

Evaluation of Injury Risks and Benefits of a Crush Protection Device (CPD) for All-Terrain Vehicles (ATVs)

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ABSTRACT

An updated evaluation of the effects on predicted injuries of an example crush protective device (CPD) proposed for application to All-Terrain Vehicles (ATVs) is described. As in previous evaluations, this involved extending and applying the test and analysis methods defined in ISO 13232 (2005) for motorcycle impacts, to evaluate the effects of the example CPD in a sample of simulated ATV overturn events. Updated modeling refinements included lowering the energy levels of the simulated overturn events; accounting for potential mechanical/ traumatic (compressive) asphyxia mechanisms; refining and calibrating the force-deflection characteristics of helmet, head, legs and soil so as to reduce potential over-prediction of head and leg injuries; and calibrating the simulation against aggregated injury distributions from actual accidents. Approximately 3,080 computer simulations were run, and the results indicated that, for the simulation sample and in comparison to the helmeted baseline ATV, addition of the example CPD created injury and fatality risks that were greater than its injury and fatality benefits. This study also confirmed results of other research indicating that helmet wearing has substantial net injury benefits, and a low risk/benefit percentage, confirming the importance, effectiveness and low additional injury risk of helmet wearing.

CITATION: Zellner, J., Kebschull, S., and Van Auken, R., "Evaluation of Injury Risks and Benefits of a Crush Protection Device (CPD) for All-Terrain Vehicles (ATVs)," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 7(1):2014, doi: 10.4271/2013-32-9173.

INTRODUCTION

This paper describes results of an updated evaluation of the effects on predicted injuries of an example Crush Protection Device (CPD)¹ that has been proposed for application to All Terrain Vehicles (ATVs). The updates took into account desired refinements to and all known, valid comments on the previous evaluation methodology including: lowering the energy level of the overturn events used; considering potential mechanical/traumatic (compressive) asphyxia factors; refining the control inputs used to induce each of the overturn events; additional calibrations of the simulation models against actual injuries in accidents and literature on helmet net injury benefits; and other refinements.

As in previous evaluations described by Van Auken, et al. (1998)[1], Zellner, et al. (2004)[2], Munoz, et al. (2007)[3] and Zellner, et al. (2008)[4], this evaluation adapts the relevant portions of the test and analysis methods specified in

ISO 13232 (2005)[5] for motorcycle protective devices, extended so as to be applicable to ATV overturn events. This evaluation estimates and evaluates the predicted injury benefits and injury risks of fitting the Quadbar to ATVs, and a comparison of these results to published data for other occupant protection systems for automobiles, as well as to guidelines for motorcycle rider protection systems given in ISO 13232 (2005)[5].

The analysis described in this paper evaluates the Quadbar using a procedure similar to that used in previous evaluations, namely by predicting the injury benefits and injury risks that would result from fitment of a protective device, by means of paired comparisons (i.e., predicted injuries with and without the proposed device), across a representative set of overturn "types" (and variations thereto), in which the types of overturn are based on two different samples of actual ATV accidents.

¹ The example CPD evaluated was the "Quadbar" CPD.

A more extensive description of the methods and results summarized in this paper is provided by Zellner, et al. (2012) [6].

This paper summarizes the extensive research methodology and prior results in this area; the most recent methodology updates; the results of applying the updated methodology to an example CPD; and the conclusions and recommendations. As the methodology in this area has been a topic of considerable interest, the focus of this paper is on the methodology and updates to it, as well as on the updated results.

BACKGROUND

An overview of the methodology and results of previous similar evaluations is summarized.

Overview Of Methodology

When evaluating protective devices that are proposed to be fitted to vehicles, it is important to consider the effects of the device on injuries.

For automobiles, since the 1960's, consideration of the effects of protective devices on injuries has been done by means of tests with appropriate, standardized, injury-monitoring crash dummies. The tests represent one or more “types” of crash event, which are based upon (to a greater or lesser extent) information about actual accidents.

While one or more “types” of crash event are typically used for baseline evaluations, in general, it is desirable in principle to evaluate the effects of a proposed protective device across a range of conditions representing the intended use of the device. A device which reduces injuries in one test condition (producing an “injury benefit”) may have other (e.g., unintended) effects under other test conditions (i.e., an “injury risk”). It is desirable that the injury benefits of a protective device should be its primary effect, and that the sum of any “injury risks” of a protective device be very small or effectively zero, if possible, in comparison to the sum of its injury benefits, as is typically found to be the case, for example, in published data for automotive occupant protection systems such as safety belts, head restraints and airbags.

More recently, computer modeling and simulation of crash tests, suitably calibrated against real crash tests and crash dummies, have become more widely applied methodologies for research and development purposes (e.g., Iijima, et al. (1998)[7], Osendorfer, et al. (2001)[8], Weiss, et al. (2001)[9], Van Hoof, et al. (2003)[10], ISO 13232 (2005) [5], Kuroe, et al. (2005)[11], Ootani, et al. (2007)[12], to mention a just a few examples). Simulation methods generally require that the models be experimentally verified and calibrated using a sufficiently wide range of actual tests. The advantages of simulations and models are that they can be used to cover a wider range of events far more quickly and economically than full-scale testing can, and that they can do so with perfect repeatability. For this reason, and within these

limitations, simulations and models are increasingly widely relied upon in many fields (e.g., aerospace and automotive engineering) when they achieve a reasonable level of agreement with a reasonably wide range of calibration tests. In addition, simulations and models can be further refined and improved, based on further test data and refined assumptions.

In regard to another aspect of injury evaluation, it is important to note that crash dummies, while representing the current state-of-technology in injury evaluation, have several limitations, e.g., crash dummies:

- Can monitor only a limited set of locations, types and severities of human injury;
- Are passive, i.e., they cannot actively move by themselves as humans do (e.g., lean or shift weight uphill or into a turn, purposefully separate from an ATV prior to rollover, etc.);
- Each represent a given category of human (e.g., in terms of sex, age, size and weight), and only a limited set of categories exist. Crash dummies do not exist that represent all conceivable heights, weights, girths, sexes, ages, physical conditions, etc., of humans present in actual accident case files.

Nevertheless, evaluation with crash dummies is the widely accepted state-of-technology for injury evaluation in vehicles. A hypothetical alternative, conducting crash tests with live humans in potentially injurious events, has significant moral and ethical issues associated with it, not to mention practical issues with experimental reproducibility and repeatability. Another alternative would be conducting crash tests without any injury-monitoring biofidelic crash dummies however the results from such tests would be meaningless and speculative regarding the effect of the device on rider kinematics and resulting injuries without any objective measurements. Any meaningful test must take into account the actual *position and orientation* of a given surrogate rider body region at a given point in time, which can affect the measured forces, deflections and accelerations that are directly related to the probability of human injury based upon the scientific literature.

In virtually all such research and evaluations, the crash tests, simulations of crash tests and crash dummies involve “baseline” conditions (i.e., a baseline dummy size, age category and sex, a baseline vehicle and baseline crash conditions, based on one or more general baseline “types” of crash event, which in turn may be generally based on what is recorded by investigators in a sample of actual accidents). They virtually never involve an attempt to reproduce all of the details of the actual accident-involved vehicles, persons, environments, injuries, or contacts that occur in specific actual crashes, because a) generally many or most of these variables are not recorded in accident case files, b) in reality there is an enormous diversity of such details occurring across a sample or census of actual accident cases, and c) as noted previously, the current state-of-technology of crash

dummies cannot monitor all potential locations, types and severities of human injury, or the enormous diversity of age, sex, stature, girth, weight, etc. of accident-involved persons. Instead, systematic tests and/or simulations are conventionally done with one or more baseline dummies, a baseline vehicle, and baseline “types” of crash event/environment. In this way, the number of input variables is controlled, and the effects of the device are assessed relative to the baseline conditions.

Application Of Injury Evaluation Methods To Potential ATV Overturn Protective Devices

An “All Terrain Vehicle” is a particular type of standardized off-highway vehicle, which is defined by (among other factors (as in, e.g., ANSI/SVIA-1-2010 (2010) [13])) its “straddle seat, handlebar-controlled, helmet-required” configuration. An All Terrain Vehicle has a precise legal definition in the United States,² which is currently the largest market for ATVs, accounting for approximately 90% of sales worldwide.

At the current time, only one standard exists, worldwide, for evaluating the effects on injuries of protective devices for one type of “straddle seat, handlebar-controlled, helmet-required” vehicle, namely motorcycles, and that is International Standard ISO 13232 (2005)[5]. This Standard defines test and analysis methods for research evaluation of rider crash protective devices applicable to two wheeled motorcycle-to-car impacts. Many, but not all, of the tools available in the Standard are potentially applicable to evaluating the effects on injuries of candidate overturn protective devices on another category of “straddle seat, handlebar-controlled, helmet-required” vehicle, namely ATVs. Obviously, those aspects of the Standard which specifically involve only “two wheeled motorcycle-to-car impacts” are not applicable to ATV overturn events. However, the tools that are defined and available in the Standard that are broader in nature and potentially applicable to evaluating the effects of protective devices in ATV overturn events include:

- The only standardized injury-monitoring crash dummy worldwide which is designed to be compatible with “straddle seat, handlebar-controlled, helmet-required” vehicles (of which motorcycles and ATVs are two examples);
- The only standardized injury-monitoring crash dummy worldwide which can monitor for injuries in several directions (i.e., lateral, fore-aft and vertical), which may occur in ATV lateral, forward, rearward and multi-axis axis overturns,³

- The only standardized injury-monitoring crash dummy worldwide which can monitor for a range of injury severities at several body regions (i.e., for which injury probability curves exist for different Abbreviated Injury Scale (AIS) injury severities);

- A requirement that the motions calculated by computer simulation be calibrated against those recorded in full-scale tests, in order to obtain a correlation figure-of-merit;

- A requirement for calibrating the response of the simulated crash dummy against laboratory tests done with the actual crash dummy;

- Definition of a sample of accidents - ideally a representative sample including all injury severities - from which to define several general “types” (or “configurations”) of accident event, which are then used for simulation and testing purposes;

- Evaluation of the “injury benefits” of a proposed protective device, as well as the “injury risks” (i.e., unintended consequences) of a proposed protective device, across all of the general “types” of event, and taking into account their frequency of occurrence, with the guideline in the Standard (i.e., Part 5, Annex E) being that the average injury risks of the proposed protective device should be small in comparison to the average injury benefits of the proposed protective device.

Note that ISO 13232 (2005)[5] is intended for research purposes, which is also the purpose of the current study, and (due to its paired comparison methodology and other aspects) it is not intended for, or suitable for, regulatory purposes.

The main portions of ISO 13232 (2005)[5] that are not applicable to ATV overturns are the “definition of impact conditions in relation to accident data” (i.e., Part 2) and “Full-scale impact test procedures” (i.e., Part 6) of the Standard, which are defined specifically for two wheeled motorcycle-to-car impacts (and therefore are not directly applicable to off-road vehicles such as ATVs), and which are not defined (in ISO 13232 or in any other standard) for ATV overturn events.

Consequently, in the current and previous ATV Roll Over Protection System (ROPS) and CPD feasibility research, an informal approach was adopted in order to define several types of ATV overturn events, which was analogous to the approach formally used in ISO 13232 for two wheeled motorcycle-to-car impacts. This informal approach involved collecting available samples of ATV overturn accident case files - comprising a sample of US/Consumer Product Safety Commission (CPSC) In-Depth Investigation (IDI) case files and a sample of UK Health and Safety Executive (HSE) case files [14] - and using the available case information to define

² Under the US Consumer Product Safety Improvement Act (CPSIA), an ATV is as defined in ANSI/SVIA-1-2010.

³ Other standardized injury monitoring crash dummies monitor in one direction. For example the Hybrid III dummy monitors specified types of injuries from forward impact; the ISO World Side Impact Dummy (WorldSID, <http://www.worldsid.org/>) monitors specified types of injuries from lateral impact.

a set of general “types” of ATV overturn events, for testing and/or computer simulation purposes.

It is important to note that the general “types” of ATV overturn events that were defined for the purposes of this paper - and the predecessor related reports - were not intended to reproduce any specific individual accident cases in these samples, or their specific outcomes (e.g., in terms of specific vehicle or rider motions, or specific rider injuries), as the original case files are insufficiently detailed and are inadequate to enable that to be done. Instead, the general “types” of ATV overturn that were defined were intended to be: a) consistent (i.e., not in conflict) with the very limited set of overturn “input” variables that were described in each case, the number of which varied case by case, and b) relevant and feasible to be tested or simulated by means of selected baseline conditions, i.e., a baseline adult-sized ATV, with the baseline ISO 13232 (2005)[5] mid-sized adult male crash dummy, c) consistent with the other ATV overturn full-scale test methods described by Van Auker, et al. (1998)[1] and Zellner, et al. (2008)[4], e.g., based on using suitable ATV control inputs from vehicle remote controllers and suitable simplified terrains, in order to provide repeatable inputs, so as to induce several types of ATV overturn events, and d) involve convenient “rounded” values of input variables, e.g., speed, slope, obstacle size, etc., as would be used in, for example, a standardized test.⁴ Note that while it might be of interest, at the current time there are no small female, large male or child crash dummies that exist that are compatible with “straddle seat, handlebar-controlled, helmet-required” vehicles, or with the other injury monitoring requirements of, e.g., ISO 13232 (2005)[5].

In this research, the emphasis was on evaluating the consequences of an overturn, and not on the event(s) that might cause an overturn. Therefore, modeling of ATV tires, suspension, and vehicle response to rider steering, braking, throttle inputs, etc., while done at a generally accurate level, were not highly detailed or calibrated in high detail against test data for those particular subsystems, as they were secondary to the topic of interest, namely the consequences of an overturn. Moreover, the available accident case files did not contain any specific (and often times, not even general) information regarding ATV make-model-year, tire type and inflation pressure, or actual steering, braking or throttle input magnitudes or time histories, or detailed description of the vehicle response to such inputs prior to the overturn event. Furthermore, even if such information had been recorded in one or more accidents, invariably these variables would differ from case to case, thereby not allowing any generalized assumptions to be made about, or standardized test conditions defined for, their magnitudes or time histories. Instead, the

general “types” of overturn were defined based on whatever general information was available in the associated case file (e.g., general type of terrain, operating conditions, general types of control inputs, general types of resulting motions, etc.), nominal input magnitudes and conditions for those were assumed, and then the unspecified inputs were systematically varied, as described in Appendices C and D of Zellner, et al. (2012)[6], so that a simulated overturn would occur.

It is also important to note that the original ATV case file information from the US and UK government agencies was, in many cases, extremely limited, and in many cases did not contain all or even a majority of the minimum of 17 variables that are needed to model an ATV overturn (e.g., see Appendix D of Zellner, et al. (2012)[6]). In addition, the available ATV overturn samples (i.e., in the current analysis, a total of n=110 cases⁵ identified as involving an “ATV” overturn) were relatively small in comparison to, for example, the motorcycle impact sample of n=501 cases used in ISO 13232 to define a set of 200 general “types” of impact).

Therefore, in the current research, an approach based on the “best available information” was used which involved using all of the general “input” variables for which some information was available or inferable for each case, plus implementing a set of systematic, consistent, plausible assumptions regarding the missing “input” variables (as outlined in Appendix C of Zellner, et al. (2012)[6]) so as to define one general “type” of baseline dummy/ATV overturn per case. Note that the occurrence of ATV overturn was the one common variable that described all the actual cases as well as all of the 110 general “types” of simulated overturn. In addition, recognizing that the detailed assumed conditions can affect the outcome of any crash or overturn event, each of the 110 general “types” of overturn was systematically varied in six additional ways (e.g., comprising a “perturbation” analysis), as further described in Zellner et al. (2012)[6], so that a total of 770 conditions were simulated, for each ATV configuration (i.e., baseline ATV and Quadbar ATV) and helmet configuration. The latter perturbation analysis helped reduce the sensitivity of the overall outcomes to the exact initial conditions assumed for each “type” of overturn. Conceptually, each actual accident case could be considered to be similar to the set of seven overturn “types” (i.e., the baseline overturn and the six variations of it) defined for each case. Note, however, that in general it is not possible to verify whether or not the actual case lay within or outside this set of seven overturn types, as many of the needed variables were not recorded by the original government accident investigators that compiled the cases.

⁴ ISO 13232 (2005)[5] also uses “rounded” values to define the motorcycle impact “types” used for testing and simulation purposes.

⁵ In the previous ATV ROPS/CPD research, 59 cases from the UK Health and Safety Executive (HSE) and 54 cases from the US Consumer Product Safety Commission (CPSC), which were all of the cases in the group of cases received that involved overturn formed the basis for defining 113 general “types” of ATV overturn. In the current study, it was found that three of these cases involved vehicles that were not ATVs, and which were subsequently excluded from the analysis. This resulted in a total of n=110 ATV cases being used as the basis for defining 110 general “types” of ATV overturn.

It is also important to note that, in reviewing the outcomes of tests and/or test-calibrated computer simulations involving crash dummies, the injury outcomes fundamentally cannot match those of specific actual accidents, nor can they even exactly match the “frequency distributions” of injury outcomes from samples of actual accidents, for the reasons stated previously. Nevertheless, to a greater or lesser extent, the “aggregated”⁶ frequency distributions of injuries measured with a crash dummy in a sample of tests and/or simulations of several general types of crash events can be “generally” similar to those observed in a sample of actual accidents, but if and only if the particulars of the test/simulation sample are “generally” similar to those of the accident sample (in terms of types of injuries monitored, person types modeled, vehicle types modeled, types and severities of accidents, etc.)

Note that case-by-case matching of injuries for large samples of cases exceeds the state-of-technology in the biomechanics field, as well as the state of the available accident data; and there are no known published examples of it in the scientific literature.

Matching the “aggregated” injury distribution (between modeled distribution and the actual distribution) is within the state-of-technology in safety research, as illustrated for example in Kuchar (2001)[15], Kramer, et al. (1990)[16] and Rogers, et al. (2004)[17].

The generally close agreement between the baseline ATV aggregated injury frequency distributions of the simulation sample and those of the ATV accident sample that was found in the current analysis is described subsequently and in more detail in Appendix G of Zellner, et al. (2012)[6].

Injury Risk/Benefit Evaluation Methods

Finally, as noted previously, it is appropriate (as in this paper, and as is required in ISO 13232 (2005)[5]) to evaluate both the injuries prevented by a protective device (benefits) as well as the unintended new injuries that may be caused by a protective device (risks, or health costs), because (as generally discussed by Thompson et al. (2001)[18] and Thompson (2011)[19]):

- In principle, a health or safety intervention should provide health benefits and “do no harm” (to the extent practicable and feasible);⁷
- The “risk assessment” (of a task, procedure, vehicle, equipment, etc.) is an evaluation process that is entirely different from the risk/benefit analysis of an intervention. Risk assessment characterizes the impacts of potential application of countermeasures such as engineering controls,

administrative controls, substitution, elimination, etc. Generally, all products (e.g., airplanes, cars, pencils, etc.) have some risk associated with their use, which in general cannot be reduced to zero without losing some of the functionality of the product, and risk assessments characterize the risks considering the entire system in which they occur;

- “Net benefit” and “risk/benefit” analysis of an intervention are fundamentally very different but complementary concepts that both warrant consideration;
- The “net benefit” (i.e., the injury benefits minus the injury risks) of a protective device (or other intervention) should be a positive number (e.g., as recommended in ISO 13232-5, Annex E) when analyzed across a sample of events.
- In addition, when extending the simulation sample estimate to the population of events, the net benefit should be “statistically significant” across the range of conditions evaluated (i.e., the statistical confidence interval on the estimate of net benefit should generally not include negative numbers);
- Notwithstanding the fact that a given protective device may have a positive net benefit, the potential harm to individuals from a protective device (or other intervention) is not measurable or quantifiable by the “net benefit” index. A device can have a positive, statistically significant “net benefit,” and also have any level of risk/benefit percentage, as the two indices are independent, cannot be calculated one from the other, and describe different aspects of risk and benefit, as described by Thompson, et al. (2001);
- A goal of product development is to remove or reduce to a minimum the “protective device” risk from products, before and as a pre-condition to their being placed on a market;
- “Risk/benefit percentage” is one useful index for describing the relative magnitude (i.e., ratio) of the risks in relation to the benefits. “Risk/benefit percentage” is calculated in, e.g., ISO 13232 (2005)[5];
- Although risk/benefit considerations have not to date been used as part of the formal “benefits analysis” process used by vehicle safety agencies (e.g., the US National Highway Traffic Safety Administration (NHTSA)), largely because “protective device” risk removal is assumed to be the responsibility of manufacturers, risk/benefit considerations are used by other consumer product agencies (e.g., US Food and Drug Administration for health interventions, e.g., Pharmaceuticals, medical devices, etc.);
- Vehicle safety agencies often consider relative safety device risk, e.g., in the case of NHTSA, the risk of an airbag injuring

⁶ “Aggregated” refers to the summation of all injuries of a given location, type and severity across all cases in a sample. This is different from case-by-case reporting of injuries.

⁷ Examples of this principle that are found in US/DOT/NHTSA documents include: 1) “NHTSA sent a letter to twenty-one vehicle manufacturers urging them to personally ensure that their side-mounted air bags are designed to “do no harm” to occupants.” (Report to Congress, Status of NHTSA plan for Side Impact Regulation Harmonization and Upgrade, NHTSA, March 1999) [20]; 2) “New technology or regulations can both have unintended consequences. We will therefore proceed expeditiously but deliberately. The physician's overriding ethic is “first, do no harm.”” (The Honorable Jeffrey W. Runge, M.D., Administrator, National Highway Traffic Safety Administration before the Committee On Commerce, Science, and Transportation, United States Senate, February 26, 2003)[21].

small front seat passengers, as in the first generation Light Passenger Vehicle airbag depowering and subsequent related rulings;⁸

- Traditionally, acceptable health and safety interventions have small risks in comparison to their benefits (especially those to which a large population is exposed). Examples are non-prescription medications;
- Automotive safety devices (e.g., safety belts, airbags, head restraints, etc.) have demonstrably small risk/benefit percentages (e.g., less than 7 percent as described by Thompson, et al. (2001));
- International Standard ISO 13232-5 (2005), Annex E contains a guideline that the risk/benefit percentage “should be less than 7 percent and should not be more than 12 percent,” which has been applied to the evaluation of various real safety devices in the market place (e.g., Honda Goldwing motorcycle airbag (i.e., Kuroe, et al. (2005)), BMW C1 frontal crash frame (i.e., Osendorfer, et al. (2001)), and is the guideline applied in this current analysis.

In addition, although it is not part of the main risk/benefit literature, it was noted in the Australia-New Zealand Heads of Workplace Health and Safety Authorities (HWSA) Trans-Tasman QuadBike Working Party's (TQWP) Technical Engineering Group (TEG) meeting and report that “in the regulatory policies of several of the states, the benefits needed to be at least 2 times the risks” (i.e., 2 deaths prevented for every 1 new death caused by a device, or 50 percent risk/benefit).⁹

Although the latter criterion, if accurate, would be a very high risk/benefit percentage criterion, for example, higher than any known and measured risk/benefit percentage of any automotive safety device, it provides a further point of reference for the current evaluation, as it may represent a policy in place in at least some regulatory agencies.

Review Of Previous ATV ROPS/CPD Feasibility Research

Zellner, et al. (2008)[4] reviewed previous research of several devices proposed for application to ATVs, including:

- Dahl (1987)[25], including an evaluation by Piziali, et al. (1993)[26];
- Johnson (1991)[27], including an evaluation by Piziali, et al. (1994)[28];

- New Zealand T-bar CPD;

- UK U-bar CPD, as described in Allinson (1996)[29] and Allinson (1997)[30];

- MUARC ROPS, as described in Rechnitzer, et al. (2003)[31] and an evaluation by Zellner, et al. (2004)[2].

Zellner, et al. (2008)[4] summarized the previous findings, and then evaluated all of these devices using an ISO 13232 (2005)[5]-based simulation methodology.

Van Auken, et al. (1998)[1] conducted full-scale overturn tests with the NZ T-bar CPD and the UK U-bar CPD for the purposes of the calibrating the computer simulation of those devices.

In addition, Munoz, et al. (2007)[3] evaluated the Quadbar CPD that is the subject of this paper, using the same methodology as Zellner et al. (2008)[4].

Methodology Used in Previous Injury Analysis by Means of ISO 13232

The methodology used in the previous evaluations by Zellner et al. (2008)[4] and Munoz, et al. (2007)[3], which is the starting point for the updated analysis in this paper, is briefly summarized.

Models of Rider Dummy, ATV, ROPS/CPDs

Mathematical models to simulate the overturn motions of a rider on an ATV, with and without a ROPS/CPD fitted to the ATV, in a representative sample of 113 general “types” of ATV overturn, were developed and as described subsequently, were calibrated against laboratory and full-scale tests, in order to estimate the injury risks and benefits of the candidate ROPS/CPD devices.

The principle used in the model development was to model only at the level of detail necessary to support the injury evaluations, and in view of the large number of simulations planned and the relatively coarse representation of the 113 UK/US overturn types about which relatively little was known. In addition, as it is typical that ATV overturns typically do not result in large vehicle deformations, a multi-body modeling approach was used rather than a finite element modeling approach.

The simulations models were based on the Articulated Total Body (ATB) computer program developed by Calspan and the US Air Force for the US National Highway Traffic

⁸ For example, from the 1997 NHTSA Airbag Depowering Notice of Proposed Rule Making, “Finally, the ratio of lives saved by air bags to persons fatally injured is very different for driver air bags than passenger air bags. Driver air bags are estimated to have saved 1500 lives, as compared to 19 persons fatally injured [i.e., a risk/benefit percentage of 1.3%]. Passenger air bags are estimated to have saved 164 lives, as compared to 32 persons fatally injured” [i.e., a risk/benefit percentage of 19.5%] (62 FR 807, “Federal Motor Vehicle Safety Standards; Occupant Crash Protection, Notice of Proposed Rulemaking,” National Highway Traffic Safety Administration, DOT, Docket No. 74-14; Notice 108, Section V.C.3, Paragraph 10, Page 823, Column 3, Line 29, January 6, 1997[22]). However, note that although the ratio (of saved to injured) is mentioned, the risk/benefit ratio (or risk/benefit percentage) for quantifying the effects of airbags on children was not part of the formal regulatory analysis used by the NHTSA, for which NHTSA states “In confronting the possibility of inevitable short-term safety tradeoffs between young children and unbelted occupants over 12 years of age, the agency believes that greater weight must be placed on protecting young children. NHTSA has always given a high priority to protecting children and accordingly has applied these different *cost-benefit* [emphasis added] considerations to its rulemaking affecting children.” (62 FR 12960, “Federal Motor Vehicle Safety Standards; Occupant Crash Protection, Final Rule,” National Highway Traffic Safety Administration, DOT, Docket No. 74-14; Notice 114, Section V.A, Paragraph 14, Pages 12964-12965, Column 3, Line 58, March 19, 1997[23]).

⁹ TEG Report[24], p. 32, footnote 7, November 2010.

Safety Administration (Obergefell, et al. (1988)[50]). The ATB models are summarized in [Table 1](#).

Rider dummy model

The rider model was a Motorcyclist Anthropometric Test Device (MATD) specified in Part 3 of the ISO 13232 (2005) [5]. The physical MATD is based on the Hybrid III passenger car dummy but has 28 special modifications which make it suitable for testing and analysis of crash protective devices for motorcycles and therefore for other straddle seat, handlebar-controlled, helmet-required vehicles such as ATVs, including frangible legs and abdomen, and a biofidelic neck that has been calibrated against Navy volunteer dynamic tests in several directions. In addition, with its pedestrian pelvis, aerospace lumbar spine and gripping hands, the MATD is better suited than the Hybrid III for positioning in typical riding postures involving motorcycle and ATV straddle seats and handlebars. The modified soft tissue of its headform enables a helmet to be fitted and properly retained by means of helmet retention straps, which is not feasible with a standard Hybrid III dummy.

Table 1. ATB Model Summary

Model	Description	Mass (kg)	Number of Rigid Bodies (ATB segments)	Number of Degrees of Freedom
Rider	MATD dummy	71.2	35	69
ATV	TRX 350	243.2	8	11
ROPS/CPD	Dahle	16.3	2	3
	Johnson	106.6		4
	NZ T-bar	9.5		4
	HSE U-bar	7.5		4
	MUARC	43.1		3

The MATD was mathematically modeled for computer simulation purposes by 35 articulated rigid body segments with 57 nominal degrees-of-freedom as further described in Zellner, et al. (2012)[6] and as shown in [Figure 1](#). The MATD model was based on the simulation model of a Hybrid III ATD described by Kaleps, et al. (1988)[32], suitably modified to represent the ISO 13232 MATD, including the frangible legs and neck. The basic model was calibrated against laboratory test data according to ISO 13232 as described by Kerschull, et al. (1998)[33] and as described in Appendix E of Zellner, et al. (2012)[6]. The model of the neck, which was revised in the 2005 revision of the Standard, is described by Van Auken, et al. (2003)[34].

The probability of specific levels of AIS injury of the head, face, neck, chest, abdomen, and lower extremities injury were estimated from objective injury assessment values using methods adapted from Part 5 of ISO 13232 (2005)[5]. Part 5 injury criteria were used for the closed skull brain, chest, abdomen, and lower leg injuries. It was assumed that the ROPS/CPD may have an effect on the probability of neck injury, and therefore this probability was estimated using neck injury criteria described in ISO 13232-5 (2005) and by Van Auken, et al. (2005)[35]. It was assumed that the ROPS/CPD may also have an effect on the probability of skull fracture of unhelmeted riders, and in the Zellner et al. (2008)[4] analysis this probability was estimated using a preliminary version of the criteria described by Van Auken, et al. (2011)[36]. It was assumed that probability of a skull fracture for helmeted riders wearing a full-face helmet such as the one specified in ISO 13232 (2005)[5] was very small and could be neglected in this analysis.

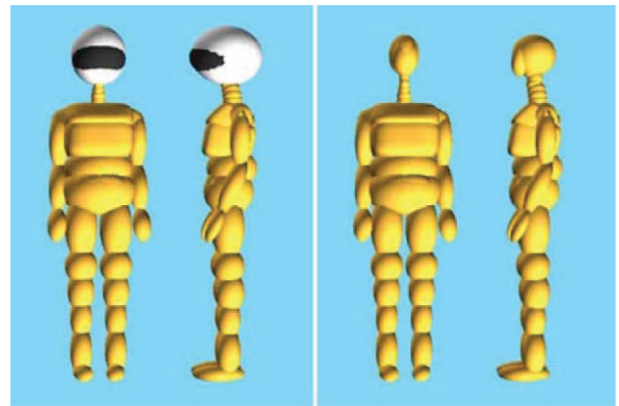


Figure 1. Image of computer simulation model of the rider dummy (MATD), helmeted and unhelmeted

The overall injury severity was quantified by the ISO 13232-5 Normalized Injury Cost (ICnorm), which is a medical and ancillary economic cost-weighted measure of injuries in terms of equivalent life units. A value of zero corresponds to no injury, and value of 1 corresponds to a fatality equivalent. Medical and ancillary costs include medical care and initial and subsequent hospitalization, household productivity, lost wages, workplace costs, and legal costs but exclude “pain and suffering”. The incremental ICnorm was also computed for each body region, which is defined as the value of ICnorm assuming that other body regions did not sustain any injuries.

ATV model

The baseline ATV was a Honda TRX 350. It was modeled by 8 articulated rigid body “segments” with 11 effective degrees-of-freedom. The model had six degrees-of-freedom for the overall vehicle motion plus nine degrees-of-freedom (DOF) for the steering system (1 DOF), front independent suspension (2 DOF) and rear rigid axle suspension (2 DOF), and rotations of the 4 wheels (4 DOF). The overall number of

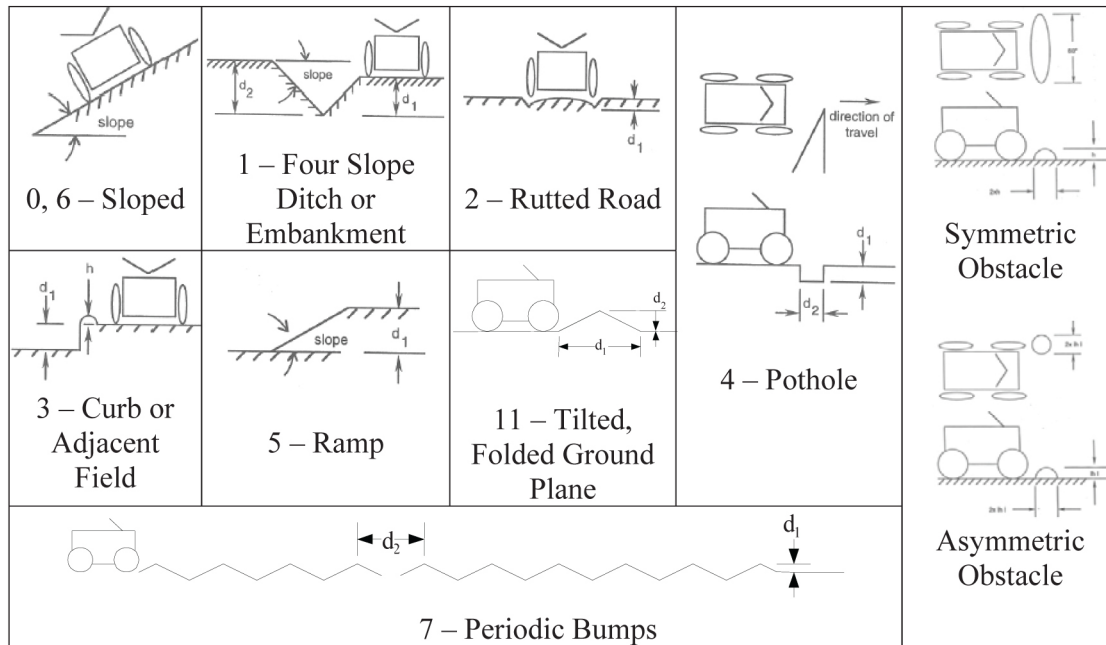


Figure 3. Simulated Ground Terrain Types and Obstacles

degrees-of-freedom was effectively reduced by stiff springs representing the steering tie rods and four-wheel drive train.

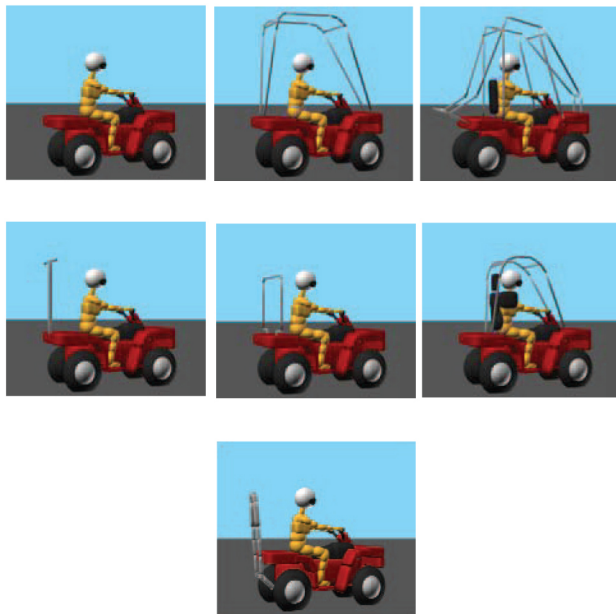


Figure 2. Models of ATV with and without ROPS/CPDs, from top, left to right: Baseline ATV, Dahl ROPS, Johnson ROPS, NZ T-bar CPD, UK U-bar CPD, MUARC ROPS, Quadbar CPD

The exterior contact geometry of the ATV was modeled with ellipsoids and hyper-ellipsoids as illustrated in Figure 2.¹⁰ Contacts between the ATV and rider and ground were

modeled by force-deflection characteristics based on various measurements, estimates and assumptions. Overall, the predictive capability of the model was verified using full-scale tests which are described subsequently.

ROPS/CPD models

The ATB simulations included models of the ROPS/CPD designs illustrated in Figure 3. These were each constructed of multiple tubular hyper-ellipsoids, with calibrated force-deflection and moment-deflection characteristics. The Quadbar had sliding upper mounts and pivoting bottom mount, as in its design. The three ROPS models had belts attached to their respective anchor points, and the belt retractors were assumed to be in locked positions.

113 UK/US Misuse Cases

The 113 general “types” of overturn event were developed based on 59 case files from the UK Health and Safety Executive (HSE) and 54 case files from the US Consumer Product Safety Commission (CPSC) involving ATV misuse as described in HSE (1994)[14] and CPSC 1998 IDI files.

The 59 UK HSE cases were selected from a larger set of 105 incidents based on whether their narrative descriptions indicated that the ATV overturned, flipped, somersaulted, or toppled. In some cases the overturn or topple was not explicitly noted in the narratives, but was assumed if, for example, the narrative indicated the ATV “landed on” the rider.

For simulation purposes the overturn events were described by a set of initial conditions and other parameters

¹⁰ Some of the exterior geometry for the TRX 350 was adapted from an existing MADYMO model of the TRX 350 developed by MUARC (Rechnitzer, et al. (2007), 31).

describing the ATV, rider, and ground terrain as listed in Appendix E of Zellner, et al. (2004)[2]. The simulated ground terrains and obstacles are illustrated in Figure 3 where the ground terrain type, slope, and parameters d1, d2, and h are case-dependent parameters. Values for these parameters were based either on those values explicitly mentioned in the case file; or else on assumed plausible values which were otherwise consistent (i.e., not inconsistent) with the description of the overturn precipitating event in the associated case file. Note that the ground terrain models represent the assumed effective ground terrain in the near vicinity of the overturn event (e.g., locally linearized ground planes). More complex ground terrains and features would require additional parameters to describe and to model, which are usually unknown from the case files and which would likely require an on-scene inspection to obtain.

The previous simulations and risk/benefit analyses were based on 113 general “types” of overturn event. The method used to define each general “type” of (as contrasted with the specific) overturn event was based on taking the information in each baseline ATV accident case file, coding the known variables using a set of assumed, plausible conventions, and then making systematic, plausible assumptions regarding the remaining unknown (i.e., missing) variables needed to define an ATV overturn event, as described in Appendices B and C of Zellner, et al. (2012)[6]. This method, while obviously based on a set of systematic assumptions, cannot reconstruct specific accidents, for which a very large number of additional variables would need to be known. In addition, the outcome of each general “type” of overturn so identified can exhibit substantial sensitivity to changes in initial conditions.

Therefore, systematic variation of the initial conditions (i.e., of the plausible conventions and assumptions) associated with each of the 113 general “types” of overturn events was undertaken, in order to include the effects of variation in initial conditions, to reduce the sensitivity of the overall outcome to the exact conditions used in each type of overturn, and to increase the sample size.

Variation in Overturn Events

As noted, for each of the 113 general “types” of overturn event six additional overturn events were simulated by introducing minor variations in the initial conditions. This was done to reduce potential oversensitivity of the outcomes to the details of the individual events and in order to increase the number of statistical degrees-of-freedom in the risk/benefit analysis.

This was accomplished by systematically varying various overturn event parameters as listed in Appendix E of Zellner, et al. (2004)[2] according to a stated set of priorities and conditions, until six additional overturn events were obtained. The number of additional runs was chosen to be a fixed value of six in order to uniformly represent variations about each of the 113 original types of overturn event. The amount of variation in each of the parameters was chosen to be relatively small, but large enough to result in variation in the

ATV and rider motions and estimated injuries. The result was a total of 791 overturn events.

Calibration Against Full-Scale ATV Overturn Tests

In regard to the methodology, the ATB models of the MATD, ATV (in this case, a TRX 400) with and without ROPS/CPD was calibrated in 1998 by means of 12 full scale tests, each involving an ATV overturn, as described in Van Auken, et al. (1998)[1]. As noted previously, although the analysis of the ROPS/CPDs reported herein was done with the TRX 350, both the TRX 350 and TRX 400 have been used as the basis for various simulation models. Since an earlier simulation analysis of the T-bar and U-bar CPDs had been done with a Honda TRX 400, the latter ATV along with these two CPDs was used for both the full-scale tests and for the simulation model, for the purposes of calibration. The primary purpose of the calibration was to verify and to refine as needed the dynamic force-deflection characteristics between the ATV, the ROPS, the soil and the dummy. These dynamic force-deflection characteristics are relatively independent of the ATV used, and are applicable to either the TRX 350 or TRX 400. Moreover, these two ATV's are very similar in design, in any case. The full-scale tests comprised four overturn events, each involving a different type of overturn, and each involving a baseline ATV and a CPD ATV configuration, as illustrated in Figure 4 and Table 2. Each test was filmed with high speed cameras and electronic data recorded within the ISO 13232 MATD dummy.

Table 2. Full Scale Tests

Test Condition	Ground Slope	Initial Speed	Rider (MATD)	ROPS	HSE Misuse Case	Number of Tests
Cross Slope	45 deg	0	Unhelmeted	U-bar T-bar	62	3
Uphill with step wide open throttle	45 deg	2 mph	Unhelmeted	U-bar (x2)	17, 59	3
Large steer input at higher speed	Level	30 mph	Helmeted	U-bar T-bar	94	3
Locked wheel braking while travelling over 6 inch semi-cylindrical bump at high speed	Level	30 mph	Helmeted	U-bar (x2)	74	3

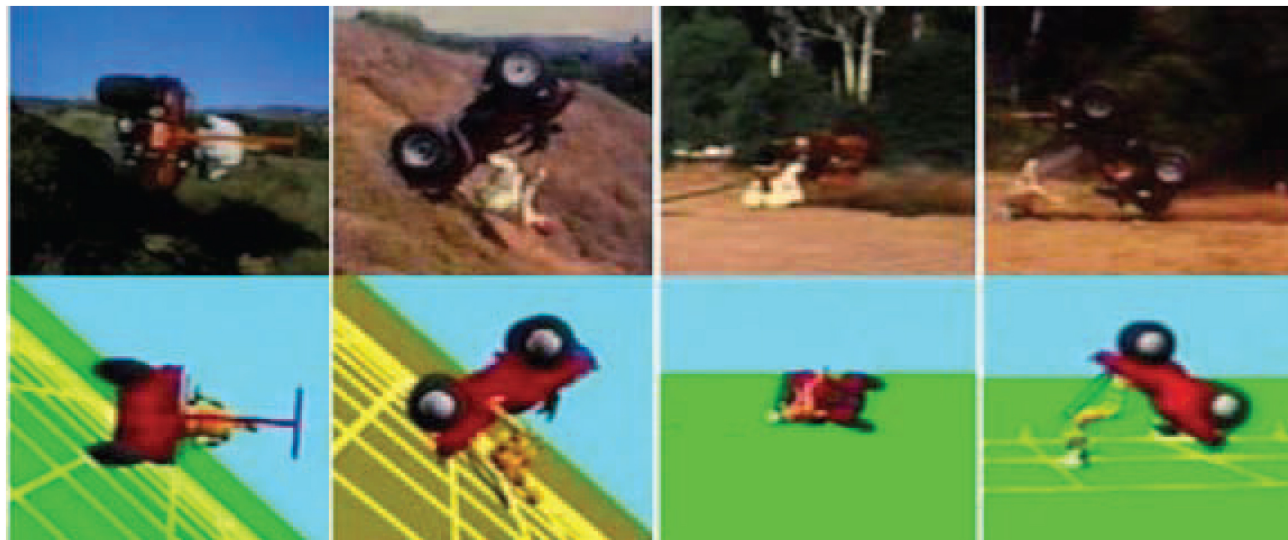


Figure 4. Example Full-Scale Tests and Corresponding Computer Simulations

For each test, the motions of the rider, ATV and CPD were numerically correlated with the motions predicted by the simulation. This was accomplished by digitizing various points on the rider, ATV and CPD using a sequence of frames from the high speed films of the test and comparing these values to corresponding values from the computer simulation.

¹¹ For example, [Figure 5](#) illustrates the motion of several points in the film plane of camera 1 in test 97101612, a cross slope with U-bar. The dashed lines illustrate the motion of each digitized point over time, and the solid lines illustrate the corresponding motion of the simulated point as it would appear in the film plane. The curves representing the digitized and simulated points are connected by lines at every 5 film frames (approximately 0.033 sec). In this example the correlation coefficient between the digitized and simulated points was $r^2 = 0.98$, indicating that the simulation and full-scale test are in very close agreement. Correlation results for each of the tests and camera views are summarized in [Appendix A](#) herein and Appendix F of Zellner, et al. (2012) [6]. Overall the average correlation coefficient for the 12 tests and all available camera views was $r^2 = 0.91$, indicating a relatively high level of correlation and close agreement between the tests and the simulations.

Results of Previous Injury Risk/Benefit Analysis

For the baseline ATV and for each of the ROPS/CPDs, computer simulations were run for each of the 113 overturn events $\times$ 6 variations $\times$ 2 (or 4) use/misuse configurations.

The latter comprised helmet versus unhelmeted (for all ATV configurations), and belted versus unbelted (for the ROPS configurations which were fitted with belts). The outputs of the simulations were time histories of all relevant rider and ATV motions and forces; and based on this, Injury Assessment Values (IAVs) and other injury indices for each simulated overturn event.

Injury Risk/Benefit Results

The injury risks and benefits of the proposed ROPS/CPDs were calculated based on ISO 13232-5 (2005)[5] for both helmeted and unhelmeted riders (and also including skull fracture for unhelmeted riders). The risk/benefit percentage and 95% confidence intervals¹² in square brackets [] were calculated. Whenever the confidence interval for risk/benefit percentage includes 100%, it is considered that the risk/benefit percentage is not statistically significantly different from 100% (i.e., wherein the risk is equal to the benefit), or in other words, there is no statistically significant net benefit.¹³ In addition, guidelines in Annex E of ISO 13232-5 (2005)[5] indicate that the risk/benefit percentage of protective devices “should be less than seven percent and should not be more than 12 percent.”

The Zellner et al. (2008)[4] risk/benefit results for the previously analyzed ROPS/CPDs are summarized in [Table 3](#). In all cases it was found that either the ROPS/CPD had no statistically significant net injury benefit (i.e., the injury risks from the device were approximately equal in magnitude to the injury benefits from the device), or if there was a

¹¹ The ground terrains in these simulations were modeled by “planes” representing the effective locally linear ground terrain in the vicinity of the test location. The “planes” used in the simulation model are not intended to be representative of the overall ground terrain and features farther away from the immediate test location, or of small surface irregularities.

² Under the US Consumer Product Safety Improvement Act (CPSIA), an ATV is as defined in ANSI/SVIA-1-2010.

¹² The 95% confidence intervals for the Risk/Benefit percentages were estimated by replacing the values for Δx with $\Delta x \pm \Delta \bar{x}_{95\%CI}$ in the risk/benefit calculation procedure specified in clause 5.9.4.2 of ISO 13232-5.

¹³ The risk/benefit percentage equaling 100% is mathematically equivalent to a statement that the risk is equal to the benefit, or the net benefit is equal to zero.