Crashworthiness Engineering of Automobiles and Aircraft: Progress and Promise

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This paper reviews progress made in improving the technological resources of crashworthiness engineering: physical testing developments, analytical simulation techniques, and inventions and design tools. It defines some of the unresolved problems associated with development of design tools by discussing modeling of structures and exteriors. It concludes that physical test technology is well advanced for highway vehicles, and that available mathematical models, principally for structures and bioengineering, are of limited value because of inadequate work in assuring numerical modeling fidelity and strengthening test-analysis correlation, and that significant improvements in crashworthiness of in-use vehicles awaits more design tools.

I. Introduction

CRASHWORTHINESS engineering is designing to minimize injuries in vehicle impact. To an automotive engineer, this involves design of a range of features from the bumpers (so negligible car damage occurs at low speeds) to restraints (so the passenger will survive high-speed impact). For the aircraft designer, this involves design of the landing gear for repeated shock absorption at low impact velocity to design of ejection seats to save the pilot from high-speed impacts.

Crashworthiness engineering is important. The importance is reflected by the yearly toll of 56,000 deaths (including about 8,000 pedestrian deaths) caused by highway vehicles, and the 2,000 deaths caused by aircraft. It is mirrored in the U.S. Air Force's establishment of the first military specification for airplane safety in 1963; in Congress passing the Federal Motor Vehicle Safety Standards Law establishing the authority of the National Highway Traffic Safety Agency for defining design standards of safety for highway vehicles in 1966; and in the growing volume of Department of Transportation, military, SAE, and ASTM standards, specifications, and procedures.

A surprising aspect of crashworthiness engineering is the small amount of federal government support of research and development activity. Perrone and Saczalski[1] identify a current funding of only 15 million dollars for crashworthiness projects in the structures and biomechanics areas. Most of this (about 12 million or 77%) is managed by the Department of Transportation. This is a small part of an 8.6 billion dollar department budget and a negligible allocation when compared with over 19 billion dollars lost yearly in highway and aircraft accidents.

The purpose of this paper is to review progress in crashworthiness engineering and evaluate the potential for realizing the payoff of crashworthy design of automobiles and airplanes. This review includes an examination of previous work and a description of the difficulties to be overcome to realize the potential for successful crashworthiness engineering.

Section II defines crashworthiness progress criteria. Section III reviews the previous progress. Section IV describes some of the remaining problems and the promise in their solution. Section V contains conclusions of the paper.

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II. Crashworthiness Engineering

For purposes of assaying progress, this engineering will be characterized by three ingredients: 1) data quantifying injury and the relation of the injury to accident initial configuration; 2) relevant models of the crash components – vehicle, restraints handling dynamics, biomechanics, and interfaces; and 3) active use of the data and models in developing injury-reducing configurations. Collecting appropriate data for crashworthiness engineering – initial impact velocity and impact and vehicle configurations – has not resulted in much useful data. Haddon notes that records of motor vehicle departments on hundreds of millions of accidents are virtually worthless in this regard.[2] Though aircraft accidents have been studied more thoroughly, many of the similar data for these are largely guesswork, since so many aircraft do not have inflight recorders. Work sponsored by DOT is underway to address these problems. Since identifying injurious configurations is the primary target of safety engineering, it will not be considered further here.

Models of crash components include physical, mathematical, and numerical representations. The "physical model" involves suitable test specimens, instrumentation, procedures, and an understanding of how to interpret test results and transfer them to classes of components. The "mathematical model" is the formulative basis for idealizing the principal characteristics of the crash components and system. It includes representation of geometry, material characteristics, and boundary conditions. The "numerical model" is the basis for quantifying a particular physical system by a set of numbers for the mathematical model.

Physical testing evolves from parametric studies, to development of dedicated test facilities, to standardized test procedures. Mathematical modeling has proceeded from lumped parameter models with few equations, to continuum models, to complicated models which are coordinated closely with the capabilities of making physical measurements for model parameters. Accordingly, these categories will be used to judge progress.

Progress in developing crashworthy configurations will be measured by the extent of safety devices invented and the availability of design tools for engineering. These categories represent the transformation of capabilities from a localized to a more comprehensive view of crashworthiness engineering.

III. Progress in Crashworthiness Engineering

Though crashworthy engineering can be dated from studies to develop parachute descent techniques for escape from balloons around 1800, physical testing for most technical problem areas began in earnest around 1930. The more rapid progress in the last 10 years reflects the exponential growth of the application of science to an unexplored area.

Table 1 represents the state of crashworthiness technology for airborne and highway vehicles. Since shaded areas of this chart indicate regions with significant deficiencies, the chart graphically exhibits the opportunities for continued progress. The unavailability of validated design tools in most areas further reflects the immaturity of the technology.

The next paragraphs summarize highlights of progess in each area over the last 43 years. Much of the literature referenced can be obtained from the National Technical Information Service.

Structures and Exteriors

Extensive investment in testing of highway vehicles has resulted in a number of dedicated test facilities and standard test procedures. The same is not true for airborne vehicles. In both cases, however, simulated technology is rapidly growing. Both auto and aircraft designing for crashworthiness are enhanced by safety devices and design principles arising from studies of accident and test data.

Data generation experiments for cars have been extensive both for determining how various models behave and to explore alternate design concepts. Full-scale flat-barrier, oblique-barrier, pole, and vehicle-vehicle dynamic tests have contributed to the large volume of data on controlled crash of production models.[3-6] Safety concepts such as the hardtop, rear engine, engine deflector, door stiffener, and energy absorbing configurations similarly have been studied.[7-9] As a consequence of this investment, the number of facilities has grown to more than 20 since the 1930's. Specifications for procedures and instrumentation have been standarized. Recent studies have shown that subscale testing is both effective and economical for representing structural behavior in impact.[10,11]

Testing of aircraft structures has benefited from a limited number of full-scale helicopter and light aircraft tests.[12-14] Data developed in vertical drop tests of helicopters are currently being supplemented by data from airplane crash landing tests. For both helicopters and light aircraft, data generation is an important purpose in testing; test facilities have been modified to suit, and standardization of test procedures and instrumentation is evolving.

Much of the early car testing data are ad hoc, generated without extensive analytical support, and leading to only a general understanding of postimpact behavior. Difficulties of test repeatability with the same model are common.

Work in the last 10 years has resulted in the availability of a number of mathematical models for predicting highway and airborne vehicle postimpact response. For highway vehicles, these have involved nonlinear frame models with various degrees of complexity.[15-19] Simulations for aircraft include shell and membrane components to model the semimonocoque construction.[20,21] The frame models have been used successfully in representing helicopter response but have not been satisfactory for unitized-body cars or airplanes. Kamal has had remarkable success in predicting postimpact velocities, displacements, and mean accelerations for cars by computer synthesis of the dynamic response of the vehicle using full-scale component static test load-deflection data.[22] The concept also has been successfully used with dynamic tests of components.[23] Though lumped parameter and continuum mathematical models are available, satisfactory comparisons between production model physical and numerical simulations have not been demonstrated except by the Kamal approach.

Structural testing has supported a number of vehicle design changes. For cars, this includes low-speed bumpers, car door stiffening, and passenger compartment stiffening of pillars and sills.[3,24] In addition, hydraulic and foam energy dissipation devices, collapsing metal structures, and engine deflectors have been tested under the Experimental Safety Vehicle Program.[25,26] For aircraft, a design guide has been produced (and updated) defining crashworthiness design principles and criteria for structure.[12] The multiplicity of crash configurations and nonlinearity of the crash behavior of the structure can be expected to continue to thwart efforts to validate design tools, unless more imaginative attacks are made upon the problem.

Interiors and Restraints

Crashworthiness engineering technology for restraints and interior cushioning represents the most advanced area. Not only is there a substantial amount of test data and proven practices, but there are component and subsystem design criteria and procedures whose use has resulted in the design of improved restraint systems.

Starting in the late 1930's, data have been generated defining torso accelerations and belt forces for lap and shoulder harnesses.[27-30] Tests of such restraint systems for forward deceleration of aircraft have covered forward, sideward, and rearward facing passengers.[31,32] More recent tests of automobile drive and passenger restraint systems include head and chest accelerations and femur loads for unrestrained, lap belted, lap and shoulder belted, and air bag, airbelt, and bolster restraints. Measurements have been taken

Table 1 State of crashworthiness technology – 1930-1973[a]

Aspect / Area	Physical Testing			Mathematical Modeling			Action	
	Parameter Studies	Dedicated Facilities	Standard Procedures	Lumped	Continuum	Closely Coordinated	Devices	Design Tools
Structures and Exteriors								
Interiors and Restraints								
Biomechanics								N.A.
Handling and Dynamics								
Systems and Interfaces								

[a] Shading indicates significant omissions: upper half of block for airborne vehicles, lower for highway vehicles.

from frontal impact (the most common), side impact, rear impact, and roll-over tests of full-scale vehicles.[23-35] Though the anthropometric dummy is most commonly used, the use of cadavers is not unusual and the use of human volunteers appears to be increasing.[36]

Though the inflatable restraint systems offered an unanswered challenge to analysts, simulations of belt restraints and seats have been assembled from simple mechanical models and test data of components. The kinematic model of the passenger has been used in conjunction with these components in predicting impact effects.[27,35,37]

Some of the devices used to improve restraints are the inertia takeup reel, single-point attachment and release fitting, knee restraint load limiter, WW stitched belt webbing, airbelt, lap belt, tie-down strap, crash sensor, squib gas source, double air bag, head support, crash helmet, urethane foam head padding, IMPAC III car door padding, and polyvinyl chloride glazing. Special systems have been developed for children, for the adult passenger and pilot, for full-size, compact, and subcompact cars.[27,38-42]

The U.S. Army Crash Survival Design Guide is a collation which includes detailed criteria for designing personnel restraints.[12] Many of the restraint system components are covered by military specifications.[43-45]

In this design environment, engineering improved restraint systems which perform as expected is not unusual. The common steps are 1) design the system, 2) evaluate its performance using a kinematic simulation of the passenger interpreting anthropomorphic response based on previous tests, (e.g., Gadd Severity Index), and 3) validate the design by extensive testing on full-scale vehicles.

Bioengineering

The application of bioengineering to crashworthiness is in predicting trauma associated with impact. Valuable data on the relation between fatal spine and head accelerations are available. Continuum mathematical models of the spine, head, and total system have been used in conjunction with physical tests. A continuing effort to produce an anthropomorphic dummy can be expected to result in a much improved full-scale surrogate.

Test data measuring tolerance limits have been reduced to simple criteria. Test data using live humans and cadavers identify limits for uniaxial acceleration pulses from various directions for sitting and supine positions.[46-49] Curves relating acceleration (velocity change) to average acceleration and pulse duration have been used to reduce accident sled and centrifuge test data.[50,51] Fitting Wayne State tolerance curves from animal and cadaver head tests resulted in the SAE criterion for head injury, the Gadd Severity Index, which replaced less relevant criteria based on linear dynamic models.[52-54] Chest impact injury criteria relating injury to deflection recently have been proposed using monkey, baboon, fresh cadaver, and human volunteer test data.[55-57] Data on human tolerance for heat and burns rest on early NACA tests.[58]

Though a number of special testing facilities are now available, testing developments are hindered by lack of standards for performing and reporting experiments. Communication among experimenters with different backgrounds (engineer, physician, mathematician) has slowed progress in attacking this complex problem.[12]

A number of advanced models for spine and head-neck injury are available, as well as kinematic models of the complete human. Recent spinal column models employed tapered, curved, viscoelastic column components.[59-61] This type of modeling has been most successful, reflecting the amenability of bone damage to engineering analysis. The modern head injury simulation represents the skull as a three-dimensional sphere enclosing a linear viscoelastic brain.[62-64] Head-neck models similarly have advanced to complex continuum models which, based on extensive study, necessarily include head and neck rotation.[65-67] Kinematic models using point masses, rigid links, springs, dashpots, and interference ellipses and involving up to 40 degrees of freedom have been validated successfully against dummy tests.[68,69]

The advanced models are a mixed blessing: they may result in better predictions, but they require extensive anthropometric experiments to particularize parameters. Despite model sophistication, each model has been constructed for a limited set of injury mechanisms and has been validated in a friendly environment – one where physical test results were known ab initio and the testing procedures were well known by the analyst.[46]

The principle bioengineering device for improving crashworthiness is the dummy surrogate. The readily available anthropometric dummies, complying with SAE and federal specifications, are largely an outgrowth of work to create a dummy for pilot ejection seat testing.[70] Development of an anthropomorphic dummy with injury measuring characteristics based on the large volume of experimental data now available is now proceeding.[71,72]

The problem of scaling animal, cadaver, and dummy tests to live humans continues to perplex. Biological variations may result in the large scatter using available scaling techniques, but this is not well established.

Handling and Dynamics

This area encompasses improving vehicle controls to reduce accident probability or severity. Testing and simulation have yielded a sound technological foundation for engineering linear vehicular systems for either open-or closed-loop criteria. Extension of this technology to embrace limit conditions recently has been stimulated by development of nonlinear simulation models. A number of braking and steering devices to improve crashworthiness are in use.

Standards for measuring under and oversteer, roll gradient, and effects of braking on turning stability have been established following testing initiated in the 1930's.[73,74] Data relating directional stability to brake response-time lags, pavement conditions, vehicle loading, linkage play, geometry, tire pressure, and kingpin damping have accumulated, prompted by runway hydroplaning, wheel hop, and jackknifing.[75-81] Tests to validate simulations have demonstrated the value of special experiments for comparing physical and analytical tests. Six other standardized test procedures also have been proposed and used in test-analysis studies.[82-84]

Similar closed-loop testing has produced data on linear and limit performance for lateral obstacle avoidance, turning over pavement irregularities, negotiating curbs, and braking while turning. Measures of performance have often been related to overall control such as minimum stopping distance and maximum speed through the course. Other tests have focused on measuring parameters for particular pilot models such as gains, indifference threshholds, time-delays, and neuromuscular dynamic characteristics.[74,85,86]

Though testing for linear systems appears well in hand, limit testing of closed-loop systems is largely an unfulfilled need. Though the importance of the pilot and driver inputs to vehicle path controls is well-established, rapid progress in closed-loop testing is impeded by a lack of standards for quantifying pilot control actions.

The last 10 years have included development of advanced models for evaluating vehicle dynamics.[87-89] The currently used complete nonlinear models date to Mikulcik's work.[88] They include nonlinear braking and tire dynamic components. Implementation of simulations using this model, using the hybrid computer, permit economical studies which cover the broad bandwidth and meet the high accuracy requirements of handling studies.[83,84,90]

Though these simulations require particularizing many model parameters (100 or more), those associated with the vehicle (e.g., moments of inertia, gear ratios, load-deflection curves, joint play, orifice damping) are measured readily on real vehicles. The close correlation between simulation and physical systems is yet to be obtained for closed-loop systems.

The antiskid brake, fifth-wheel locking mechanism, multidisk brake, oleo damper, anti-wheel-locking systems, simplified control cockpit instruments and arrangements are some of the devices developed and used to improve handling parameters. Linear mathematical models serve as design tools with capabilities limited to open-loop applications.

Systems and Interfaces

This area includes all and no one of the preceding crashworthiness areas. Work has concentrated on hazard reduction and postcrash safety. Testing has been useful in establishing the validity of design concepts and crashworthiness devices. Use of special analytical and numerical simulators has been limited.

Hazard reduction devices tested or under development and test include mechanisms for anticipating crash (using radar or inertia effects), detecting vehicle defects (improved diagnostic instruments primarily for handling and control components), and measuring the vehicle state before and during impact (inflight and onboard recorders sensing acceleration-time histories).[91-95] Previous success has included the antiblowout tire, power and disk brakes, safety glass, noise suppressers, antipollution valve, improved cockpit instrument arrangements, and easier-to-interpret attitude instrumentation.[96-98]

The emphasis on postcrash safety has been on escape, fire, and rescue. Criteria for locating, sizing, and lighting exits for aircraft are established.[12] Testing has furnished technology for designing ejection seats for high-speed aircraft. Testing to inhibit postcrash fire and explosion has involved fuel tank design, fuel line materials, fire barriers, and shielding, metal sparking, and insulation. Many of the useful data on the fire environment were generated by NACA in an extensive series of component and complete aircraft fire tests of the last decade.[99,100]

IV. Fulfilling the Promise of Crashworthiness Designing

Current evidence indicates that aircraft can be designed for nonfatal impacts with velocity changes up to 60 mph. The goal of design for survivability for velocity changes of a 50 mph equivalent barrier speed for automobiles has been established to be attainable. The conclusion of the review of crashworthiness engineering, summarized in Sec. III, is that the principle obstacle to achieving this promise is the lack of adequate design tools.[27,101]

The missing ingredient, especially obvious in the areas of structures and exteriors and bioengineering, is a strong link between the test technology simulation capabilities, and the designer. The omission is represented in bioengineering by the lack of standardized procedures; in structures by the inability of analysts to predict response a priori. The omission is blocking the progress in highway vehicle crashworthiness engineering where the test and simulation technologies have reached a high level of sophistication. It is not evidently acute in aircraft crashworthiness engineering, since valuable test data of controlled crashes are just accumulating. The omission is evident to Dodge, a consumer advocate, who characterizes it by the underutilization of research findings.[102]

The missing link is represented by two concepts: numerical modeling fidelty, and test-analysis correlation. The first concept involves relevant use of simulation tools to represent the particular vehicle configurations of interest. The second involves intensive coordination between the analyst and test engineer to determine the significance of test and analyses data for design.

V. Conclusions

This review of the state of crashworthiness technology indicates the following:

1) The physical test technology (setups, instrumentation, procedures, standards, data reduction, data) for automobile crashworthiness is well-advanced. Extensive testing has been performed by a handful of organizations with the benefit that a high degree of expertise with broad experience has accumulated. Controlled crash testing of aircraft, by comparison, is in its infancy, not so much with respect to chronology, but with respect to the amount of technology developed.

2) A number of mathematical models are available for simulation in all areas of crashworthiness. The significant omissions in current technology are in insuring simulation fidelity and correlating with the real environment. This is particularly evident in the structures and bioengineering areas.

3) Many injury-reducing devices have been invented, tested, and are in use for highway and airborne vehicles. Better utilization of the technology available, in terms of total system effectiveness, awaits a spectrum of design tools to support the growing volume of specifications.

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