Analysis of the Dynamics of Automobile Passenger-Restraint Systems

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ABSTRACT

A seven-degree-of-freedom nonlinear mathematical model of a human body and a restraint system (lap belt or combination of lap belt and shoulder restraint) has been formulated, and a digital computer calculation has been programmed, for purposes of investigating the dynamic behavior of automobile restraint systems. The system response is calculated in the form of time histories of the forces, accelerations, velocities, and displacements at various points in the dynamic system for either: 1) an experimental or idealized time history of vehicle deceleration, entered as a forcing function, or 2) deceleration by a specified form of vehicle-stopping mechanism.

A lack of detailed parameter and test data has prevented complete validation of the model; however, comparisons between calculated (estimated parameters) and experimental (from the literature) responses indicate a good agreement.

Major system parameters (e.g., belt properties, stopping distance, deceleration pulse shape, etc.) have been varied to explore their effects on restraint system performance, and preliminary conclusions are presented.

FOREWORD

M ANY persons may pose the question, why, at this late stage in the development of automobile passenger restraint systems, is it thought necessary to devote attention to detailed analytical treatment of the dynamics of these systems?

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Although much excellent experimental and analytical work has been done on passenger-restraint systems, a great deal of empiricism also exists and several aspects of performance specifications and acceptance testing remain controversial. A complete resolution of existing controversy is made difficult by: 1) the response complexity produced by system nonlinearities, 2) wide variations in test cart results, and 3) the wide range of variations that exist in impact conditions, passenger size and weight, and automobile compartment space.

The analytical study described in this paper was performed to advance understanding of the system dynamics, with nonlinearities included, and thereby to provide insight regarding the relative importance of restraint system parameters. This form of analytical approach, although suffering slightly in realism when compared with the more elaborate cart experiments, has the advantage of providing a general, theoretical frame of references for correlating experimental results obtained with diverse test procedures. It also provides a research tool that can be manipulated quickly, easily, and at low cost, to examine the effects of a wide range of trial modifications in individual system elements under identical impact conditions.

This study was performed in parallel with an investigation by the Subcommittee on Dynamic Testing of the SAE Motor Vehicle Seat Belt Committee, to provide guidance in its deliberations concerning: 1) fundamental differences in the results obtained by static and dynamic testing, and 2) the possible need for dynamic acceptance testing of seat belts. It is hoped that the study will also be of general use to the large community of scientists and engineers engaged in research and development for improved automobile passenger-restraint systems.

INTRODUCTION

In actual use, automobile seat belts and harnesses must function under conditions of dynamic loading. Therefore, a rational selection of acceptance test conditions or system performance specifications for optimum protection of the passenger requires a complete understanding of applied loads and system response dynamics.

Restraint system dynamics are often investigated by means of a physical simulation of collision loading, using anthropometric dummies in actual vehicle collisions or in cart tests. This type of research has produced a large amount of information about the dynamics of discrete systems under particular test conditions; however, the experimental results lack generality. Variations in equipment and procedures prevent a direct correlation of the results obtained by different investigators. Also, there is a lack of agreement on the procedures, equipment and instrumentation required for a realistic and repeatable simulation.

Factors that influence both the overall system performance and the repeatability of physical simulations include the following:

a) Vehicle (or cart) speed.
b) Stopping distance.
c) Wave form of vehicle deceleration.
d) Cart weight (effects of dummy-to-cart interactions).
e) Size and weight of dummy.
f) Degree of sophistication in dummy.
g) Degree of joint fixation (restraint) in dummy.
h) Seat construction.
i) Slack in belts.

Questions have also been raised regarding the existence of significant variations between static and dynamic properties of webbing materials, and the effects of such variations on system response.

Specific webbing properties of interest are: 1) the maximum load capacity, 2) the dynamic load elongation for increasing load, and 3) hysteresis.

Even if a generally acceptable physical simulation is developed for purposes of research and the development of specifications, a point of controversy will remain regarding the need for elaborate dynamic, as opposed to static, production-type acceptance tests

of the belts themselves. It is obvious that a resolution of the problems associated with a realistic and repeatable dynamic physical simulation procedure, and a determination of the need (or lack of need) for dynamic acceptance tests, requires a clarification of the dynamics of restraint systems.

The development of a general mathematical model lends itself to advancing the understanding of several forms of restraint systems, and for this reason, an analytical investigation, with major nonlinearities included, was considered to be the most fruitful undertaking at this stage of restraint system development.

OBJECTIVES

In view of the system complexity, the objectives of the analysis employed in this initial phase of the study program have been: 1) to develop, by means of appropriate simplifying assumptions, the simplest and most general mathematical model capable of producing correlation of major responses with the results of experiments, in which anthropometric dummies (a first approximation of the human body) have been used, 2) to apply such a first-approximation mathematical model in an investigation of fundamental points of present controversy (e.g., load elongation of webbing, stopping distance for test cart, wave form of test cart deceleration, etc.), 3) to determine both the feasibility and the utility of a more sophisticated model, and 4) to develop methodology and parameter data that may be useful in related studies.

The major part of this initial phase of the study has been devoted to the lap belt because of its relative simplicity, the more widespread use of lap belts in the United States, and the greater availability of experimental data. However, the developed model includes the simulation of a shoulder restraint that is either isolated from the lap belt, or allowed to equalize tension with the lap belt through a slip-joint connection.

METHOD

A seven-degree-of-freedom, nonlinear mathematical model of a human body and restraint system (lap belt, or combination of lap belt and shoulder restraint) on a test cart (or vehicle) has been formulated, Figure 1, and a digital computer calculation has been programmed for two forms of time-history solutions.
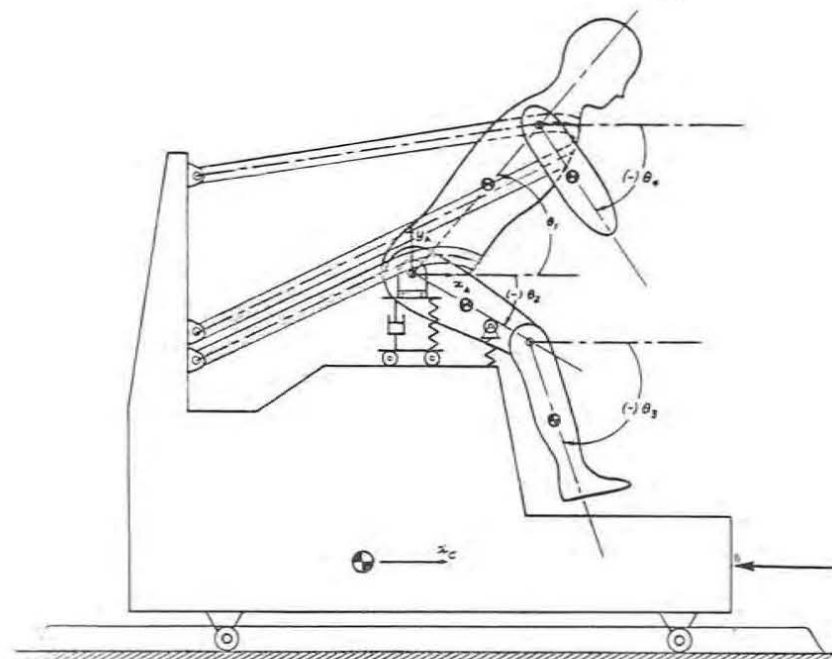

Figure 1. Mathematical model of human body and restraint system on test cart (seven degrees of freedom).

In the first form, where dummy-to-cart interactions are simulated, the free response of the complete seven-degree-of-freedom system is determined. A general form of cart-stopping mechanism, that responds to the velocity and displacement of the cart, decelerates the system from an initial velocity. With this form of solution, the adequacy of a cart and its stopping mechanism for simulation of actual vehicle collisions can be evaluated.

In the second form of solution, the forced response of the six-degree-of-freedom articulated body, restrained by the belts, is determined with an experimental or idealized time history of cart (or vehicle) deceleration serving as the forcing function.

The model illustrated in Figure 1 includes the effects of major system nonlinearities, such as varying belt angularity, slack, seat cushion deflection and friction, nonlinearity in belt load elongation, and variations in the effective inertia of the articulated body. A detailed theoretical formulation is presented in Ref. 13.

The system response is calculated in the form of time histories of the following items:

a) Body orientation and position relative to the vehicle (or test cart).

b) Horizontal and vertical components of acceleration and velocity at the hip.

c) Magnitude and direction of acceleration at a general point on the torso centerline.

d) Belt forces and angularities.

e) Friction force on the seat cushion.

f) Vehicle (or test cart) acceleration, velocity, and displacement.

g) Cart-stopping force.

h) Joint-restraining couples at hip and knees.

i) Restraining moment of the seat cushion on the upper legs.

The development of the calculation procedure has required that the human body, restraining belts, automobile seat, and test cart (if not by-passed by direct tabular entry of vehicle deceleration data) be simulated by mathematical equations. As indicated previously, the analysis philosophy employed in this study has been to develop, by means of appropriate simplifying assumptions, the simplest and most general mathematical model capable of producing correlation with major system responses. The system complexity has therefore been reduced by eliminating those degrees of freedom and system parameters that are considered to be of secondary importance in determining the major system responses, and by introducing simplified representations of the dynamic characteristics of various system components. The major simplifying assumptions are presented and discussed in the following:

Simulation of Human Body

This initial mathematical model has been aimed at a simulation of major system responses, rather than a detailed treatment of the biomechanical characteristics of the human body. The body is, therefore, treated as an articulated assembly of rigid-mass segments, with dimensions and inertias that are sufficiently representative to provide characteristic motions of the torso and extremities for purposes of determining vehicle clearances and body acceleration vectors.

The simulated body consists of four rigid segments connected by pin joints, that are fixed in the segments, with a total of six
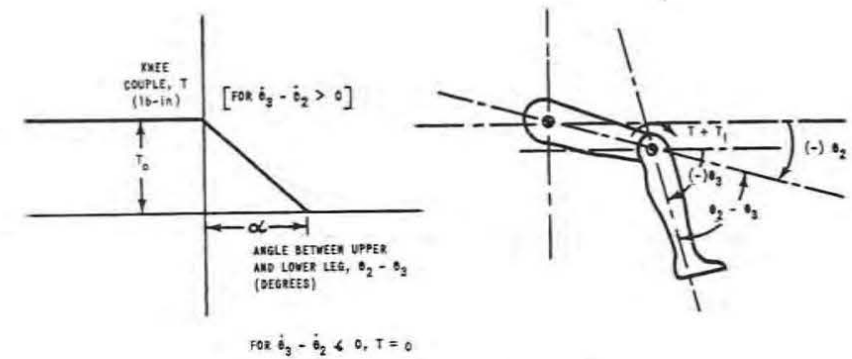

Figure 2. Knee-stopping couple.

degrees of freedom, Figure 1. Reverse bending of the knee is prevented by a knee stop, Figure 2, and muscular restraints are simulated by constant restoring couples.

It is recognized that rigid segments with fixed-position pivots constitute a crude approximation of the human body. However, within the scope of the stated objectives of this study, sufficient detail can be obtained to permit clarification of certain fundamental points of controversy regarding belt characteristics and dynamic test procedures. Previous analyses with similar objectives (8, 10, 15) have developed linear approximations of the system with from one to three degrees of freedom.

A secondary objective has been the determination of both the feasibility and the utility of a nonlinear representation, with solutions in the form of detailed time histories. With the developed methodology, the incorporation of additional degrees of freedom and sophistication (e.g., head movement relative to torso, torso bending, lower arm, foot restraint on floor, movement of internal organs, variable muscular restraint of joints, indirect path of webbing, seat movements, etc.) appears to be limited more by the lack of biomechanical parameter data than by the obvious analytical complications.

Restraining Belt Forces

The individual belt forces, and the cart-stopping force are treated as general polynomial functions of deflection and the velocity of deflection for increasing loads and as parabolic functions of deflection for decreasing loads, Figure 3. The effects of body
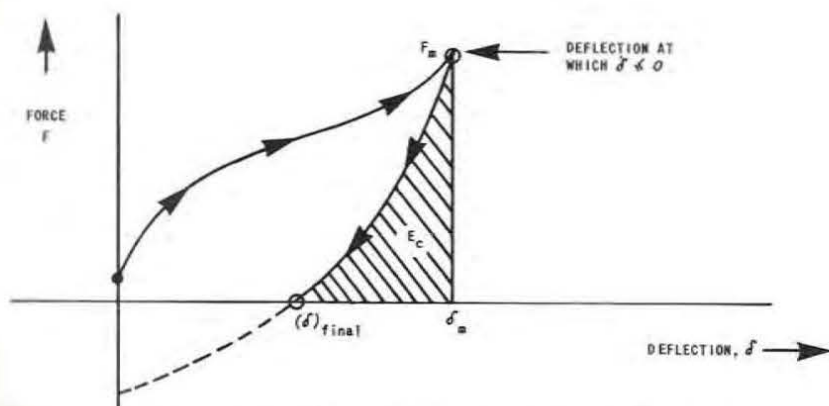
Figure 3. General form of belt and cart-stopping forces.

deformations, and of deflections in the vehicle structure supporting the belt anchorage points, are assumed to be included, so that the fitted mathematical representations of the belts are composite load-elongation relationships. This analytical treatment was employed to permit the application of: 1) experimental load-elongation data for belt loops and 2) idealized belt characteristics.

The parabolic representations of unloading characteristics are determined by specified (input data) ratios of: 1) conserved energy to maximum absorbed energy, and 2) final elongation to maximum elongation for the belt loop. Published load-elongation curves (either measured or "typical") for webbing materials (1, 10, 14, 17), indicate a generally parabolic form of the unloading curve. Also, the 1960 German Test Specification (10) and the specification being prepared by the Economic Commission for Europe (17) include tests of energy absorption and of permanent elongation. Therefore, it appeared desirable to incorporate a parabolic unloading characteristic, in which the energy absorption and the permanent elongation could be independently specified, for purposes of parameter studies.

A provision is made in the simulation for recurrent loading of the belts, Figure 4. When recurrent loading takes place, the residual elongation from each cycle is added to the belt slack for subsequent cycles. If the belt unloading between cycles is incomplete, a value of belt slack is determined such that the new loading curve will pass through the final point on the preceding unloading curve.
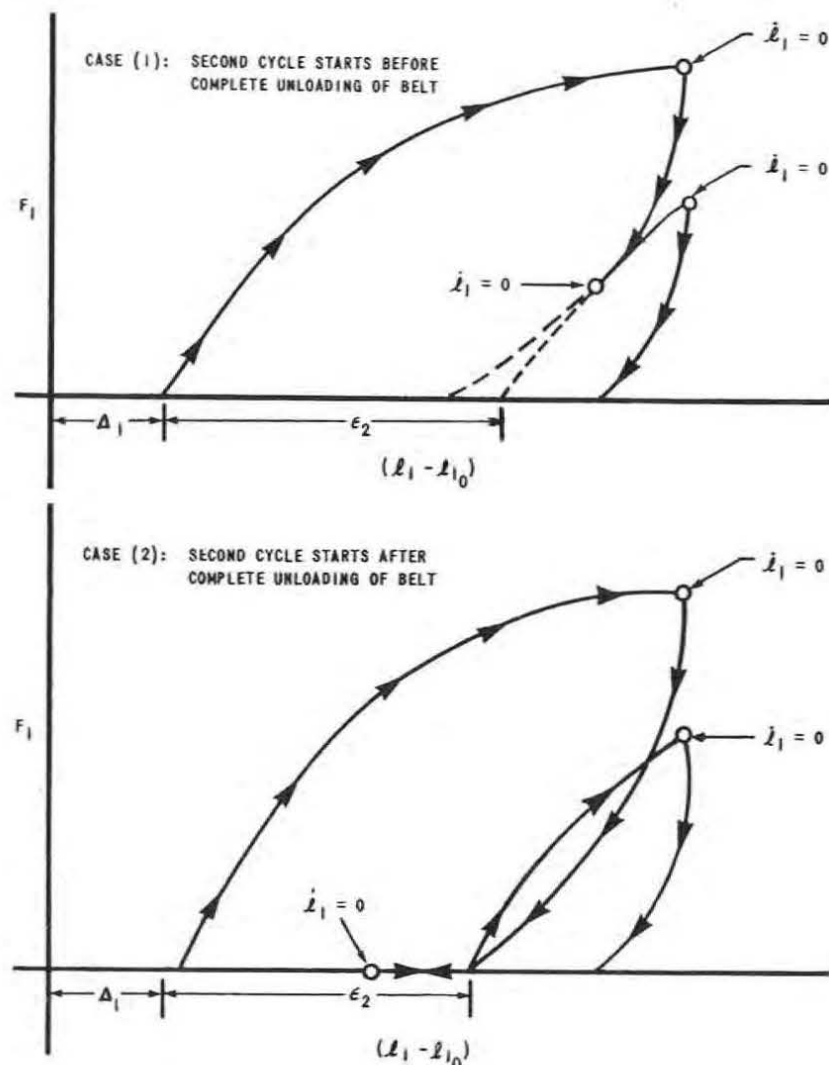

Figure 4. Load-elongation for belt with recurrent loading.

Automotive Seat

The vertical load produced by the seat cushion is represented by two separate forces, Figure 5. The primary force, a nonlinear function of vertical cushion deflection, is assumed to act vertically through the hip. The secondary force, a linear function of vertical deflection of the front edge of the seat cushion, acts vertically at the front edge of the seat cushion. The secondary force was intro-
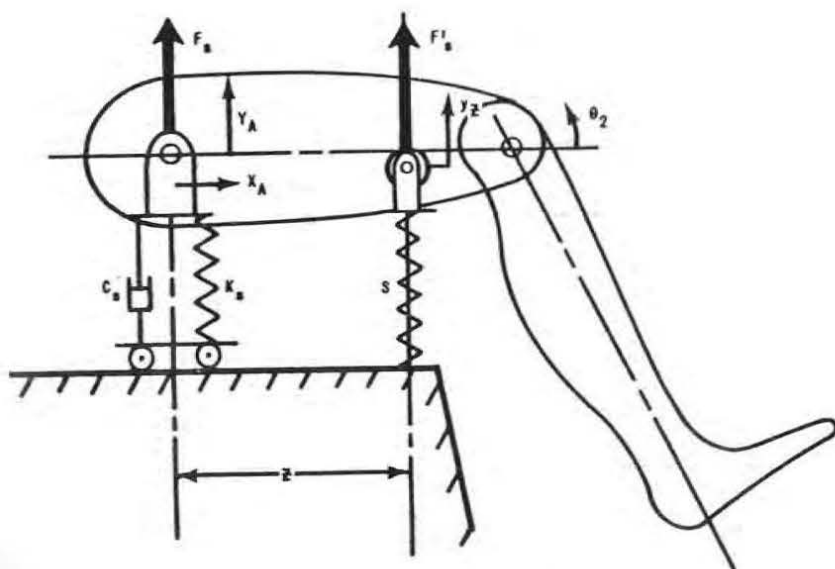
Figure 5. Seat cushion restraint of upper leg.

duced to provide an approximate simulation of the restraint of angular deflections of the upper legs (about the hip pivot) that is produced by the seat cushion.

During forward motion of the hip, prior to the peak belt loading, the simplifying assumption, whereby the resultant dynamic seat force acts vertically through the hip, appears to be reasonable. Following the peak belt load, the torso rotates rapidly about the hip, as the hip slides back relative to the seat. During the latter motion, muscular restraint in the hip produces angular deflection of the upper leg. For a realistic simulation, a resistance to this upper-leg deflection must be provided by the seat cushion.

COMPARISON OF ANALYTICAL PREDICTIONS AND EXPERIMENTAL DATA

The comparisons presented cannot be interpreted as a complete validation of the mathematical model, since some of the parameter data were estimated. Also, variations of the estimated parameters were employed to achieve the degree of agreement in response shown in Figures 6 through 10. The comparisons, therefore, demonstrate only the fact that the mathematical model is capable
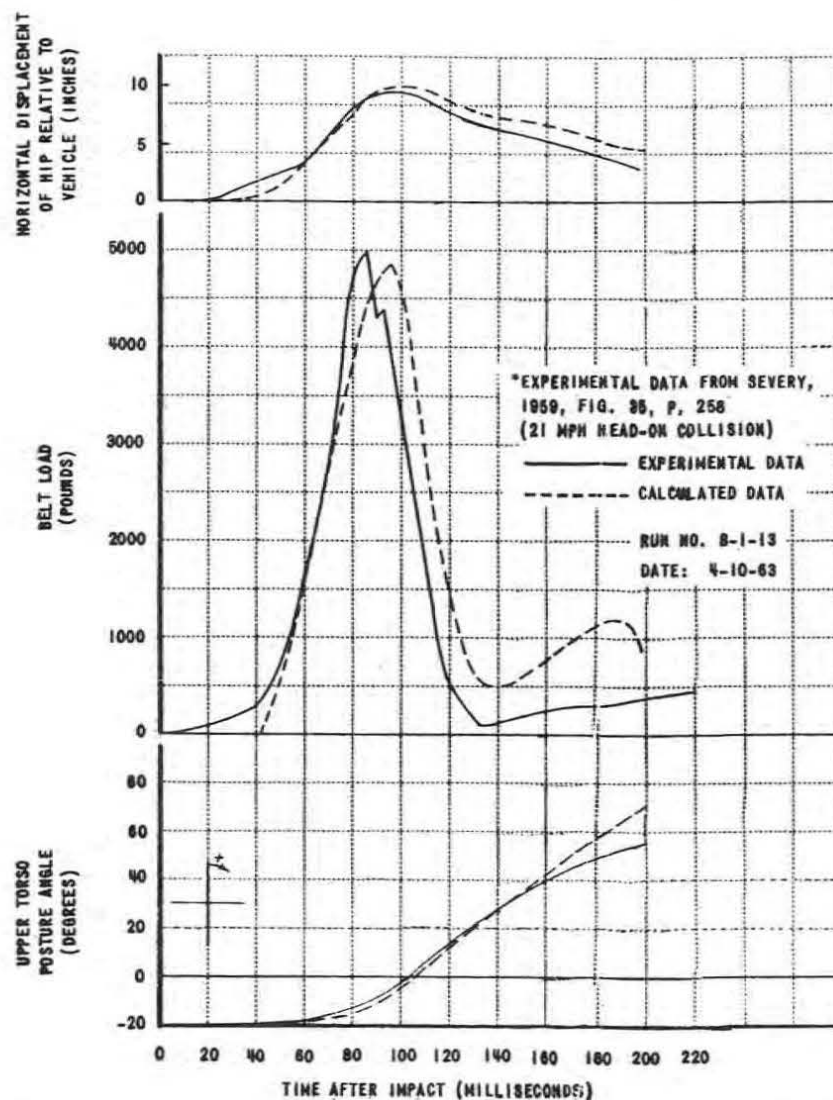
Figure 6. Comparison of experimental* and calculated system responses. (Experimental time-history of passenger compartment deceleration used as input for calculation, system parameters estimated.)

of responding like the physical system, with parameter data that is considered to be realistic.

In Figure 6, calculated time histories of: 1) the horizontal position of the hip, relative to the seat; 2) the loop load of the

NOTE: IN PRESENT MODEL (4/15/63), HIP AND KNEE JOINTS PRODUCE CONSTANT RESTORING COUPLES RATHER THAN FRICTION COUPLES. THIS FEATURE WAS BASED ON DATA FOR THE SIERRA SAM MODEL 120 (KINDRED, 1959). HOWEVER, FRICTION APPEARS TO BE MORE WIDELY USED THAN RESTORING SPRINGS. THIS FACT MAY EXPLAIN THE DOWNWARD ROTATION OF THE LOWER LEG AFTER 160 MILLISEC. WHICH DOES NOT OCCUR IN THE EXPERIMENTAL DATA.
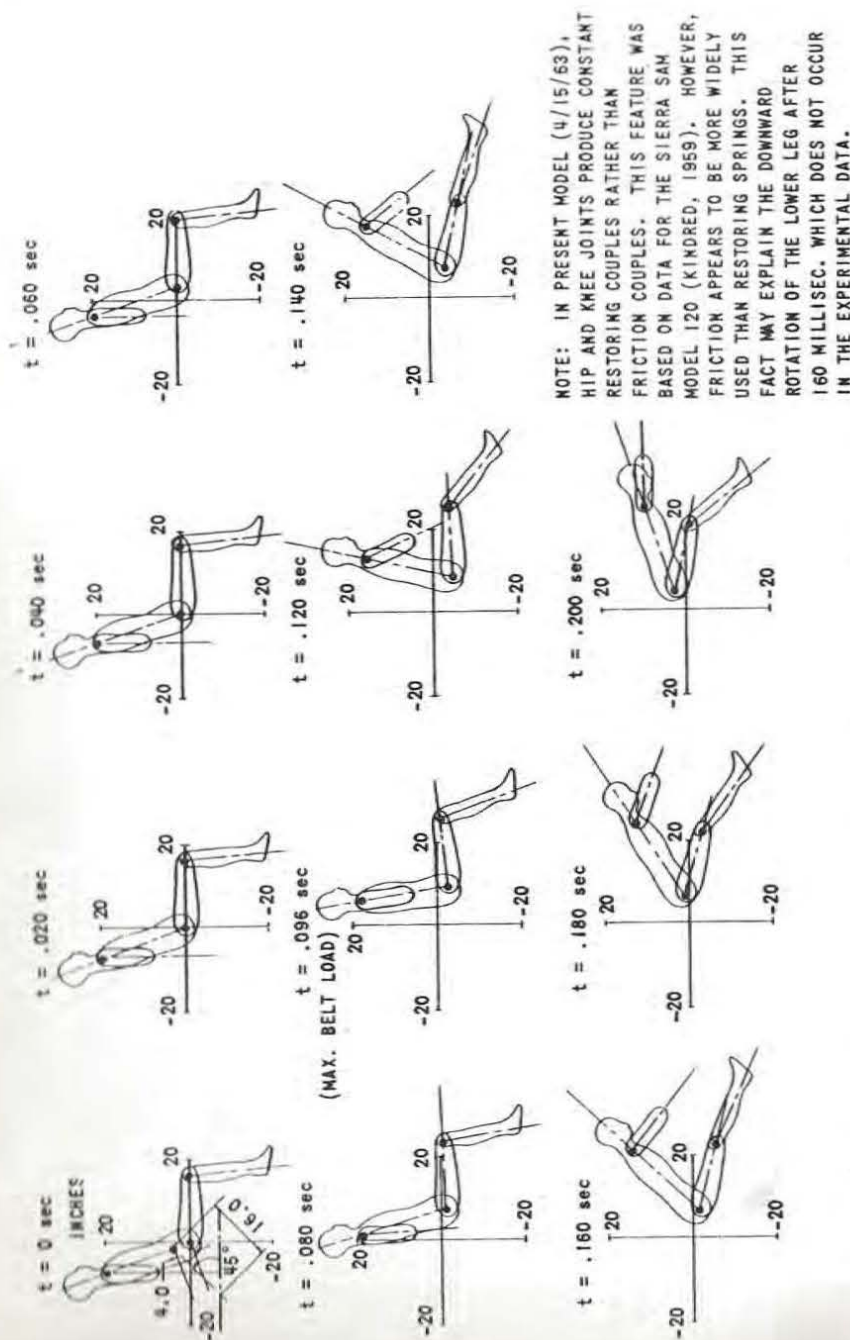
Figure 7. Body orientation and position relative to cart for various values of time after impact, run no. B-1-13.
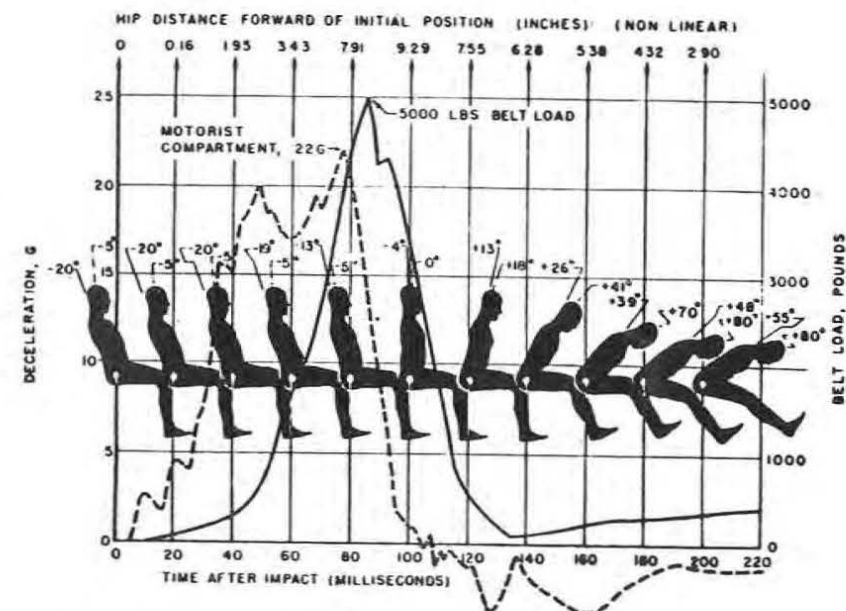

Figure 8. Kinematics of restrained occupant as related to belt loadings, head-on collision (Nash, 21 m.p.h.). (Reprinted from Severy, 1959, by permission of the author.)

lap belt, and 3) the upper torso posture angle, are compared with experimental data for an anthropometric dummy located in a rear seat during an actual head-on vehicle collision (18). The experimental time history of passenger compartment deceleration was used for the forcing function in the calculation. In Figure 7, the calculated position and orientation of the articulated body are shown at various values of time throughout the collision for further comparison with the experimental data in Figure 8. Detailed parameter data for the specific dummy, belt webbing, seat cushion, and the initial side-view angle of the lap belt could not be obtained during the course of this study. It was, therefore, necessary to estimate parameters on the basis of typical data from several sources (see Appendix).

In Figure 9, calculated time histories of: 1) the loop load of the lap belt; 2) the resultant chest acceleration, and 3) the component of chest acceleration perpendicular to the centerline of the torso are compared with experimental data from a cart test (16). The
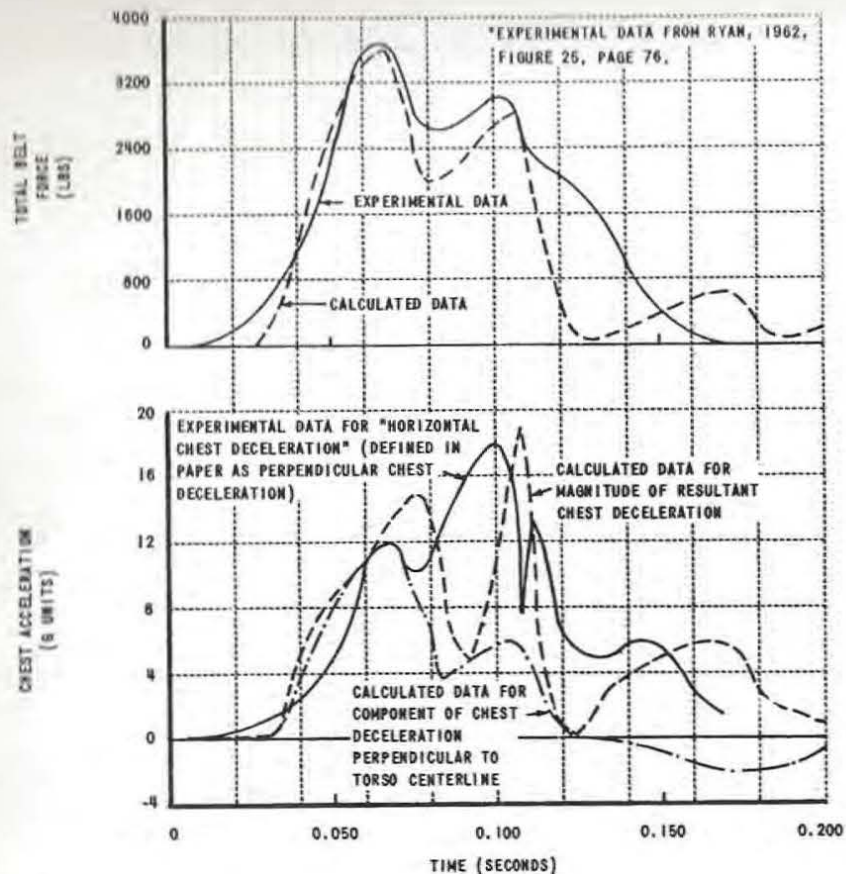
Figure 9. Comparison of experimental* and calculated system responses, run no. B-2-24. (Experimental time-history of cart deceleration used as unput for calculation, system parameters estimated.)

experimental time history of cart deceleration, Figure 10, was used for the forcing function in the calculation. In this case, a lack of experimental data for the position and orientation of the dummy is a handicap in evaluating the results.

To obtain the two closely spaced peaks in the calculated belt load in Figure 9, it was found necessary to simulate an extremely stiff seat cushion and, also, a relatively stiff (low-elongation) belt. The simulated stiff seat cushion appears to be realistic, however, since the test employed an aircraft type seat with a cushion thick-
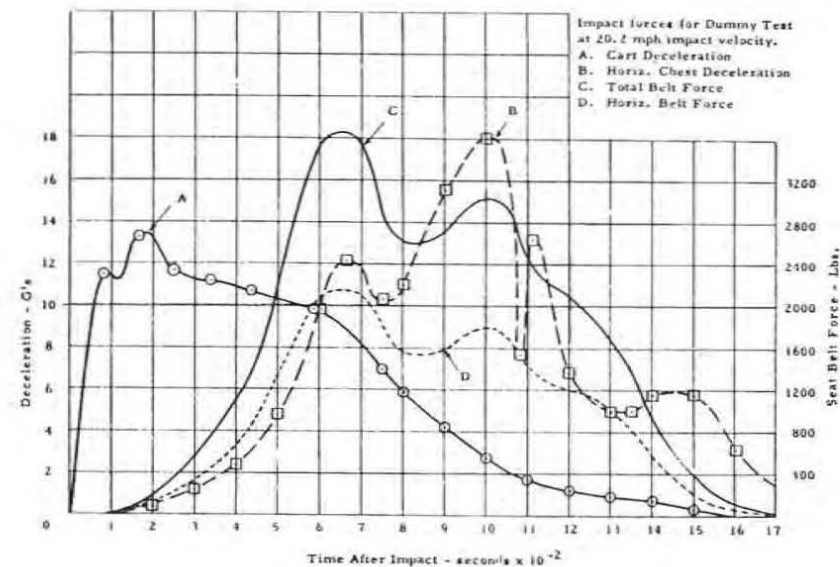

Figure 10. Impact forces for dummy test at 20.2 m.p.h. impact velocity. (Reprinted from Ryan, 1962, by permission of the author.)

ness of only one inch. The actual belt characteristics are not available.

In the comparison of calculated and experimental chest acceleration, it should be noted first that an eighteen-inch distance between the hip and the "accelerometer" was used in both the test and the calculation. It is seen in Figure 9, that the calculated magnitude of the resultant chest acceleration agrees more closely with the experimental "horizontal" chest acceleration. This may be due, in part, to torso deflections in the actual dummy, that are not simulated in the rigid-body mathematical model (e.g., curvature of the dummy spine, caused by the rearward hip loading, would tend to align a chest accelerometer more closely with the direction of the resultant chest acceleration).

RESULTS

Typical detailed results from the mathematical simulation, for the case of a lap belt, are presented in Figures 11 through 17.
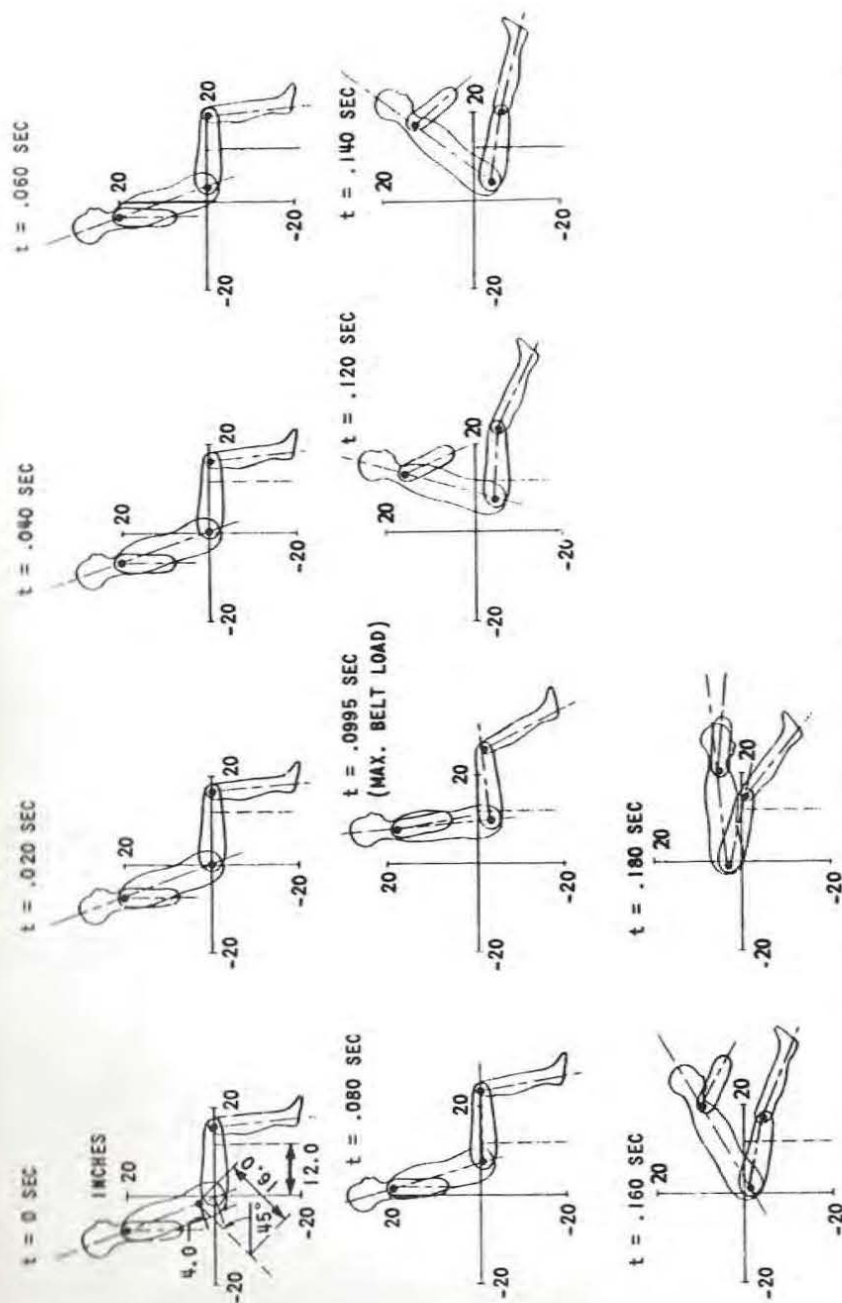
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Figure 11. Body orientation and position relative to cart for various values of time after impact, run no. B-1-12 (lap belt).
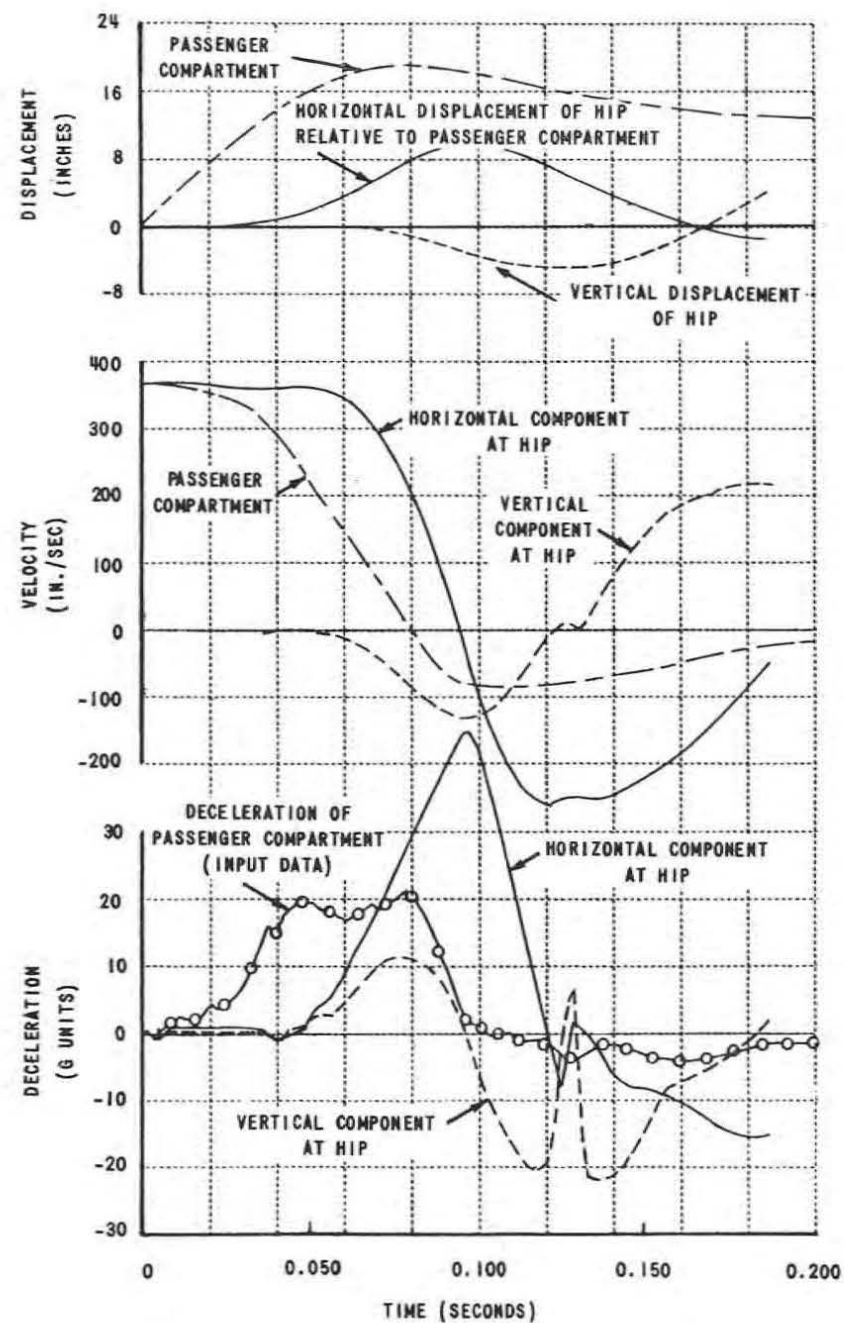
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Figure 12. Body and cart responses vs. time, run no. B-1-12 (lap belt).

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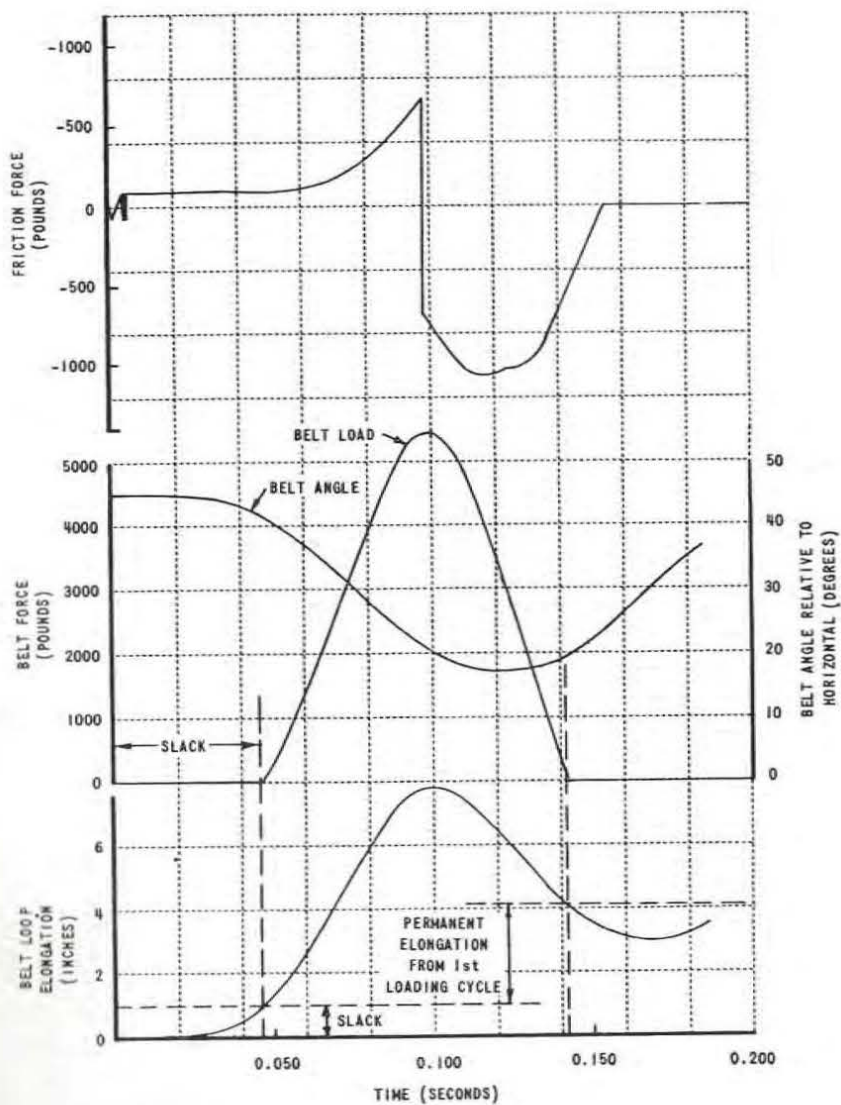
Figure 13. Friction and belt forces, run no. B-1-12 (lap belt).
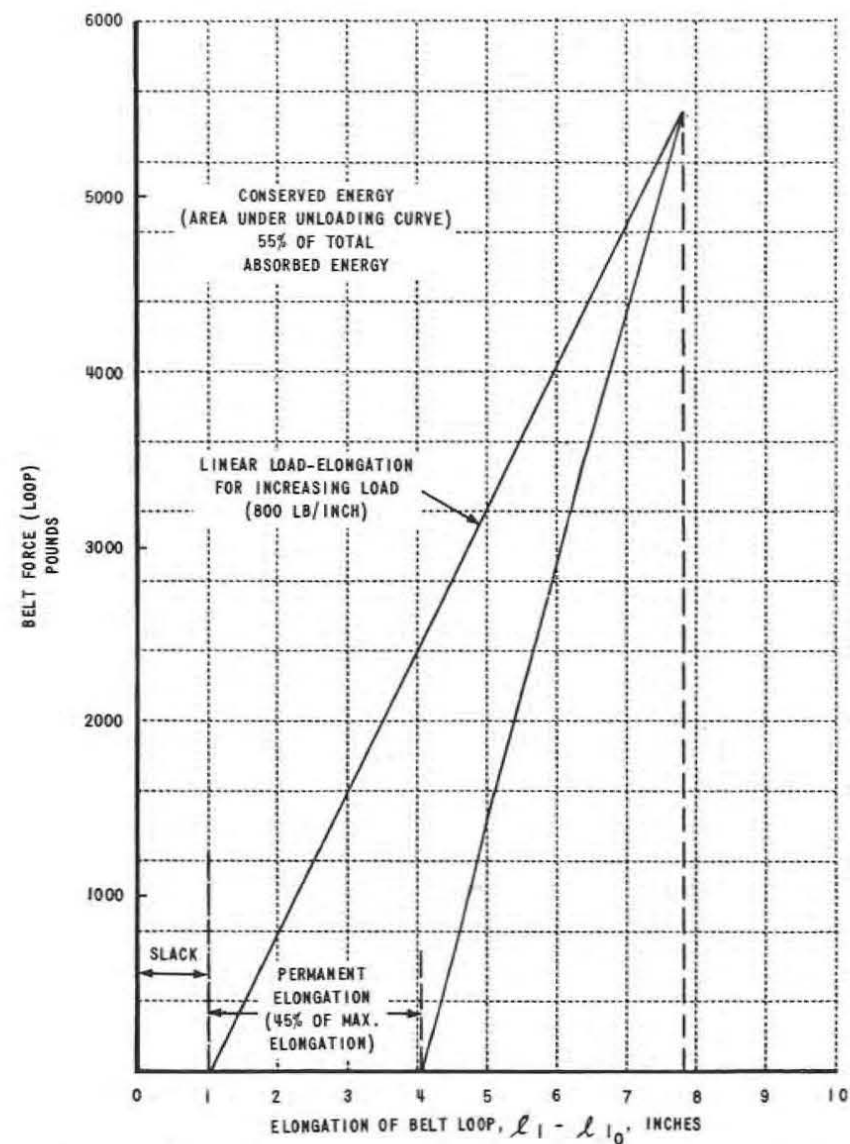
Figure 14. Assumed load-deflection of belt loop, run no. B-1-12 (lap belt).
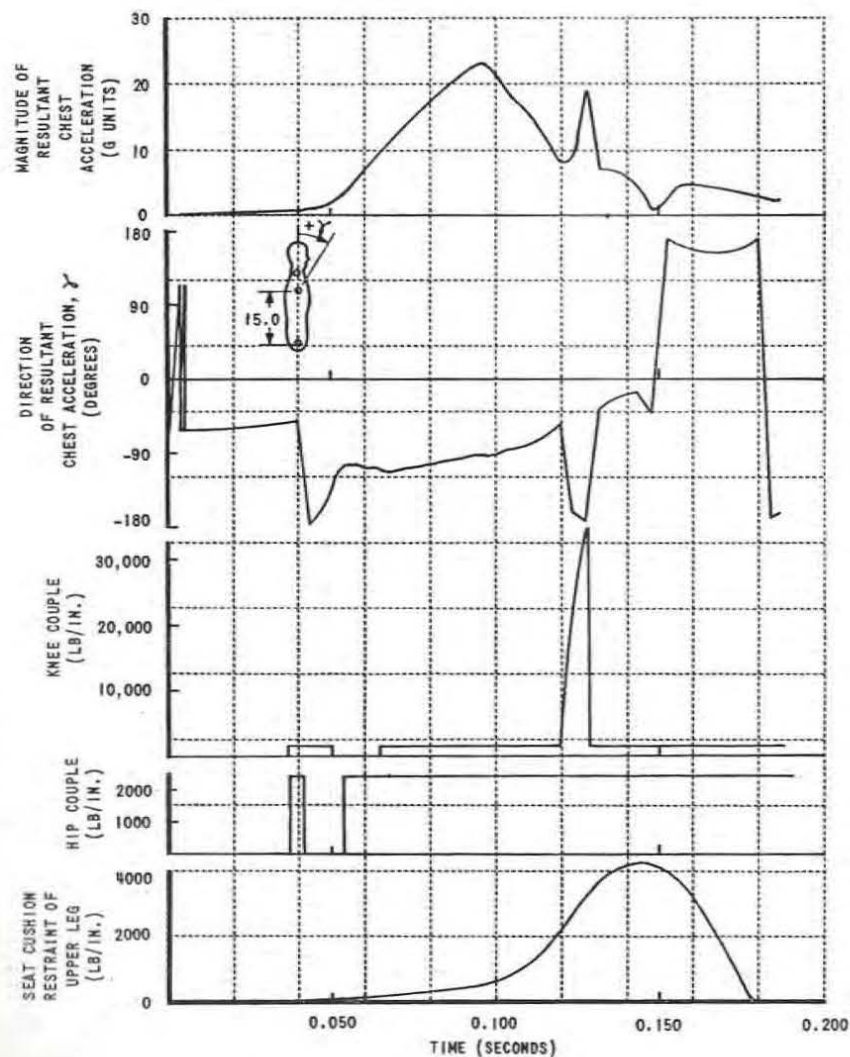
Figure 15. Chest acceleration and restraining couples, run no. B-1-12 (lap belt).

$\longrightarrow$

Figure 16. (*top of facing page*) "Equivalent mass" of segmented body for horizontal forces at hip, run no. B-1-12 (lap belt).

Figure 17. (*bottom*) Vector diagram of chest acceleration, run no. B-1-12 (lap belt). (Resultant acceleration at 4 millisecond intervals about the peak value.)
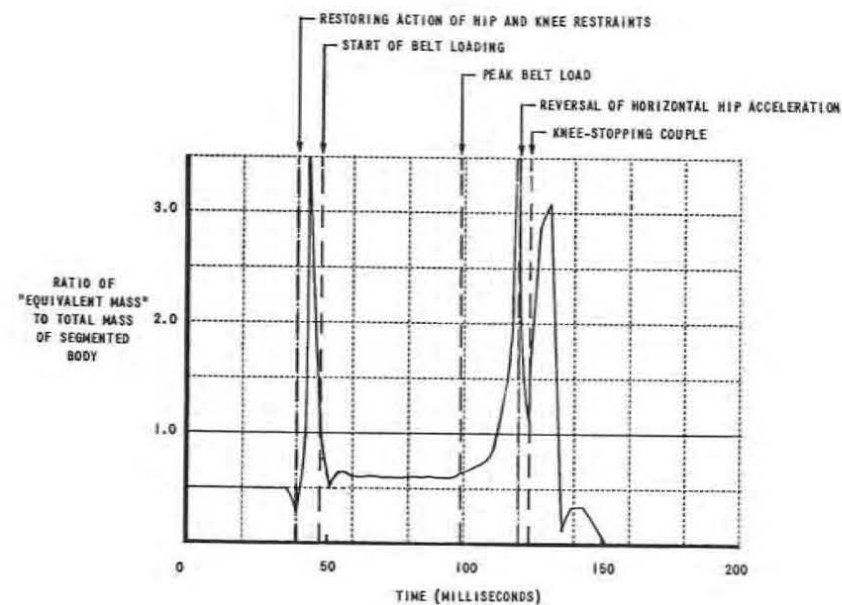
$$\text{"EQUIVALENT MASS"} = \frac{F_1 \cos \phi_1 + f}{\ddot{X}_A}$$

NOTE: THAT THE HIP AND KNEE RESTORING COUPLES AND THE UPPER LEG RESTRAINT (PRODUCED BY THE SEAT CUSHION) EACH PRODUCE HORIZONTAL ACCELERATIONS AT THE HIP.

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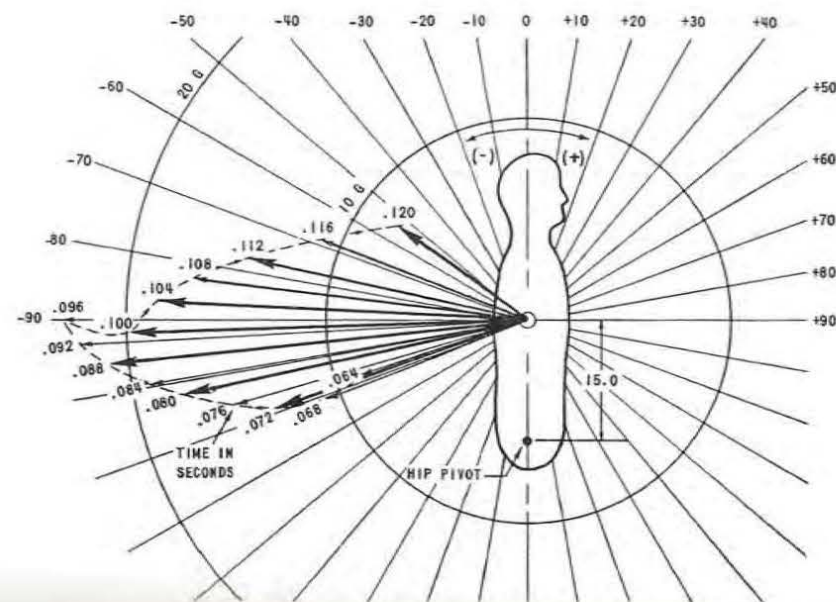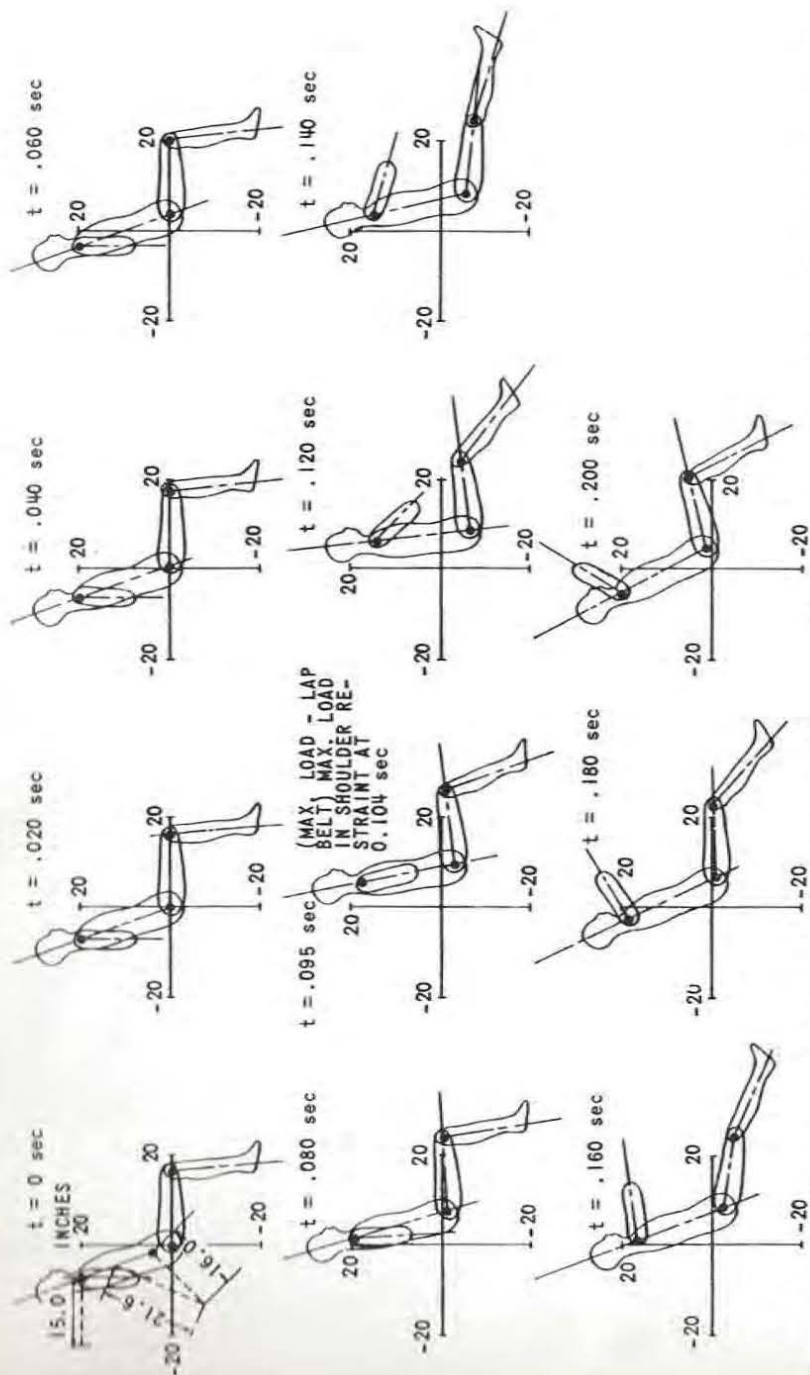
Figure 18. Body orientation and position relative to cart for various values of time after impact, run no. A-1-4 (lap and shoulder restraint).
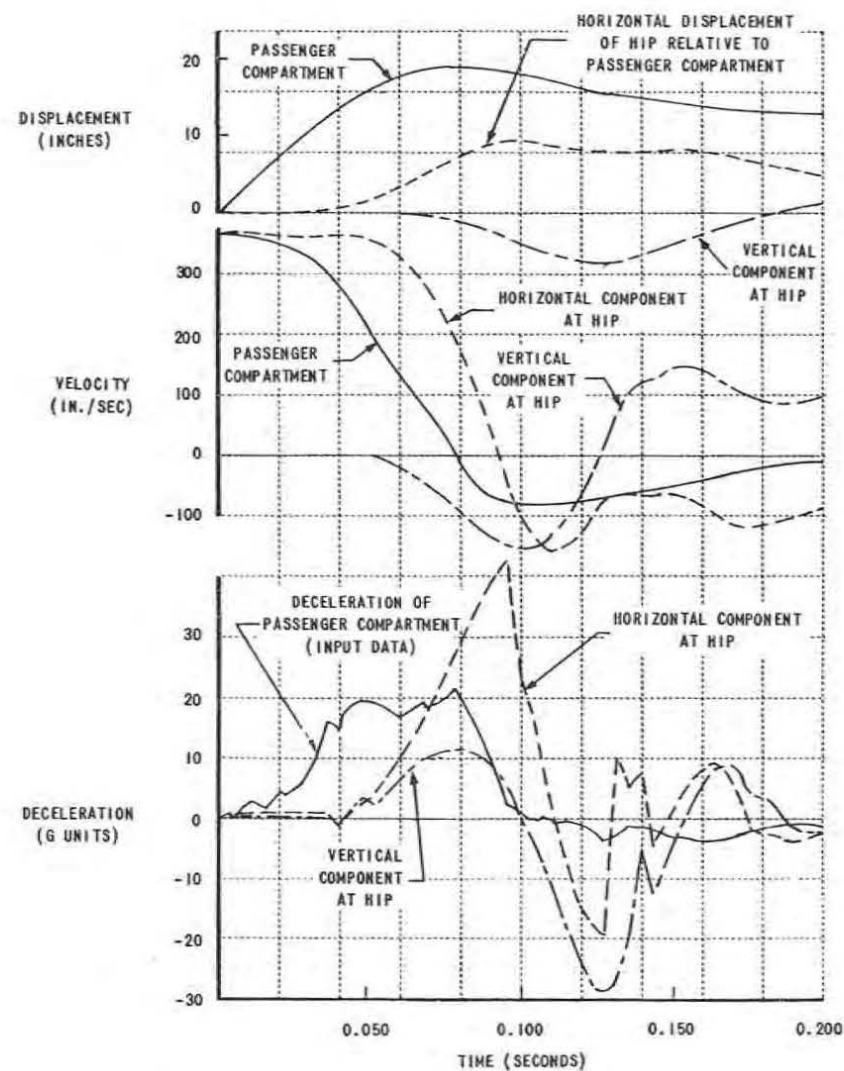
Figure 19. Body and cart responses vs. time, run no. A-1-4 (lap and shoulder restraint).

Similarly, for the case of a combination of lap belt and shoulder restraint, typical detailed results are presented in Figures 18 through 22. In each case, identical vehicle deceleration pulses, from Figure 8, were used.

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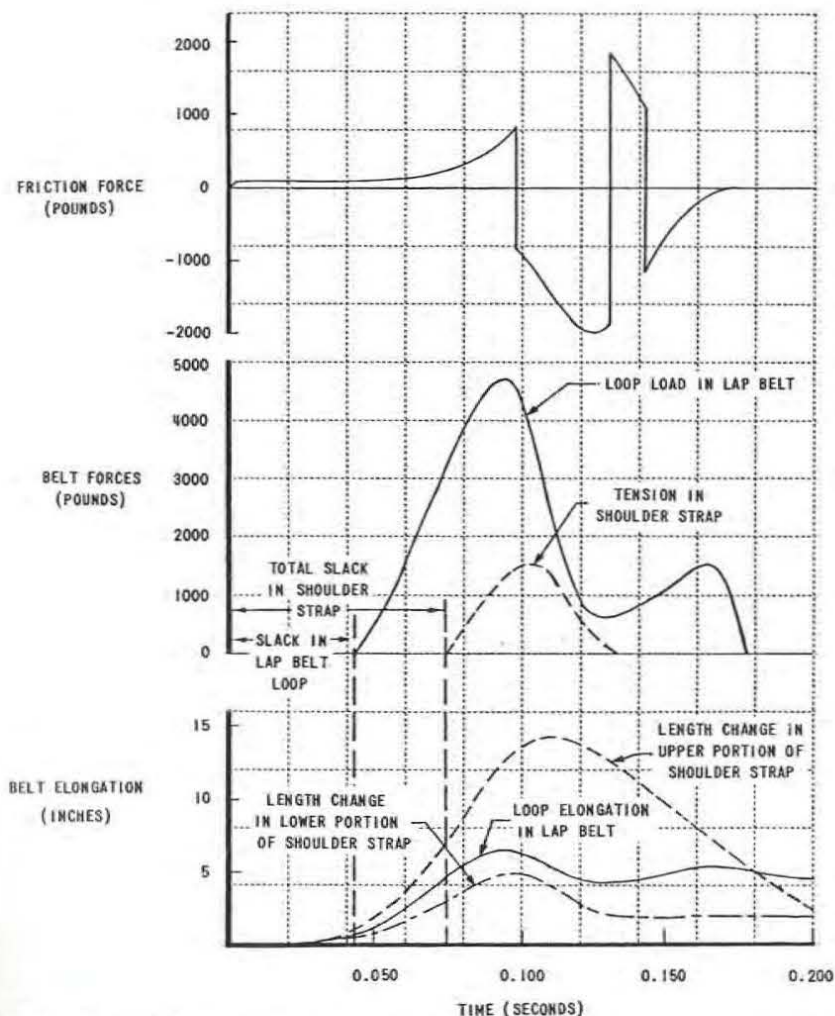
Figure 20. Friction and belt forces, run no. A-1-4 (lap and shoulder restraint).

It is obvious from an examination of the results, that a variety of factors must be considered in an evaluation of performance, or "protection-level." Since absolute human tolerance is not clearly defined for this type of loading, the present study was restricted to a preliminary evaluation of the relative protection level, as parameters were varied. The following items were included (where applicable) in the evaluations:
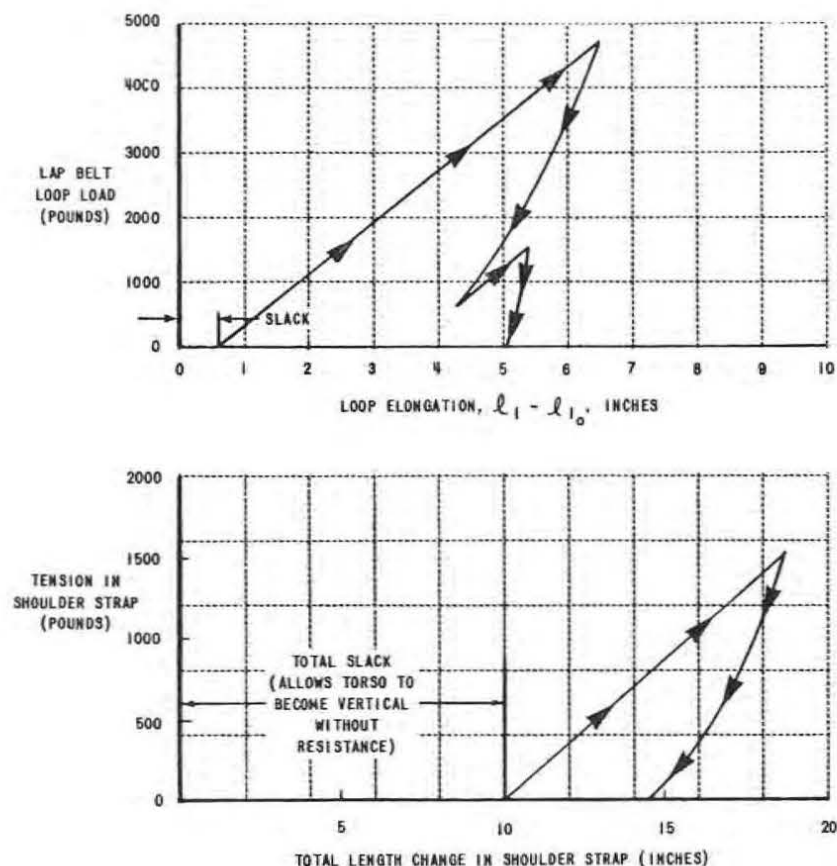
Figure 21. Assumed load-deflection characteristics of belts, run no. A-1-4 (lap and shoulder restraint).

1) Peak belt load (primary).
2) Duration of primary peak belt load (90% level).
3) Secondary peak belt load.
4) Duration of secondary peak belt load (90% level).
5) Magnitude of peak chest acceleration (primary).
6) Angle of primary peak chest acceleration relative to torso centerline.
7) Duration of primary peak chest acceleration (90% level).
8) Maximum rate-of-onset of primary chest acceleration.
9) Magnitude of secondary peak chest acceleration.

MAGNITUDE OF
RESULTANT CHEST
ACCELERATION,
(G UNITS)

DIRECTION OF
RESULTANT CHEST
ACCELERATION,
(DEGREES)

KNEE COUPLE
(LB/IN.)

HIP COUPLE
(LB/IN.)

SEAT CUSHION
RESTRAINT OF
UPPER LEG
(LB/IN.)

TIME (SECONDS)

Figure 22. Chest acceleration and restraining couples (lap and shoulder restraint).

10) Angle of secondary peak chest acceleration relative to torso centerline.

11) Duration of secondary peak chest acceleration (90% level).

12) Maximum rate-of-onset of secondary chest acceleration.

13) Time for $\theta_1 \leq 45°$

14) Time for $\theta_1 \leq 0°$

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15) Maximum horizontal displacement of hip, relative to cart.

16) Maximum vertical displacement of hip.

17) Final hip displacement—horizontal ⎱ at $\theta_1 = 0$,

18) Final hip displacement—vertical ⎰ at $t = 0.200$ sec.

19) Peak hip acceleration—horizontal.

20) Peak hip acceleration—vertical.

21) Maximum knee couple.

22) Time of maximum knee couple.

23) Horizontal velocity at shoulder, relative to cart, on return to initial horizontal position, or at $t \pm 0.200$ sec.

24) Peak value of tension in shoulder straps.

25) Duration of peak tension in straps (90% level).

26) Angle of upper shoulder strap at peak tension.

27) Angle of lower shoulder strap at peak tension.

28) Torso angle at peak tension in shoulder strap.

PRELIMINARY CONCLUSIONS

The following conclusions are based on early results of parameter variations in the described simulation. Because of a lack of complete data for validatio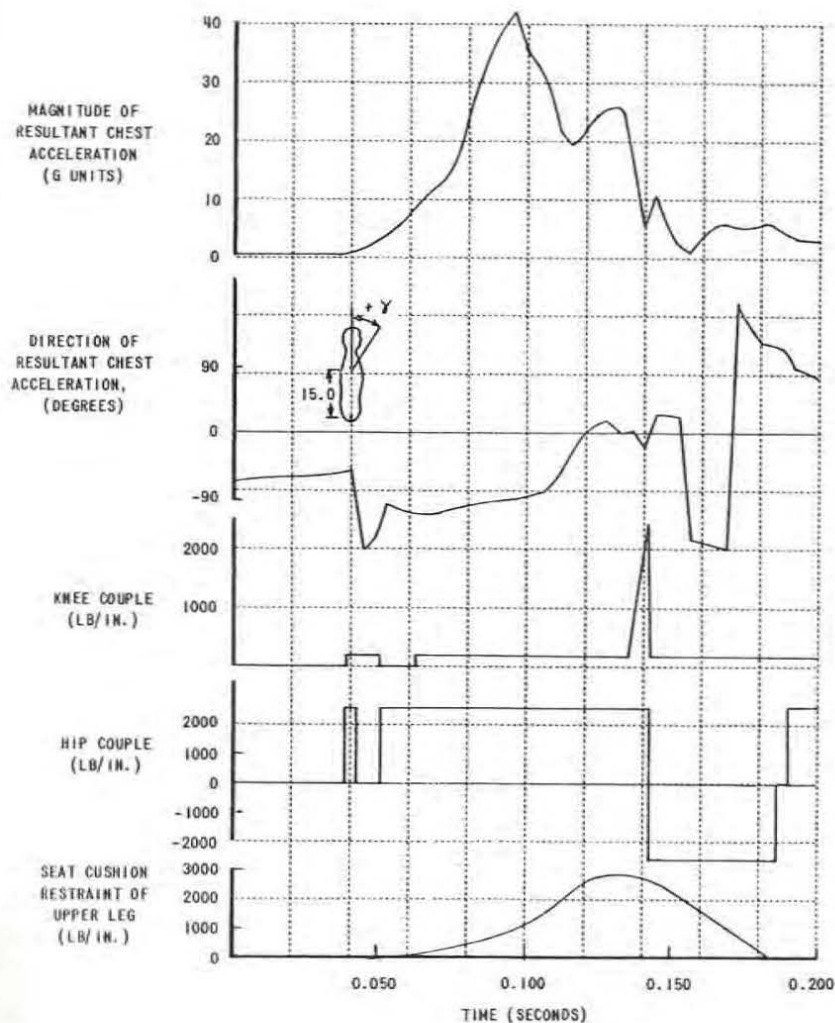n of the mathematical model, the conclusions drawn from its response must necessarily be considered preliminary. In the interest of brevity, less significant findings have been omitted.

Criteria for Evaluation of Protection Level

It appears that this type of analytical approach to the automobile restraint-system problem, if extended in sophistication and supported by further research of human tolerance, can lead to rational criteria for evaluating the overall relative protection level (where trade-offs are involved) provided by various systems. It can also serve as a theoretical framework on which to establish criteria for the absolute protection level.

In existing automobile restraint systems, relatively large changes in the position and orientation of the occupant can occur during a collision. For this reason, an absolute evaluation of the protection level should include the following.

1) The response of internal organs to the complex torso accelerations, which include: a) abrupt pulses or "spikes" super-

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imposed on sustained pulses, and b) a changing orientation of the resultant acceleration relative to the torso (see Figures 15 and 22 for typical calculated time histories of torso accelerations).

2) The directions and magnitudes of structural loads on the spine, rib cage, and pelvis.

3) The impact velocity and contact forces on obstacles in the vehicle interior.

4) Surface pressure on tissue, produced by belts.

5) Expansion of model to three dimensions.

Obviously an extensive research program will be required to establish criteria for an absolute evaluation. Item (1) in particular, is beyond existing knowledge of human tolerance (see (9), for a discussion of required research in this area). For this reason, the present study has been restricted to comparisons of the relative magnitudes of belt forces, chest accelerations, position changes, etc., in a single plane, that are produced by parameter variations.

Strain Wave Effects

Some investigators have exhibited concern over the possibility that the "critical velocity," associated with strain wave propagation in woven belt materials, is being approached in present belt and harness designs. From the results of this preliminary investigation, it appears that the belt-elongation velocities to be expected in survivable automobile collisions are considerably less than the "critical velocity" values indicated in the literature for typical webbing materials. (Aldman 1962 (1) and Coskren 1962 (2), report critical velocities in excess of 100 ft/sec in typical webbing materials.) It would appear, therefore, that in practice the maximum load capacity of a belt loop should remain essentially unchanged between conditions of static and "realistic" dynamic loading.

Stiff vs. Soft Belt Webbing

There has been considerable controversy regarding the advantages and disadvantages of stiff versus soft webbing materials. This analysis indicates that, from the standpoint of minimizing belt loads and passenger accelerations, belts that have approximately linear load-elongation characteristics for increasing load should be as "soft" (large elongation) as possible within the limitations im-

posed by passenger clearance ahead of the seat. (Note that partial or complete recovery of the horizontal position of the hip can occur, in the absence of seat movement or failure, prior to extreme jackknifing.)

It is found analytically (as indicated by Grime 1963 (8)) that a soft belt produces a lower peak belt load for short duration cart decelerations, and that a stiff belt produces a lower peak belt load for long duration cart decelerations. However, the described effect is true only in the complete absence of slack in the belt loop. Since the complete elimination of slack in actual practice does not appear to be feasible, it appears that a belt loop with a linear rate should be as "soft" (large elongation) as possible.

An Idealized Load-elongation Characteristic

It is informative to speculate on what forms of loading curves for belt loops may produce maximum benefit as restraint devices. For example, if nonlinear load-elongation characteristics are considered, several distinct performance advantages can be gained by means of a "saturating" (yielding at constant load) type of belt. The advantages of such a characteristic for combination lap and shoulder restraints are discussed by Grime (7) and Willich (20). A saturating type of loading curve was tried in the model to determine its general effects on system response. For the present analysis and in the case of a lap belt, the peak belt load, the peak chest acceleration, and the forward hip movement were all found to be considerably reduced from those obtained with a linear load-elongation belt loop.

Criteria generally used to evaluate human tolerance, that may be adversely affected by a rapidly saturating loop, are: 1) The duration of the peak chest acceleration, and 2) the rate of onset of chest acceleration. (With the perfectly rigid-plastic load-elongation characteristic assumed in the calculations, the rate of onset is theoretically infinite; however, a more realistic elastic-plastic characteristic with a lower rate of build-up would tend to decrease the rate of onset.) It is pointed out that in the range of acceleration durations studied for this case (less than 30 milliseconds), the relative tolerance to such durations and rates of onset of chest acceleration has not been established. This is in the region of uncertainty discussed by Holcomb (9).

Static vs. Dynamic Webbing Tests

Some investigators have measured differences in load-elongation characteristics when the same type of webbings were tested statically and dynamically. The present study shows that, even though this may be true, the magnitude of variation between separately measured static and dynamic load-elongation characteristics, for approximately linear belts, may not be large enough to produce significant differences in dynamic system responses (insufficient experimental belt data is available to establish the magnitude of the variations, also different webbing materials may exhibit different time-loading sensitivity).

The system response does not appear to be sensitive to relatively large ($\pm 20\%$) variations in the load elongation of a linear belt loop (slack held constant). With the specific parameters and cart deceleration used in the calculation shown in Figures 6 and 7, a ± 20 per cent variation in the linear belt rate resulted in only a $+2$ per cent, -3 per cent variation in peak belt load, and $+1$ per cent, -2 per cent variation in peak chest acceleration.

Hysteresis Effects

1. Lap Belts: The determination of an optimum value of hysteresis (energy dissipation by means of webbing yield) for a lap belt will require a study of: 1) the clearance available for jackknifing of the upper torso, and 2) the anticipated slack in the specific application. When there is insufficient forward clearance available for jackknifing of the occupant, even from the initial position of the hip, the reduced speed of jackknifing, produced by a high hysteresis (early occurrence of belt yield, large inelastic deformation) belt, may more than offset the effects of the accompanying decrease in the speed of recovery of the hip position. The same would be true in cases where a large clearance is available, such as in some rear seats.

2. Combination Lap Belt and Shoulder Restraint: From a limited parameter study of combination restraints, in which the shoulder and lap belts were isolated (no equalization of webbing tension) and were identical in material properties, the use of a high hysteresis material was found to be distinctly advantageous.

Vehicle Stopping Distance

The use of a very short stopping distance in a cart test of lap belts can produce a distorted comparison of the strength (when belt loads are not measured) and the performance of webbing materials with different load-elongation characteristics. This is particularly true with slack or the effects of nonlinear low-rate elasticity (in which the rate increases with deflection) in series with the belt loop, e.g., body elasticity or padding over dummy structure.

A short (3.0 inch) cart-stopping distance, at 25 m.p.h., produces increases in the magnitudes of both the primary and secondary belt loading cycles over those obtained with a more "realistic" (17.0 inch) stopping distance, as encountered in automobile crashes. Note that the analytically predicted secondary loads do not include the effects of seat movement or failure. The described increases in belt loads are much larger for low-elongation belt loops, and further increases are produced in all cases (again, larger increases for low-elongation loops) by the presence of slack in the belt loop.

With a longer cart-stopping distance characteristic of automobile crashes, the system response is more dependent on the wave form of the cart deceleration. This effect is caused by the increased ratio of the duration of cart deceleration to the natural period of the dummy-belt system. (For a discussion of the response of the single-degree-of-freedom linear system to various types of single acceleration time pulses see Von Gierke (19)). It appears that a completely rational testing procedure (for development of specifications) would require that a "standard" wave form be developed from experimental crash data for each of the various types of vehicles (i.e., compact, full-size, unit construction, separate frame, front engine, rear engine, etc.) for which belts are to be tested. (Note that such data could also serve as a guide to possible structural modifications to improve vehicle deceleration characteristics.)

An alternate solution for immediate testing purposes would be to select an idealized wave form and stopping distance on the basis of the primary wave forms in published test data (e.g., half sine wave, A (1-cos wt), etc.). A more extensive analytical and experimental study could be performed to determine the "worst

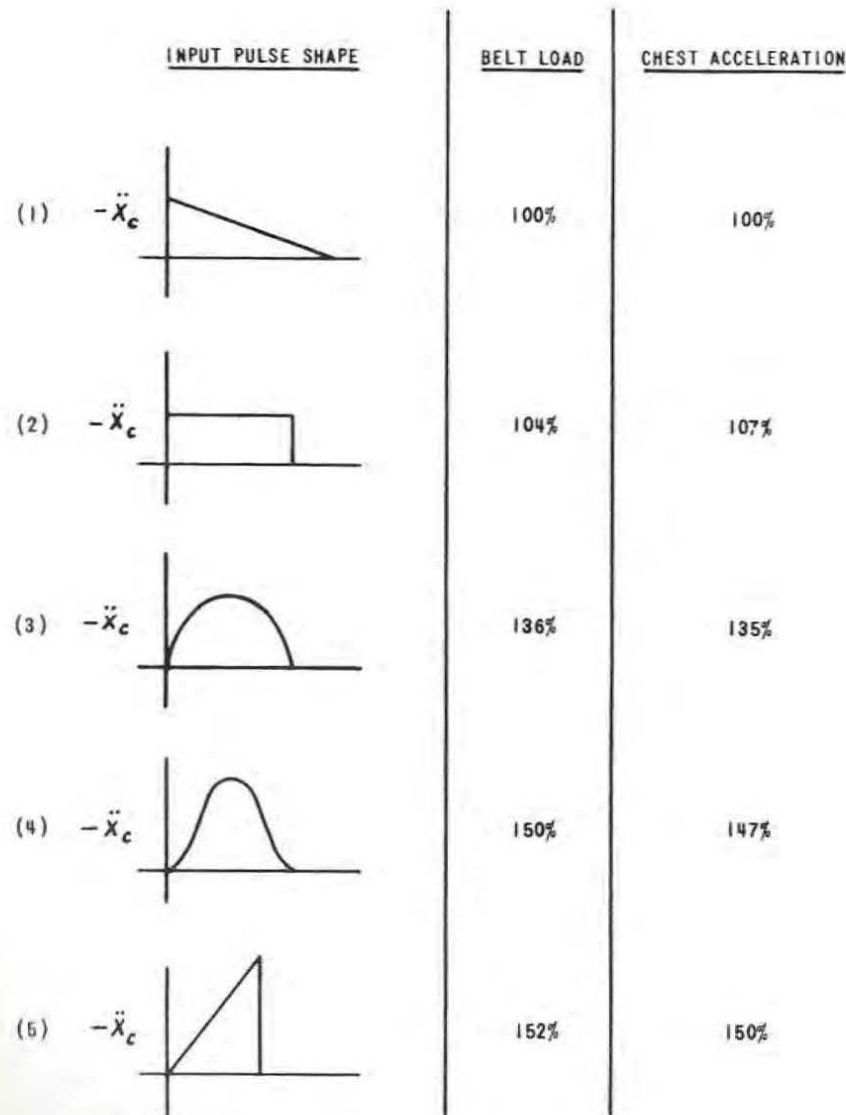| INPUT PULSE SHAPE	BELT LOAD	CHEST ACCELERATION
(1) $-\ddot{X}_c$	100%	100%
(2) $-\ddot{X}_c$	104%	107%
(3) $-\ddot{X}_c$	136%	135%
(4) $-\ddot{X}_c$	150%	147%
(5) $-\ddot{X}_c$	152%	150%

Figure 23. Response to idealized pulse shapes for 17 inch stopping-distance from 25 m.p.h. (lap belt).

possible" idealized wave form for the range of load-elongation in currently available belt loops (e.g., A (1–cos wt) appears to represent the fundamental wave form of published vehicle decel-

erations, while producing higher belt loads than a half sine wave, for the same stopping distance).

Vehicle Deceleration Pulse Shape

If the structural design of an automobile were to be modified in order to develop an improved pulse shape for reducing impact decelerations, the design goal should be a large structural defor-mation (external to the passenger compartment, of course) with an early development of the maximum resisting force. The resisting force should either decrease gradually or remain uniform as the structural deformation progresses. This conclusion is in general agreement with Ryan (16).

For the specific dummy, belt, and seat parameters used in this study program, the peak values of belt load and chest acceleration were found to be dependent on the pulse shape of the vehicle deceleration for long duration (greater than 50 milliseconds) pulses and nearly independent of the pulse shape for short duration (less than 15 milliseconds) pulses. This would be expected from con-sideration of the known response of a linear, single-degree-of-freedom system (see Grime (8) and Von Gierke (19) for discus-sions of a single-degree-of-freedom system). Since actual vehicle collisions generally produce pulse durations greater than 50 milli-seconds, the response to various idealized pulse shapes for a con-stant (17 inch) stopping distance at 25 m.p.h., corresponding to pulse durations greater than 50 milliseconds, was investigated. The results, listed in the order of increasing belt loads and chest accelerations, as indicated by the percentage figures, are shown in Figure 23. The required dynamic force deflection of a cart-stopping mechanism (or vehicle front structure) for the various pulse shapes is shown in Figure 24.

Effects of Shoulder Restraint

The addition of a shoulder restraint to a lap belt system (isolated restraints, with no equalization of webbing tension) produces in-creases in both the rate of onset and the magnitude of the resultant torso acceleration. This appears to be true for all values of linear load-elongation characteristics and slack in the shoulder restraint.

The rate of onset of the resultant torso acceleration is larger with "stiff" (low elongation) webbing in the shoulder restraint.
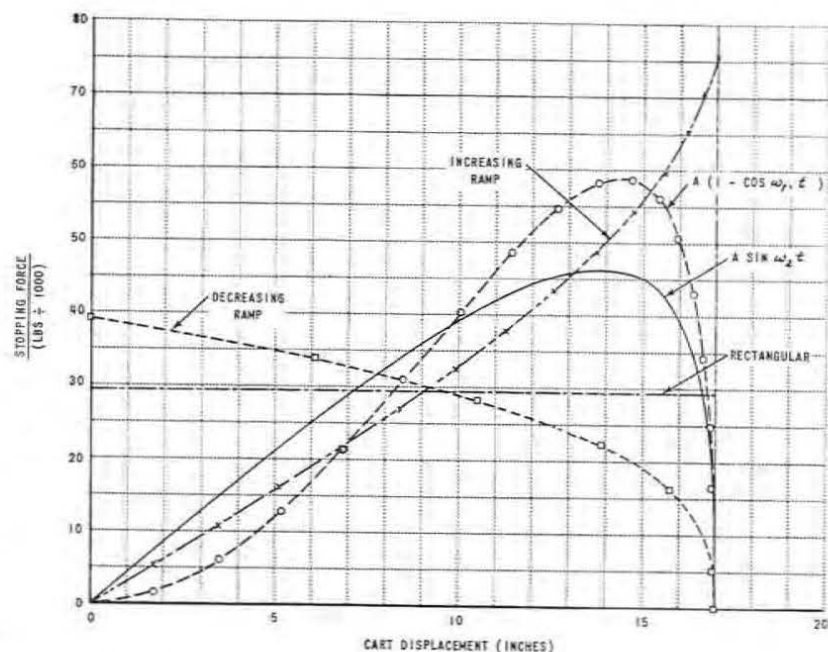
Figure 24. Dynamic force—deflection required in cart—stopping mechanism for Various deceleration wave forms. (2000 lb. cart—17 inch stopping distance) 25 m.p.h.

Also, for a given amount of slack, the peak value of the torso acceleration tends to be larger with "stiff" webbing in the shoulder restraint. However, the sequence of the peak loads in the lap and shoulder restraints, as influenced by slack, can produce minor exceptions to the indicated relationship between peak acceleration and webbing stiffness.

The described effects occur in a duration range where human tolerance is not defined at present. The advantages to be gained by preventing impact of the upper torso with the vehicle interior are obvious, but the possible penalty in terms of increased internal injuries is not clear. Future studies are planned to examine the overall effects on human tolerance in more detail.

Belt Slack

The fact that slack is detrimental to restraint system performance is, of course, generally recognized and is verified in this analysis. The elimination of slack in crash simulations, as a means of improving repeatability, can produce uncertain and unrealistic results.

Trials of increased slack in the mathematical model have resulted in increases in: 1) the peak belt load; 2) the peak value of chest acceleration; 3) the speed of jackknifing, and 4) the forward displacement of the hip relative to the cart. A greater effect occurs with stiffer belts (low-elongation webbing).

Dummy Joint Restraints

A complete test of a lap belt (for research or the development of specifications) should include runs: 1) with realistic joint restraints to test the strength of the belt and associated hardware, and to determine the maximum values of accelerations and loads on the occupant that can originate from the belt, and 2) without joint restraints to evaluate the occupant injury that can be produced by impact on portions of the vehicle interior, for the case of an occupant in a confined space who is not alerted to the impending crash.

The use of large resisting or restoring couples in the principal body joints of anthropometric dummies, to simulate muscle tone, has the effect (with a lap belt) of increasing both the belt load and the resultant chest acceleration, while reducing both the speed of jackknifing and the speed of recovery of the horizontal hip position relative to the cart (note that, in this case, the effect of the decreased speed of jackknifing appears to more than offset the slightly reduced speed of recovery of the hip position, as far as influencing the violence of impact on interior structure).

Rebound Velocity of Test Vehicle

In a cart (or vehicle) test, any rebound velocity of the cart must be added to the impact velocity, before comparisons can be made between "equivalent" test runs. This correction is made necessary by the fact that the velocity change of the cart relative to the dummy determines the severity of the impact for the restraint system. In cases where a small cart mass permits large dummy-to-cart interactions, the problem of comparing runs is obviously much more complicated.

Interaction between Lap Belt and Shoulder Restraint

The use of a slip-ring type of connection between a lap belt and shoulder restraint, through which equalization of belt tension is allowed to occur, appears to be detrimental to the restraint-system performance.

The investigation of shoulder restraints in this study has been very limited; however, a trial calculation was run to explore the effects of tension equalization between lap and shoulder restraint, through a slip-ring type of connection at a common anchorage point. The trial run used data that were identical to those for the calculation shown in Figures 18 through 22, except for the tension equalization. The changes in response were as follows:

1) The peak value of chest acceleration was increased by 31 per cent, primarily because of the simultaneous occurrence of the peak loads in shoulder and lap belts.

2) The peak value of tension in the shoulder restraint was increased by 50 per cent.

3) The peak value of the lap belt loop load was reduced by approximately 3 per cent.

4) Forward movement of the hip was increased by 44 per cent (4.3 inches), because of the transfer of shoulder-restraint slack to the lap belt.

GENERAL RECOMMENDATIONS FOR IMPROVED OCCUPANT PROTECTION AND PLANS FOR FURTHER RESEARCH

General Recommendations

In connection with the parameter variation studies, some of the results appear to be sufficiently clear-cut to justify preliminary recommendation of design goals for improved occupant protection. The specific items are discussed in the following paragraphs.

Yielding Belts or Anchorage: The development of yielding (elongating with a constant resisting force) belts or anchorages should be explored for the purposes of: 1) limiting the maximum belt force, and 2) reducing the total belt elongation for a given force level (by means of an early development of the yield force).

This recommendation is in general agreement with the conclusions drawn by Grime (8) from an analytical study and Willich (20) from an experimental study. Cart-test results, obtained with an experimental inelastic "stretch" member in the shoulder restraint, are presented by Willich (20).

Slack-eliminating Devices: The incorporation of a slack-eliminating device (e.g., inertia-actuated locking mechanism) should be considered as a possible requirement in restraint-system specifications, particularly for the case of a shoulder restraint. The effects of slack in a shoulder restraint appear to be similar to those in the lap belt, but they are made more extreme by the relatively large magnitude of slack that is generally required for access to the vehicle controls.

Vehicle Structure: Modifications in the design of the front structure on automobiles, that would tend to produce: 1) an early occurrence of the maximum resistance to impact loading, and 2) a gradually decreasing or uniform resistance as structural deformation progresses should be explored for the purpose of improving the protection of restrained occupants. This recommendation is in general agreement with Ryan (16). Idealized load-deflection characteristics to produce rectangular or decreasing-ramp deceleration wave forms are shown in Figure 24.

Plans for Further Research

As indicated previously, it has not been possible during the course of this study to obtain complete parameter and test data for validation of the developed mathematical simulation. It is, therefore, planned (depending on the cooperation of organizations with experimental facilities) to carry out a program of fully-instrumented cart tests of lap belts and of combination restraints, with detailed measurements of all parameter data required for the calculation program, in order to establish the validity (or required refinements) of the developed mathematical model. The initial validation will, of course, be aimed at major system responses.

After a basic validation of the model, further investigation is planned in the following areas, with analytical refinements to be incorporated as required.

A. Mathematical Model

1) Load elongation and hysteresis of belts and shoulder restraints.

2) Torso bending.

3) "Whiplash" effect (additional degree of freedom for head).

4) Anchorage location for shoulder restraint (tilting seat back).

5) Tension equalization between lap belt and shoulder restraint.

6) Constant-force restraints.

7) Joint restraints in dummy.

8) Size and weight of occupant (child restraints).

9) Seat movement or failure.

10) Restraint of feet by friction on floor.

11) Impact forces on vehicle interior.

B. Criteria for Protection Level: A comprehensive investigation is planned to determine analytical techniques and human tolerance data that may be applied, to convert the results of this simulation into rational evaluations of absolute protection level.

Appendix

SOURCES OF DATA AND PROCEDURES FOR ESTIMATING PARAMETERS

To validate the developed mathematical model, it will be necessary to obtain complete parameter data for a specific test series. Since this was not possible during the course of the present study, it was necessary to estimate parameter data, using the best means available. The objective in the following sections was, therefore, to obtain realistic estimates.

Parameters for Anthropometric Dummies and Humans

Moment of inertia data for the various body segments of anthropometric dummies and cadavers appears to be quite limited. In Table 1, a summary is presented of data collected from the literature during this study, for component weights, dimensions, and moments of inertia. In column 8 of Table I, estimates of moments of inertia, based on an homogeneous right circular cylinder for the torso and uniform slender rods for the appendages, are presented for comparison.

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TABLE I
APPROXIMATE DATA FOR ARTICULATED BODY

		1 Sierra Model 120 1953 Kindred, 1953	2 Sierra Model 757 1962 Ryan, 1962	3 Sierra Model 263 1950 Brochure	4 Fisher 1906	5 Dempster, 1955 No. 15097	6 Lay, 1940	7 M_i from I, Average of 1 through 6 for i, ρ_i, L_i	8 Theoretical Approximations**	9 Data Used in Calculations*	
Torso and Head,	M_1	0.28209	0.27950	0.27096	0.13573	0.23146	0.21066	0.28209	0.28209	0.28209	lb-sec²/in
	ρ_1	—	13.04	13.6	11.866	12.73	14.80	13.21	14.0	12.8	in.
	I_1		45.954		9.347	19.54	—	28.8	20.2	32.0	lb-sec²-in
	L_1		21.0	—	22.342	—	19.59	20.98	—	21.0	in.
	i_1		(12.8)		(8.3)	(9.2)	—	10.1	8.46	—	in.
Upper Legs,	M_2	0.11594	0.10351	0.09730	0.05517	0.08129	0.0854	0.11594	0.11594	0.11594	lb-sec²/in
	ρ_2	—	—	7.9	6.224	—	6.52	6.88	8.0	7.1	in.
	I_2			—	1.076	2.131	—	2.6	2.47	3.0	lb-sec²-in
	L_2			18.3	14.279	—	16.0	16.14	16.0	16.0	in.
	i_2	16.0			(4.416)	(5.119)	—	4.77	4.62	—	in.
Lower Legs and Feet,	M_3	0.07867	0.06987	0.06625	0.03298	0.05517	0.05150	0.07867	0.07867	0.07867	lb-sec²/in
	ρ_3	—	12.4	7.7	9.197	—	9.81	9.78	10.0	10.0	in.
	I_3		7.821	—	1.111	2.856	—	4.8	2.62	6.0	lb-sec²-in
	i_3		(10.54)		(5.796)	(7.19)	—	7.84	5.78	—	in.
Arms and Hands, 90° Elbow,	M_4	0.06418	0.05952	0.04140	0.02748	0.04476	0.04943	0.06418	0.06418	0.06418	lb-sec²/in
	ρ_4		—	8.6	9.64	—	9.39	9.21	—	—	in.
	I_4			—	1.420	—	—	3.3	—	—	lb-sec²-in.
	i_4				(7.21)	—	—	7.21	—	—	in.
Arm Straight,	ρ_4		12.0	11.38	10.53	—	12.7	11.65	12.0	11.3	in.
	I_4		8.631	—	1.429	1.839		4.7	3.08	4.7	lb-sec²-in.
	i_4		(12.04)	—	(7.21)	(6.40)		8.55	6.94	—	in.
Knee	J_1	1800								1800	lb-in.
Hip	J_2	2600								2600	lb-in.
γ										15.0	in.
Total Weight		209	198	183.6	97.12	159.83	153.4	209	209	209	lb
Height		72	72	73.1	59.25	69.45	67.5	72	72	72	in.

*Note that the complete data given in this table was not collected before the calculations were started. Therefore, the estimates in Column 9 were used. In view of the approximate nature of Column 7, the differences between Columns 7 and 9 did not appear to justify re-running the calculations.

**M_i from I, Homogeneous Right Circular Cylinder for Torso, Slender Rods for Appendages (R = 5, h = 28).
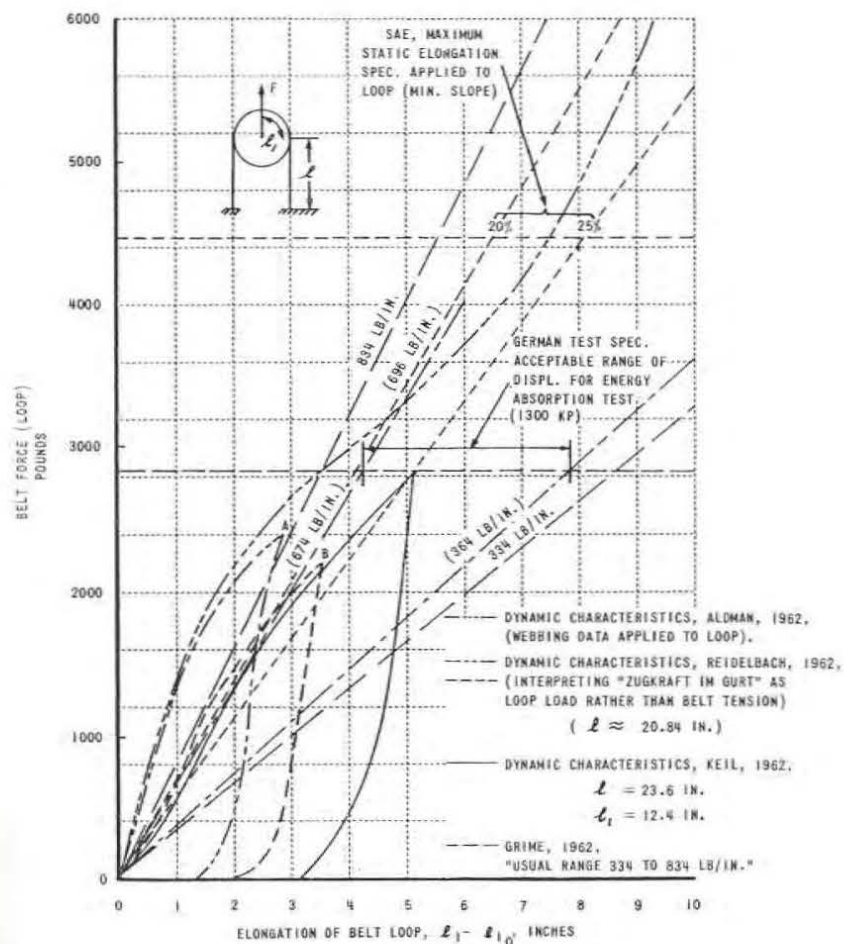
Figure 25. Load-deflection of belt loop.

In Table I, it is seen that values for the radii of gyration, i_i, and the distances to the centers of gravity of the segments from body joints, ρ_i, are in relatively close agreement for a wide range of total body weights.

Webbing and Belt Loop Characteristics

Available data for the dynamic or static load-elongation characteristics of belt loops are also quite limited. In Figure 25, a summary is presented of actual belt-loop data and estimates based on: 1) webbing characteristics and loop dimensions; 2) existing test specifications, and 3) ranges indicated in the literature. Because
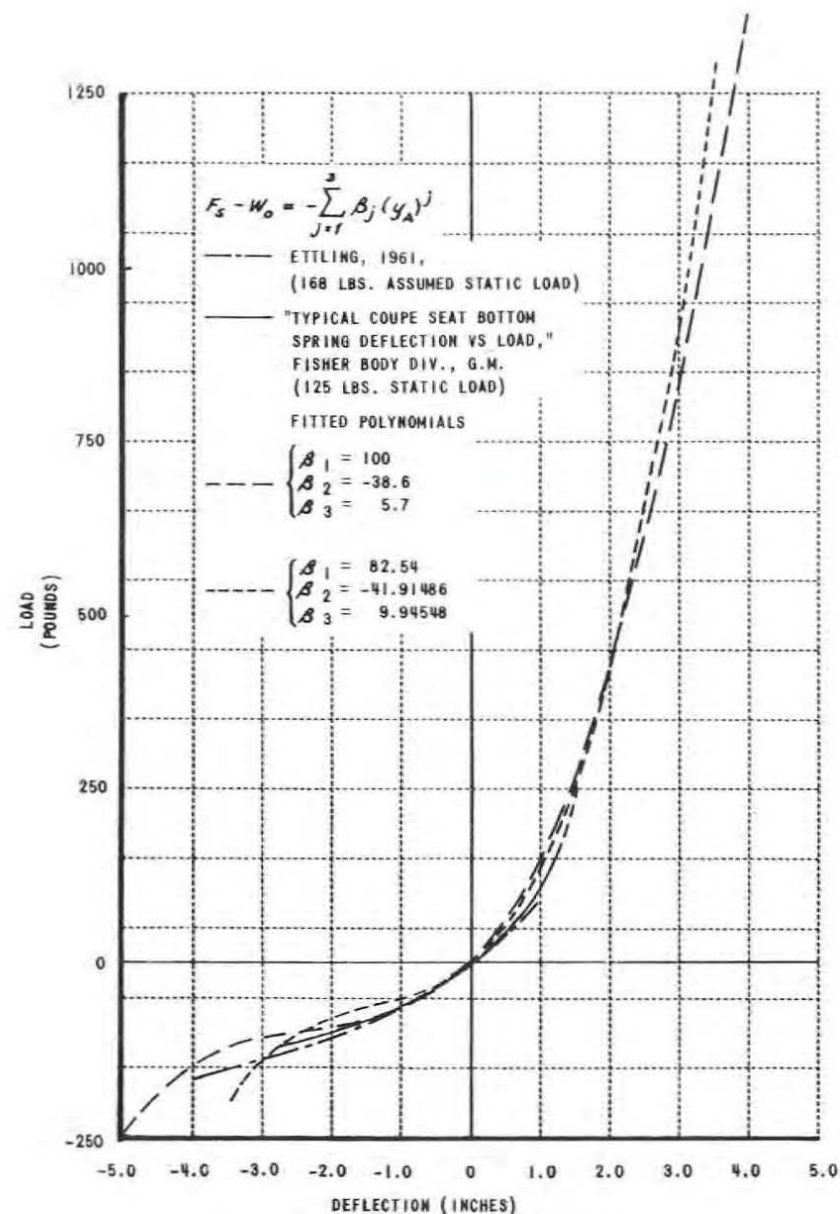
40

Figure 26. Seat cushion load—deflection.

of the lack of definitive data, linear characteristics for increasing loads have been used in all of the calculations, with the exception of those used to evaluate the effects of rigid-plastic characteristics.

Test Cart Parameters

Although preliminary calculations have been run, in which dummy-to-cart interactions were simulated, and future studies are planned to evaluate the adequacy of the cart weight and the stopping mechanism of various cart facilities, the majority of the calculations to date have by-passed the dummy-to-cart interactions. This is accomplished by means of a direct entry of cart (or passenger compartment) decelerations as a forcing function. In such cases, the only parameters that are used are: 1) initial orientation of dummy; 2) restraint system geometry, and 3) seat cushion characteristics. Items (1) and (2) have been scaled from photographs or estimated for the results presented in this paper. Item (3) has been based on the data presented in Figure 26, and on estimates of seat-cushion damping. The friction force on the seat cushion has been assumed to be directly proportional to the vertical force of the seat cushion at the hip.

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