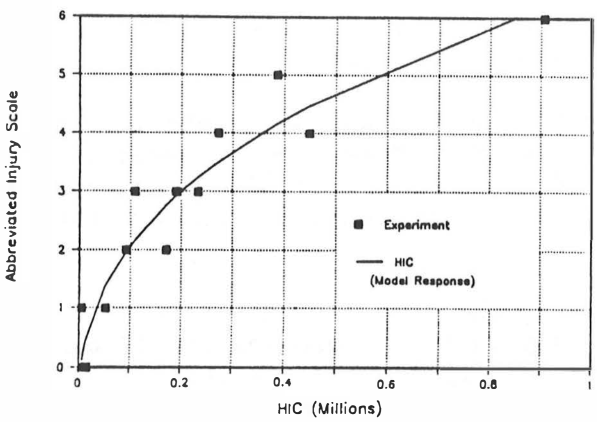


Fig 14. Regression of HIC
(Squirrel Monkey)

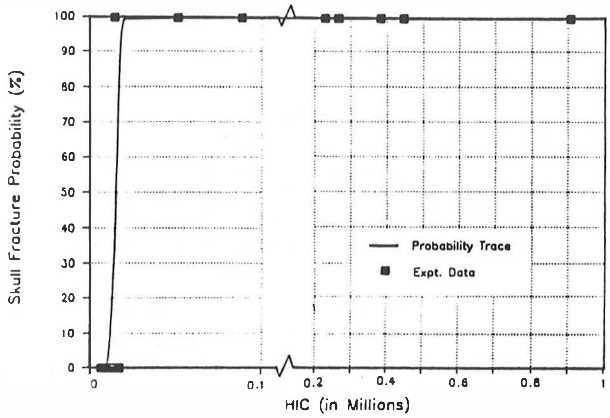


Fig 17. HIC Level for Skull Fracture
(Squirrel Monkey)

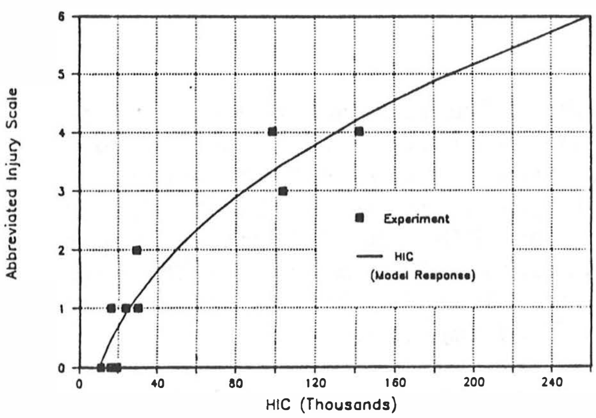


Fig 15. Regression of HIC
(Cynomolgus Monkey)

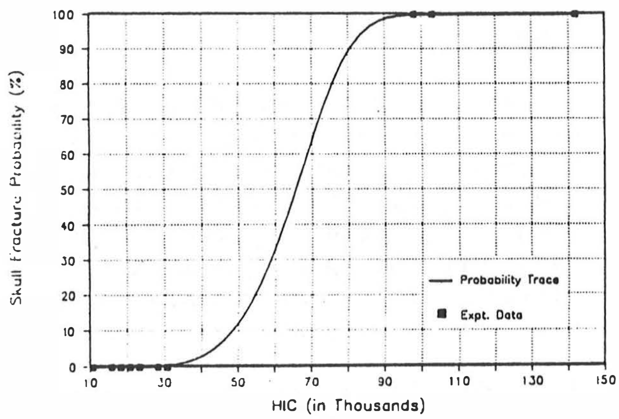


Fig 18. HIC Level for Skull Fracture
(Cynomolgus Monkey)

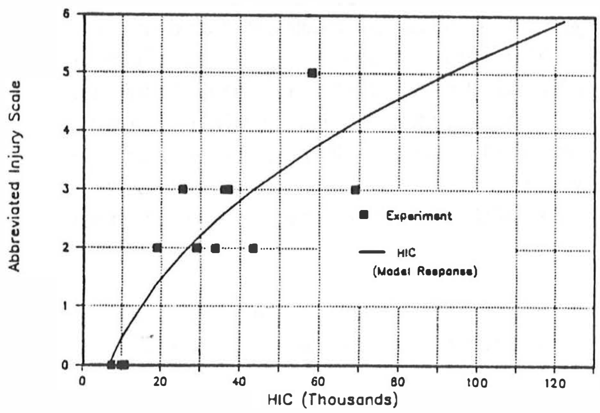


Fig 16. Regression of HIC
(Rhesus Monkey)

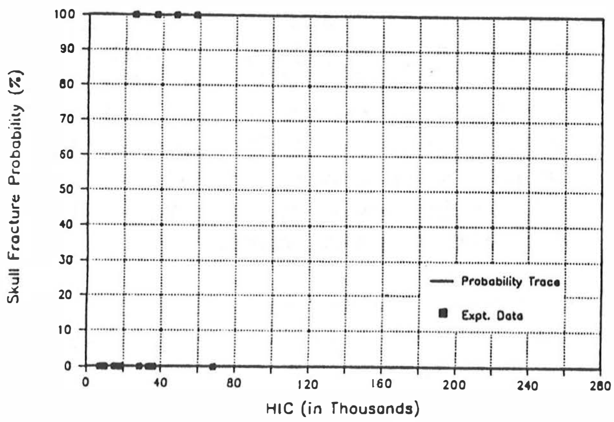


Fig 19. HIC Level for Skull Fracture
(Rhesus Monkey)

With the above discussion in mind the energy dissipated in damper C_2 could be the energy available to do brain damage. Likewise, when energy is poured into a viscoelastic skull/brain too fast to be dissipated, the skull will fail. The parameter relating to this failure will be the rate of energy or "POWER" stored in the model spring K.

The above discussion is not presented as a proof, but as a description of how the authors arrived at the relationships between energy/power and brain contusion/skull fracture. The good correlations obtained from the regression analysis on the TEC tends to support at least in part the assumption made earlier in this study.

The HIC concept was used to evaluate the same set of data used in developing the TEC. The regression analysis of the HIC versus AIS was found to be very good. This should be no surprise because the HIC was developed, in part, from rigid head impacts, and is strongly related to impact energy. The main difference noted between the HIC and the TEC was that the AIS values were distributed more uniformly over the full range of TEC values, whereas, the HIC values tended to accumulate at one end or the other of the HIC value range. Similar observations were found for the HIC values and probability of skull fracture.

SUMMARY

In summary the TEC predicts both skull fracture and contusion type brain injuries which are primarily due to direct head impact. Skull fracture is used to predict the type of brain injury, not the degree of brain injury. Because the THIM are good dynamic models of the head, and because of the way the TEC is tied to the THIM, the TEC values cannot keep increasing as the impact force increases. This makes the TEC self limiting in terms of AIS injury numbers. That is, TEC cannot predict AIS numbers much above six for realistic head impacts.

The HIC is a go, no-go criteria, and as such may be useful for compliance work but for research and developoment the HIC is extremely limited. An example of this limitation is found in the design of an automobile windshield. The windshield must break before the skull does and then the plastic inner layer must stretch to slow the head before brain injury occurs. The HIC only gives a single number predicting injury or no injury. A HIC value of 10,000 has no more meaning than a HIC value of 5,000 or of 1,001, but all of these numbers are seen in accident reconstructions. The designer would like to know what impact force level skull fracture will occur and what impact force level brain damage will occur, as well as any safety factor. For these reasons the TEC is believed to be more useful than the HIC for designing protection from direct head impact.

A final report on the THIM and TEC for the U.S. Department of Transportation will be available from the authors by the end of 1987.

CONCLUSIONS

1. The TEC in the lateral direction for three primate species has been developed.

2. The TEC was found to relate the maximum "ENERGY" dissipated in damper C_2 of the THIM to the AIS number very well.

3. The TEC was found to relate the maximum "POWER" stored in the spring of the THIM to skull fracture very well.

4. The HIC correlated very well to the AIS numbers.

5. The AIS values were not distributed over the full range of HIC values in the same way they were distributed over the range of TEC values.

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