PREDICTED EFFECTIVENESS OF POTENTIAL INJURY COUNTERMEASURES FOR ALL-TERRAIN VEHICLE OVERTURNS

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Word Count: 5690 (excluding References)

Figures/tables: 4/1

For presentation at the 93rd Annual Meeting of the Transportation Research Board

ABSTRACT

An analysis of the predicted effectiveness of three potential injury countermeasures for All-Terrain Vehicle (ATV) overturn accidents is described. These involved one passive countermeasure – an example Crush Protective Device (CPD) – and two active countermeasures: a full face helmet and a half helmet. As in previous evaluations, the methodology involved extending and applying the test and analysis methods defined in ISO 13232 for motorcycle impacts, with further updates and calibrations of the models, to evaluate the effects on injuries in a sample of 770 simulated types of ATV overturns based on accident data. The results indicated that fitment of the example CPD resulted in no statistically significant net benefit in terms of injuries and fatalities in comparison to the baseline ATV and unhelmeted dummy; while use of the example full face helmet or half helmet resulted in statistically significant net benefits. This confirms for this class of small, ride-on-top, straddle seat, handlebar-controlled, helmet-required, rider-active vehicles that helmet use - whether full face or half helmet, which offer different levels of protection – is an effective countermeasure, and that the example CPD is not an effective countermeasure. The data indicate that the example CPD analyzed has no statistically significant effect on probability of injury and fatality, and that in all paired comparisons analyzed there was an excessive probability that it is a harmful device.

KEYWORDS

All-terrain vehicle, crush protective device, Quadbar, helmet, risk, benefit, injury,

INTRODUCTION

This paper describes results of an analysis of the predicted effectiveness of three potential injury countermeasures for All-Terrain Vehicle (ATV) overturn accidents. The countermeasures involved one passive countermeasure – an example Crush Protective Device (CPD) – and two active countermeasures: a full face helmet and a half helmet.

As in previous protective device evaluations described in (*1*) through (*6*), this evaluation adapts the relevant portions of the test and analysis methods specified in ISO 13232 (2005)(*7*) for motorcycle protective devices, extended so as to be applicable to ATV overturn events. These estimate the predicted injury (and fatality) benefits and injury (and fatality) risks of fitting a protective device (in this case a CPD to an ATV; or a helmet to a crash dummy), comparing 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. This evaluation also included extensive updates involving refinements to the previous evaluation methodology, as subsequently described. As in the previous evaluations cited, the evaluation was based on predicting the injury benefits and injury risks that would result from fitment of a protective device, by means of paired comparisons using simulation models (i.e., predicting injuries with and without the proposed device) that have been extensively calibrated against test data, 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.

This paper summarizes the research methodology; the results of applying the methodology to the three example countermeasures; and the conclusions and recommendations.

BACKGROUND

An ATV is a type of standardized 4-wheeled off-highway vehicle, which is defined (e.g., by ANSI/SVIA-1-2010 (2010)(*8*)) as having a straddle seat, footrests, handlebar-controlled, helmet-required, ride-on-top configuration among other factors. ATVs have a precise legal definition in the United States, which accounts for approximately 90% of sales worldwide. In 2011 the US Consumer Product Safety Commission (CPSC) adopted ANSI/SVIA1-2010, which defines an ATV, as a mandatory safety standard.

ATVs are designed to be rider-active vehicles (e.g., (*9*)). This refers to the seating and control configuration noted above so that a rider can shift body weight fore/aft, laterally and off the seat (by standing on the footrests), and to ATV's relatively small size and mass, which together enable the rider to vary vehicle performance, including stability, mobility, ride comfort, visibility and other attributes. Such rider-active techniques are taught in ATV rider training courses (e.g., (*10*)).

Approximately 11 million ATVs are in operation worldwide and, as with other motor vehicles, a relatively small percentage of these are involved in injury and fatal accidents each year, as reported in the epidemiological literature (e.g., (*11*)). A substantial percentage of such accidents involve overturn (e.g., 56 of the 105 accidents investigated by the UK HSE involving ATV's involved a 4-wheel ATV overturn (*12*)); and a range of passive and active (i.e., engineering and administrative) countermeasures have been sought for such overturns. Example engineering countermeasures investigated for reducing or mitigating overturns include: implementing manufacturer-specific lateral stability criteria per agreement with the

CPSC; implementing pitch stability criteria in the 1990 ANSI/SVIA 1 Standard; and investigating (with no positive outcomes) several ROPS and CPD devices as summarized in (*4*)). Administrative countermeasures have included promoting state model legislation requiring helmet use, non-use of adult ATVs by youth, non-use on public roads, and other laws, which to some extent have been implemented in 47 of the 50 US states. Garland (*11*) has reported a substantial decrease in fatality and injury rates during an approximately 10 year analysis window.

ANSI/SVIA 1 (2010)(*8*) requires that a series of warning labels be visible on the ATV, among which are warnings that “Improper ATV use can result in severe injury or death” and “Always wear an approved helmet and protective gear”. In addition, ATV rider training courses stress the importance of helmet wearing; which is required by law in many jurisdictions. Therefore, for purposes of the discussion in this paper, the helmeted condition is referred to as an “intended use” of an ATV, and the unhelmeted condition is referred to as a “warned against” use of an ATV.

ATV manufacturers’ recommendations that a helmet should always be worn are consistent with the guidelines provided by the ATV Safety Institute (*10*), which mention full-face and open face helmets. Note that a “half helmet” is a subcategory of open faced helmets, with less coverage on the sides of the skull than traditional open face helmets.

Countermeasures Evaluated

In the current analysis, the protective devices examined were an example aftermarket CPD (i.e., the Quadbar, previously modeled by Munoz, et al. (*3*) and Zellner, et al. (5,*6*) and herein referred to as the “CPD”); an example full face helmet (the Bieffe B12R, the helmet specified in ISO 13232-6 (2005)); and an example open face half helmet (THH T70). Both helmets fully meet the impact and minimum coverage requirements of the current US federal helmet standard and AUS and NZ standards, although they have entirely different styles and coverage. CPD’s and helmets styles have been of recent interest in AUS and NZ, and in addition, evaluating helmet effectiveness provided a means to validate this methodology against epidemiological data for ATV helmet effectiveness.

Test and Simulation Methods for ATV Overturn Analysis

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)(*7*) entitled “Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles”, applicable to two wheeled motorcycle-to-car impacts. ISO 13232 was prepared by ISO/TC 22/SC 22/WG22. This group comprised approximately 25 experts and observers from Belgium, China, Germany, France, Italy, Japan, The Netherlands, Switzerland, UK, and US (*13*). Many, but not all, of the methods 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. Adapting and extending the applicable ISO 13232 methods to ATV overturn analysis was the approach used herein, as previously described in detail in, e.g., (*5*).

Features of ISO 13232 (2005)(*7*) relevant to ATV overturn analysis include:

- the only standardized injury-monitoring crash dummy (motorcyclist anthropometric test device – MATD) worldwide which:
    - is designed to be compatible with "straddle seat, handlebar-controlled, helmet-required" vehicles where the rider typically separates from the vehicle and where the rider trajectory can potentially have an effect on the injury outcome of which motorcycles and ATVs are two examples;
    - can monitor for injuries in lateral, fore-aft and vertical directions, which may occur in ATV lateral, forward, rearward and multi-axis axis overturns;
    - can monitor for a range of Abbreviated Injury Scale (AIS) injury severities at several body regions;
- a requirement for:
    - motions calculated by computer simulation to be calibrated against those recorded in full-scale tests (note that "calibrate" in the context of ISO 13232 means to "correlate the readings of (an instrument [e.g., a simulation]) with those of a standard [e.g., a physical test] in order to check the instrument's accuracy"(http://www.oxforddictionaries.com/us/definition/english/calibrate));
    - the response of the crash dummy components calculated by computer simulation to be calibrated against those recorded in laboratory tests;
- definition of a representative sample of accidents including all injury severities from which to define several general "types" 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 guidelines for the relative magnitudes of these.

METHODOLOGY

The methodology used in the evaluations was the same as that used in previously as described in detail in (5,*6*). Broadly, this involved the paired comparison of injury indices from computer simulations of a sample of ATV overturn types, with and without the countermeasure. Simulation outputs were used to calculate the ISO 13232-5 "Normalized Injury Cost" and the probability of fatality in of 110 ATV overturn types. These injury and fatality indices were calculated from the probability of injury to the head, face, chest and abdomen by AIS severity level, femur and tibia fractures, knee dislocations, and the probability of fatal asphyxia/breathing difficulty resulting from long term chest compression. The probability of injury to each of the body regions were estimated using published injury criteria (i.e., ISO 13232-5 (2005) and (*18*)) – as well as a preliminary criterion for asphyxia/breathing difficulty described in (5). The overturn types were based on 110 UK HSE (*12*) and US CPSC overturn cases. Each of the overturn types was simulated with 7 perturbations in the initial conditions (i.e., the nominal initial condition parameters, plus small positive and negative perturbations in 3 initial condition parameters) in order 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.

Computer Simulations Models

The computer models used to simulate the dynamic forces acting on and the motions of the ATV and dummy in the overturns were implemented with the physics based Articulated Total Body (ATB) computer program developed and validated by Calspan and the US Air Force for the US National Highway Traffic Safety Administration (e.g., (*14,15*)).

The ATB model illustrated in Figure 1 comprised 45 rigid body "segments" with a total of 84 degrees-of-freedom, comprising:

- ISO MATD dummy model with 35 segments with 69 degrees-of-freedom;
- Honda TRX 350 ATV model with 8 segments with 11 degrees-of-freedom, including steering, individual wheel rotation, independent front suspension, and rear swing arm, with constraints for front steering tie-rods and four-wheel drive;
- CPD model with 2 segments with 4 degrees-of-freedom to model the measured longitudinal and lateral bending compliance.

These segments had various ellipsoid, hyperellipsoid, or planar shaped contact surfaces with specified force-deflection characteristics.

The helmets were modeled by ellipsoids with different dimensions for the respective helmets, and external shell/liner contact force-deflection characteristics based on respective full face and open face helmet/headform dynamic drop test data. For the half helmet, the helmet ellipsoid modeled the shell/liner characteristics, and the skull vault and face ellipsoids for the exposed portions of the head modeled the head contact characteristics, based on (*18*).

The ground terrains were modeled by one of eight ground terrain types previously used including: slope, ditch/embankment, rutted road; vertical discontinuity, ramp, tilted/folded ground plane, pothole; and several types of bump. The particular characteristics varied with each of the 110 modeled overturn types.

Figure 1. Image of the test-calibrated computer simulation model of the MATD on the TRX 350 ATV with CPD and full face helmet

Computer Simulation Calibration and Validation

ATB models of the MATD dummy, and ATV with and without CPD were calibrated against several dozen laboratory tests as described in (*16*) through (*18*); and also against 12 full-scale tests, each involving an ATV overturn, as described in (*1*). Figure 2 illustrates the calibration of the unhelmeted head, full-face helmet, and half-helmet contact force-versus-deflection models. The 12 full-scale tests were to verify and to refine as needed the dynamic force-deflection characteristics acting between the ATV, the CPD, the soil and the dummy. The 12 full-scale tests comprised four different directions of overturn at different speeds and slopes, each involving a baseline ATV and a CPD ATV, some tests with a full face helmet and some tests without a helmet. Each test was filmed with high speed cameras.

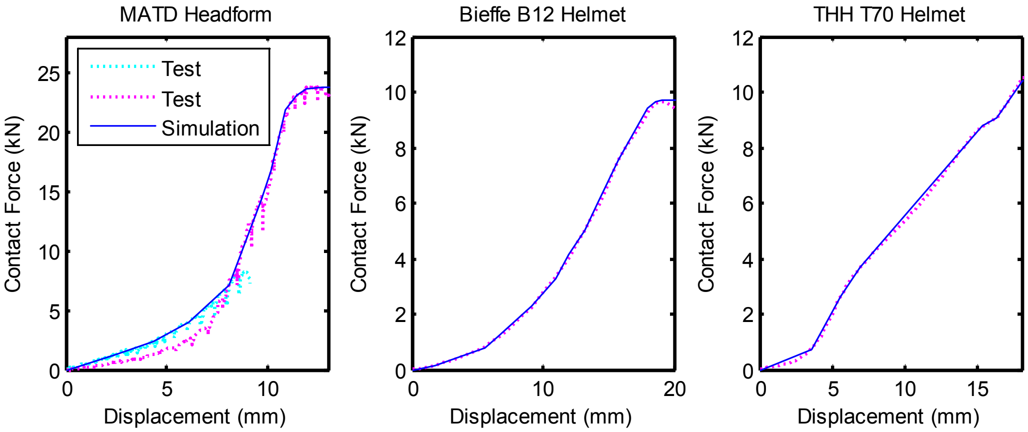


Figure 2. Calibration of Unhelmeted, Full-Face Helmet, and Half-Helmet Force-versus-Deflection models

For each full-scale test, the motions of the rider, ATV and CPD were correlated with the motions predicted by the simulation by digitizing various points on the dummy, ATV and CPD in the high speed films and comparing these values to corresponding values from the computer simulation. For example, Figure 3 illustrates the motion of several points in the film plane of Camera 1 in Test 97101612, a cross slope with U-bar. The digitized and simulated trajectories are shown connected by lines at every 5 film frames. In this example the correlation factor (as defined in clause 4.5.4 in ISO 13232-7, which is similar to the Nash-Sutcliffe (*19*) model efficiency *E* index) between the digitized and simulated points was C=0.98 indicating that the simulation and full-scale test whole body motions were in very close agreement. Overall the average correlation factor *C* value for the 12 tests and all available camera views was 0.91, indicating close agreement between the tests and the simulations.

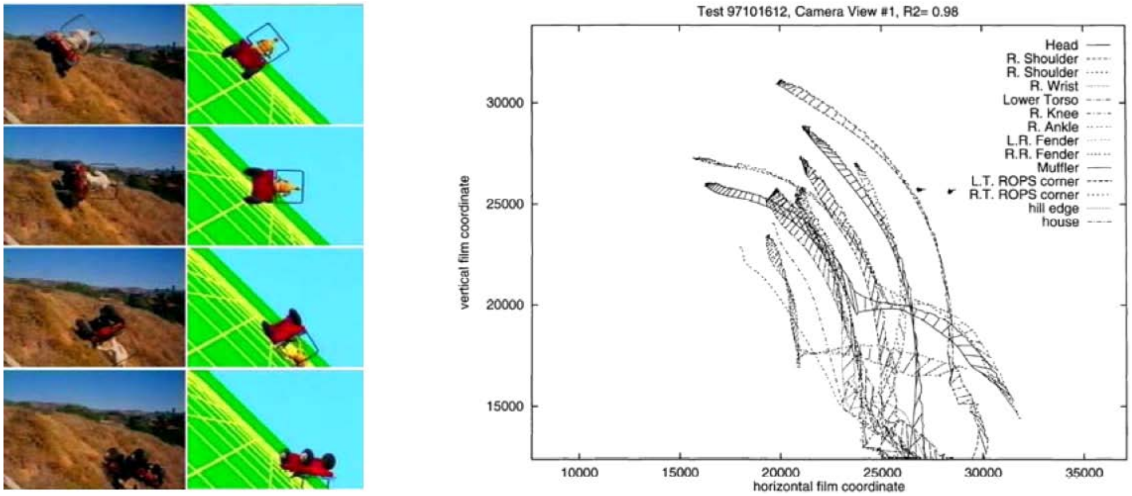


Figure 3. Example Correlation Between Full-Scale Test and Computer Simulation

Methodology Updates, Extensions and Refinements

The current evaluation also included a number of recent updates, extensions and refinements to the methodology used in previous ATV rollover protection system (ROPS)/CPD evaluations. These updates, extensions and refinements, which are extensively described in (5,*6*), included:

- “Low Energy” US and UK ATV overturn “types”
- Inclusion of a preliminary potential mechanical/traumatic (compressive) asphyxia (i.e., breathing difficulty) criterion
- Updated and revised injury coding for US/UK cases
- Revised number of US/UK cases (i.e., n=110)
- Brake, throttle, and steering control release during overturn
- Helmeted and unhelmeted head force-deflection refinements
- Measured dummy/soil friction coefficients
- Hand grip release force refinements
- Leg fracture strength refinements
- Updated contact definitions
- Simulation end time refinement
- Extent of ground planes refinement
- Comparing only cases where both the baseline and modified ATV overturned
- Refined initial condition perturbation methodology (resulting in n=770 types of overturn)
- Correction of graphics software anomalies
- Miscellaneous refinements
- Calibrations of simulated versus actual aggregated injury severity distributions
- Comparison of helmet risk/benefit analysis outcomes to published literature

Following these updates, Appendix G of (5) validated the frequency distribution of monitor-able injuries predicted by the simulation against those found in ATV accident data, finding they have similar trends across all body regions and overturn cases/types.

COUNTERMEASURE INJURY RISK/BENEFIT ANALYSIS RESULTS

The risk/benefit analysis results from the countermeasure evaluations are summarized in Table 1. All of the results are based on computer simulations of the 770 (=110 x 7) overturn types. The first two columns of Table 1 indicate the baseline and countermeasure being compared in the risk/benefit analysis. The third column indicates the injury index used in the analysis, which is either the Normalized Injury Cost (ICnorm) or the probability of fatality as defined in ISO 13232-5. The fourth and fifth columns indicate the estimated risk/benefit percentage and the net benefit, with 95% confidence intervals for the population of all overturns in parentheses ( ). The last column indicates the probability of the observed result or a more extreme result occurring (compared to 100% risk/benefit and 0% net benefit) if in fact the countermeasure did not have any real effect (e.g., if the countermeasure was merely a helmet color such as "red" versus "blue"), and whether or not the result was statistically significant at the 0.05 level. Note that probability values (p) less than 0.05 are a widely accepted criterion for statistical significance tests regarding whether an apparent non-neutral effect is real (*20*).

If a countermeasure does not have any real effect in comparison to the baseline, then by definition the expected value for the risk/benefit percentage for the population of all overturns is 100% and the net benefit for the population of all overturns is 0%. Therefore the results are statistically significant at the 0.05 level if the 95% confidence interval for the estimated risk/benefit does not include 100%, and the 95% confidence interval for the net benefit does not include 0%, and this corresponds to a p value less than or equal 0.05. If the countermeasure has a statistically significant benefit, then the results are shaded in light green in Table 1. If the countermeasure has a statistically significant risk then the results are shaded in pink.

In summary these results indicate the following:

- A full face helmet or a half helmet are statistically significantly beneficial, compared to no helmet;
- The CPD either does not have any statistically significant net benefits, or else it is statistically significantly harmful, depending on helmet use and on the baseline helmet/no helmet condition used for comparison.

The results for the full face helmet in the first two rows of Table 1 indicate that the estimated net benefit for the full face helmet is a statistically significant 60% (45%, 75%) reduction in the normalized injury cost and a statistically significant 75% (35%, 115%) reduction in the probability of fatality. More specifically, the point estimate for the normalized injury cost net benefit based on the simulated sample was 60%, but the range of estimates for the population is between 45% and 75%. Therefore according to (*20*), page 109, one can be *"somewhat convinced"* that the full face helmet will have a positive net benefit for the population based on these simulation results.

The estimated risk/benefit percentages for the normalized injury cost and probability of fatality for the full face helmet are 9% (6%, 21%) and 2% (1%, 18%) respectively. Though these are not statistically significantly less than the ISO 13232 guideline of 12% maximum risk/benefit percentage, the point estimates are below 12% and therefore the full face helmet could be considered an acceptable countermeasure.

The results for the half helmet in the third and fourth rows of Table 1 are similar to the results for the full face helmet in the first two rows of Table 1. For the normalized injury cost, the risk/benefit percentage of 12% is equal to the maximum ISO 13232 guideline of 12%.

The results for the CPD with no helmet compared to no CPD with no helmet in the fifth and sixth rows of Table 1 indicate that the estimated net benefit is a *not statistically significant* 12% (-5%, 29%) reduction in the normalized injury cost and a *not statistically significant* 14% (-7%, 35%) reduction in the probability of fatality (i.e., *both are not statistically significantly different from there being zero net benefit)*. The associated p-value of 0.153 for the normalized injury cost outcome can be interpreted as meaning that the probability that the actual net benefit is *negative* (i.e., that it is harmful in terms of injuries) is 0.076 (i.e., p/2). The associated p-value of 0.202 for the probability of fatality outcome can be interpreted as meaning that the probability that the actual net benefit is *negative* (i.e., that it is harmful in terms of fatalities) is 0.101. Therefore, according to (*20*) one *cannot* be *"somewhat convinced"* that the CPD will not be harmful for the population, based on these results.

The estimated risk/benefit percentages for the CPD normalized injury cost and probability of fatality for the CPD with no helmet compared to no CPD with no helmet are 68% (42%, 114%) and 68% (41%, 120%) respectively which are both not statistically significantly different from 100%. These risk/benefit percentages are much greater than 12%, which is the ISO 13232 guideline for an acceptable countermeasure. Moreover, a hypothetical 66.6% risk/benefit percentage corresponds to 2 injuries caused by the device for every 3 injuries eliminated by the device, which is inconsistent with a "do no harm" goal for countermeasures.

In the presence of such large uncertainties as to the direction of the outcome (i.e., harmful or beneficial) stemming from large p-values (e.g., p=0.202), it is traditionally considered not advisable to proceed with implementing such a treatment (i.e., in this case, the CPD with no helmet, instead of no CPD with no helmet).

The results for the CPD with full face helmet or half helmet in Table 1 compared to no CPD with the same helmet configuration indicate the estimated net benefit for the CPD with helmet ranges from -22% (-53%, 9%) to -3% (-24%, 18%), which are not statistically significantly different from no net benefit, and the risk benefit percentage ranges from 108% (69%, 168%) to 158% (97%, 264%), which is not statistically significantly different from 100%. Therefore this result indicates that there is a relatively large chance that the CPD may be a harmful device.

The results for the CPD without a helmet, compared to no CPD with a full face helmet or half helmet in Table 1, indicate the net benefit for the CPD with helmet ranges from -244% (-327%, -161%) to -72% (-101%, -41%), which are all statistically significantly less than zero net benefit, and the risk/benefit percentage ranges from 379% (206%, 604%) to 1088% (322%, 1987%), which are all statistically significantly greater than 100%. Therefore the CPD with no helmet, in comparison to no CPD with helmet (i.e., the intended use of the vehicle), significantly increased the normalized injury cost and probability of fatality.

Table 1. Summary of Risk/Benefit and Net Benefit Percentage Results

Baseline	**Counter-measure**	**Injury Index**	**Estimated Risk/Benefit Percentage**	**Estimated Net Benefit**	**Statistical Significance**
No helmet, No CPD	Full face helmet No CPD	ICnorm	**9% (6%, 21%)**	**60% (45%, 75%)**	**Significant p<0.001**
		Prob. of Fatality	**2% (1%, 18%)**	**75% (35%, 115%)**	**Significant p<0.001**
	Half helmet No CPD	ICnorm	**12% (8%, 24%)**	**49% (36%, 62%)**	**Significant p<0.001**
		Prob. of Fatality	**5% (3%, 23%)**	**61% (44%, 78%)**	**Significant p<0.001**
	No helmet with CPD	ICnorm	68% (42%, 114%)	12% (-5%, 29%)	**Not Significant** p=0.153
		Prob. of Fatality	68% (41%, 120%)	14% (-7%, 35%)	**Not Significant**. p=0.202
Full face helmet, No CPD (intended use)	Full face helmet and CPD	ICnorm	108% (69%, 168%)	-3% (-24%, 18%)	**Not Significant**. p=0.760
		Prob. of Fatality	134% (79%, 219%)	-15% (-44%, 14%)	**Not Significant**. p=0.309
	No helmet with CPD	ICnorm	**492% (255%, 788%)**	**-114% (-154%, -74%)**	**Significant p<0.001**
		Prob. of Fatality	**1088% (322%, 1987%)**	**-244% (-327%,-161%)**	**Significant p<0.001**
Half helmet, No CPD (intended use)	Half helmet and CPD	ICnorm	158% (97%, 248%)	-20% (-42%, 2%)	**Not Significant**. p=0.066
		Prob. of Fatality	155% (86%, 264%)	-22% (-53%, 9%)	**Not Significant**. p=0.164
	No helmet with CPD	ICnorm	**379% (206%, 604%)**	**-72% (-101%,-41%)**	**Significant p=<0.001**
		Prob. of Fatality	**543% (226%, 899%)**	**-122% (-172%,-72%)**	**Significant p=<0.001**

Color Key	
🟩	Estimated risk/benefit percentage is significantly less than 100% (p-value less than or equal to 0.05 and the injury risks of the device are much less than the injury benefits of the device), and the estimated net benefit is significantly greater than 0% (i.e., significant benefit exists). May be a reasonable device assuming acceptable functional characteristics.
🟥	Estimated risk/benefit percentage significantly more than 100% (p-value less than or equal to 0.05 and the injury risks of the device are greater than injury benefits of the device), and the estimated net benefit significantly less than 0% (i.e., significant disbenefit exists). Device causes significantly more injuries than it prevents.
⬜	Estimated risk/benefit percentage not significantly different from 100% (p-value is greater than 0.05, the injury risks of the device are effectively equal to injury benefits of the device), and the estimated net benefit percentage not significantly different from 0% (within 95% confidence interval). Injury risks of the device are effectively equal to injury benefits of the device.

CPD Injury Benefit and Injury Risk Mechanisms

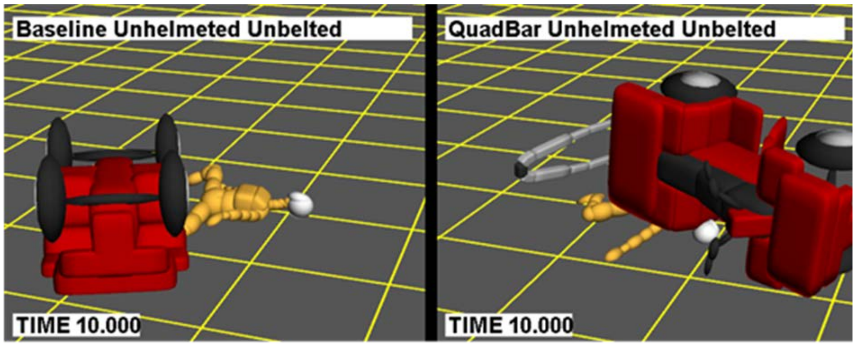
Examination of the injury summary sheets and graphics animations for individual runs generally indicated that, as in past studies:

- Injury benefits from the CPD (in comparison to no CPD) were often related to injuries that occurred with the baseline ATV that were reduced in severity or prevented by the CPD, e.g., trapping between the upper surfaces of the ATV and the ground;
- Injury risks from the CPD (in comparison to no CPD) were related to injuries that did not occur with the baseline ATV, that were caused by the CPD, e.g., impacts between portions of the dummy and the CPD; trapping of portions of the dummy between the ground and other surfaces of the ATV and/or the CPD which did not occur without the CPD; and altered overturning motions of the ATV, which in some cases increased some of the impacts and/or forces between the dummy and the ATV, the CPD and/or the ground;
- The injury risks (i.e., the newly created injuries) from the CPD due to the aforementioned and other mechanisms tended to be relatively large in comparison to (i.e., similar in magnitude to) the injury benefits of the CPD due to the aforementioned and other mechanisms.

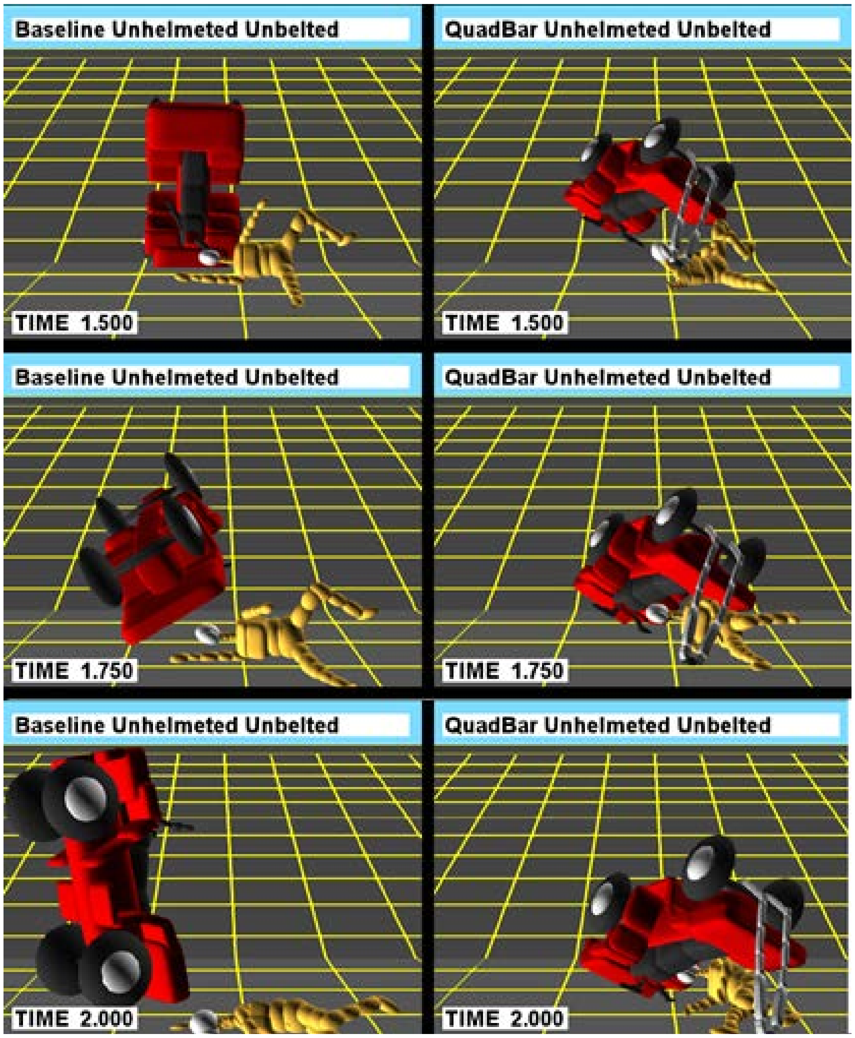
Figure 4 illustrates example injury risks of the CPD. Each pair of images shows the baseline ATV (on the left) and the ATV with CPD (on the right) at the same time instant.

In the upper example in Figure 4, the predominant change in injury was a high probability of an AIS 2 concussive head injury and also potential asphyxia (i.e., long-duration chest compressive force greater than 490 N (110 lb)) for the ATV with CPD, while dummy separation from the ATV and no monitor-able injuries occurred with the baseline ATV. In this example, the CPD caused the ATV to complete an additional quarter roll toward the right side of the image (after being raised by the action of the CPD to a greater height compared to the baseline case, resulting in the ATV with CPD continuing to roll onto and coming to rest on the dummy.

In the lower example in Figure 4, the ATV overturns on a downhill slope (after cresting a hill while in a slight turn, the ATV moving toward the camera and slightly toward the left side of the images). The CPD impacted the dummy's upper torso/shoulder/neck region at time t=1.5 s, resulting in high probabilities of an AIS 5 (critical) brain injury, an AIS 2 (moderate) upper neck injury, and an AIS 3 (serious) chest compression injury. This CPD contact and injury pattern was not unique and was observed in a number of the simulation runs.



a) Potential asphyxia and AIS 2 concussive head injury occurred with the CPD, while the baseline ATV had no monitor-able injuries



b) AIS 5 concussive brain injury, AIS 2 upper neck subluxation injury and AIS 3 chest compression injury occurred with the CPD, while the baseline ATV had no monitor-able injuries

Figure 4. Example still images illustrating CPD injury risk

As for “asphyxiation,” the simulations indicated that the CPD caused as many new potential "breathing difficulties" (i.e., 11 cases) as it prevented (i.e., 11 cases) across a total of 3,080 helmeted and unhelmeted overturns.

The mechanism behind this lack of effectiveness in reducing asphyxia potential appears to be a shift in the final resting orientation of the ATV caused by the CPD. The frequency of the ATV coming to rest on its top (i.e., upside down) decreased from 20% to 7% (note that an “upside down” final resting attitude with the CPD may occur in the presence of ditches, obstacles and other non-flat terrain conditions), and the frequency with which it comes to rest on its side increased from 25% to 31%. For the subsets of these cases that involved “breathing difficulty”, while fewer (i.e., no) ATV with CPD cases occurred when the ATV came to rest on its top (i.e., upside down), substantially more cases occurred when the ATV with CPD came to rest on its side. Since fatal and serious injuries have been known to occur when a baseline ATV comes to rest on its side on a rider, this shift toward relatively more “breathing difficulty” (i.e., potential asphyxia) cases occurring when the ATV comes to rest on its side as compared to on its top is considered to be a realistic phenomenon (for example, one of the fatal overturn cases in the 2002-2009 Victorian Coroner’s inquest involved an ATV coming to rest on its side on a rider. Another example is a New Zealand case described in (*21*) that involved an ATV coming to rest on its side, resulting in long term rider entrapment and subsequent medical leg amputation).

As noted elsewhere, it was observed that the total number of potential “breathing difficulty” outcomes were relatively small among (i.e., about 1% of) the simulated “low energy” overturns with 50th percentile adult male dummy, no accessories, mid-sized ATV, and other simulated conditions.

Helmet Injury Benefit and Injury Risk Mechanisms

Examination of the detailed injury model results and graphics animations for individual runs generally indicated that:

- Injury benefits from the full face helmet and half helmet (in comparison to no helmet) were often related to energy absorption (i.e., brain acceleration-reducing) characteristics as well as skull/face fracture protection of the covered zones;
- Injury risks from the full face helmet and half helmet (in comparison to no helmet) were related to load shifting (i.e., also referred to as edge effects) from the relatively rigid helmet to unprotected head and other body regions;
- The injury risks from the helmets due to the aforementioned and other mechanisms tended to be relatively small in comparison to the injury benefits of the helmets;
- The full face helmet had a greater net benefit and a smaller risk/benefit percentage than the half helmet, and this is attributed to the larger coverage zones of the former.

CONCLUSIONS

CPD countermeasure

Based on the results in Table 1, the overall conclusions from the analysis of the predicted effectiveness of the example Quadbar CPD for All-Terrain Vehicle (ATV) overturn accidents were that:

- With helmeted use and in comparison to the *helmeted* Baseline ATV (the intended use), the CPD was found to have estimated injury risks for the population of overturns that were *not statistically significantly different* from its injury benefits;
- With unhelmeted "warned-against" use and in comparison to the *helmeted* Baseline ATV (the intended use), the CPD was found to have estimated injury risks for the population of overturns that were *statistically significantly greater* than its injury benefits;
- With unhelmeted "warned against" use and in comparison to the *unhelmeted* Baseline ATV, the CPD was found to have estimated injury risks for the population of overturns that were *not statistically significantly different* from its injury benefits; and
- The aforementioned conclusions also apply to the probability of fatality risks and benefits;
- These CPD injury and fatality risks for both helmeted and unhelmeted conditions are:

    - much higher than those found in any published data for any automotive safety device, for which the fatality risks have been found to be less than 7% of the fatality benefits (e.g., (*7*), Annex E, footnote 1);
    - unacceptably high risks in comparison to benefits when compared to the suggested reference guideline for research purposes published in ISO 13232-5 (2005)(*7*), i.e., the CPD risk/benefit percentages were all far greater than the *"not… more than 12 percent"* guideline indicated in the Standard; and
    - unacceptably high risks in comparison to benefits, when compared to the "regulatory policies of several of the (Australian) states," mentioned in the Heads of Workplace Health and Safety Authorities TEG report (*21*), which were stated to be that the "the benefits need 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.".

Full face helmet and half helmet countermeasures

This study added to the validation of the methodology in its close agreement with other research (e.g., (*22*)) that has indicated that helmet wearing on ATVs does have substantial net injury benefits; and also indicated that helmets have a small risk/benefit percentage comparable to those for automotive safety devices (e.g., airbags, safety belts (when worn) and head restraints). As might be expected, half helmets had less net benefit and slightly greater risk/benefit than the full face helmet. Note that both helmets fully complied with current US, AUS and NZ helmet standards.

LIMITATIONS

These results are based on a number of assumptions and approximations, including:

1) The simulation models, which have been calibrated against full-scale and laboratory tests, may not be predictive in non-calibrated conditions (e.g., modeled force-deflection characteristics at impact speeds, angles, and positions that are different than the laboratory test conditions).
2) The full-scale validation tests were conducted with an ATV and CPDs that were somewhat different than those in the current study, however the basic design of the tested and modeled ATVs were very similar, and the stated design intent and characteristics of the tested and modeled CPDs were similar.
3) The measured and modeled Quadbar CPD is the 2007 version, which is slightly different from the currently produced Quadbar.

4) The full-scale test validations were based on previous versions of the simulation models that did not include the updates, extensions, and refinements described herein.
5) The test dummy and injury criteria correspond to a 50th percentile adult male, and the dummy monitor the injury regions, types and severities specified in ISO 13232, plus additional criteria that were developed for skull fracture and asphyxiation/breathing difficulty. Other sizes of dummy, and other injury regions, types and severities were not considered.
6) The MATD dummy has not been validated for human rider trajectories (i.e., for non-active-dismount subjects) in ATV overturns, due to difficulties in obtaining such trajectory data for human subjects.
7) The potential effects of the CPD on rider behaviors such as rider active dismount during overturn, injuries or entanglements caused by the CPD during active dismount, risk compensation (e.g., operating at higher speeds and slopes), and on "warned against" behaviors such as unhelmeted use, use of adult sized ATVs by children and excess loading, have not been considered in this analysis.

RECOMMENDATIONS

In the future, the Quadbar CPD device evaluated in this study should not be fitted to ATVs because, for this category of relatively small, highly mobile, straddle seat, handlebar-controlled, helmet-required, rider-active vehicle, the injury risks from (i.e., new injuries created by) a CPD are generally similar in magnitude to the injury benefits from (i.e., injuries prevented by) a CPD, and far exceed published levels for other protective devices in other vehicles, and also exceed ISO 13232 guidelines - as well as apparent workplace health and safety policies for some jurisdictions - for protective devices. Authorities and individuals should be advised of these findings.

Other safety-related factors, including the effects of other ROPS or CPD devices on: ATV overturn stability as related to raised center-of-gravity height, reduced visibility, risk compensation by riders, entanglement with or impacts from a CPD during active or passive dismount, effect of non-use of seat belts (of ROPS) and increased potential for "warned against" uses (e.g., passenger-carrying or hanging equipment on a ROPS as related to overloading) should be taken into account as well. Functional performance, including effects on ATV mobility, utility and ergonomics, has been evaluated for some ROPS, and should be taken into account in such evaluations.

The results of this study also confirm that helmet wearing – either full face or half helmet - should be encouraged and wherever feasible, required, as helmets have substantial net injury benefits and low risks. While it is apparent that full face helmets provide greater net benefits and lower risks, there may be tradeoffs between its greater protection and other factors such as potentially increased thermal stress associated with greater coverage, particularly in hot climates and/or work environments. Development of thermal stress measurement methods and criteria would be needed in order to address any such tradeoffs.

Finally, other side-by-side vehicles that are somewhat larger and heavier than ATVs exist in the market that can accommodate ROPS, and have been engineered to take into account the relevant functional factors. Such side-by-side vehicles should be considered as alternatives to smaller, lighter, more mobile ATVs, for some tasks and usages.

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