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ATV Dynamics and Pediatric Rider Safety

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ATV DYNAMICS AND PEDIATRIC RIDER SAFETY

Dissertation

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By

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and Dr. Andrew Bernard, Professor of Surgery; Chief, Section of Trauma and Acute
Surgery; Trauma Medical Director; Paul A. Kearney MD Chair of Trauma Surgery
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ABSTRACT OF DISSERTATION

ATV DYNAMICS AND PEDIATRIC RIDER SAFETY

It has been observed through numerous academic and governmental agency studies that pediatric all-terrain vehicle ridership carries significant risk of injury and death. While no doubt valuable to safety, the post-hoc approach employed in these studies does little to explain the why and how behind the risk factors. Furthermore, there has been no prolonged, widespread, organized, and concerted effort to reconstruct and catalog the details and causes of the large (20,000+) number of ATV-related injuries that occur each year as has been done for road-based motor vehicle accidents. This dissertation takes the opposite approach from a meta-analysis and instead examines the injury risk factors through a two-pronged, a priori, physics-based approach. Specifically, this dissertation study sought to: 1) experimentally determine whether age is an effective metric for assessing proper rider fit on an ATV, and 2) demonstrate experimentally and analytically how the combined dynamics of the ATV and riders can contribute to vehicular instability. These two studies were conducted using instrumented human subjects and ATVs and measured in a biodynamics laboratory. The key finding from the rider versus ATV size study was:1) contrary to publicly circulated engine size and age-based fit guidelines, age is not an effective metric for assessing rider fit on ATVs; instead, stature is the more reliable measure. The key findings from the rollover propensity study were: 2a) the combination of common terrain and throttle input can easily lead to a rearwards rollover, with or without additional riders sitting behind the ATV driver, and 2b) the minimum turning radius before initiating a sideways rollover can be easily be exceeded when ATVs are driven on commonly-encountered terrain and at surprisingly low speeds. The results of this dissertation study thus provide new evidence for mitigating two root causes of ATV injury by informing better parental guidance: first, clearly revealing that stature and not age is the key metric for who fits on what ATV model, and second, revealing the ease with which backward and sideways rollovers can occur.

Keywords: All-terrain vehicle, vehicle dynamics, rollover, anthropometry, biomechanics, operator-vehicle interaction

James Tilsley Auxier II

__5/3/2020___________

ATV DYNAMICS AND PEDIATRIC RIDER SAFETY

By

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To the director of my dissertation, Prof. David Pienkowski, his friendly, honest, and patient guidance was invaluable, both for the progress of this dissertation as well as in life in general. It was always a pleasure working with another individual who holds intellectual curiosity and technological innovation in such high regard: The best way to predict the future is to create it.

A number of other individuals contributed to the breadth and depth of the knowledge and skills necessary to complete this dissertation. Prof. David Mullineaux was a wizard in helping to collect and parse the raw data during the initial phase of this study. Prof. Christian Gerdes introduced me to the world of vehicle dynamics, both from deconstructive and constructive points of view. Prof. Scott Delp instilled a system-level understanding of biomechanical design. Dr. Paul Yock and Prof. David Kelley laid the foundation for applying design thinking to medicine.

My godfather, Ralph G. Anderson (in memoriam) insisted I continue with my graduate studies in addition to my professional endeavors, in particular at the University of Kentucky. My friend and employee of our family farm, Jerry Fields was instrumental in lending a hand to construct the lift table apparatus utilized in both study phases.

My father, Thomas A. Auxier received one of the first graduate degrees in 1962 from the University of Kentucky based on biomedical engineering research performed in Wenner-Gren Research Lab (investigating whole-body response to vibrations for the USAF) and as an extremely coincidental bookend it would seem that I am a candidate for the last. So, thanks are also due (all in memoriam) to Profs. A.J. Meyer, James H. Graham, and Karl O. Lange for the inception and transformation of such a capable and flexible research facility.

Wenner-Gren Research Lab, © 2014, Lexington Herald-Leader

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1. Chapter 1 – Introduction

1.1 Emergence of the Problem

All-terrain vehicle ownership is common in America, particularly in rural and suburban communities. Worldwide, ATV sales are a $2.45 billion market with a predicted continuous growth of 3.5% (https://www.gminsights.com/industry-analysis/all-terrain-vehicle-atv-market). Industry recommendations for safe ATV operation such as training courses, equipment and vehicle sizing have been promulgated but their efficacy is mostly unproven. Moreover, adherence to safety practices is unknown and undoubtedly incomplete. Almost 100,000 adults and children are injured annually while driving or riding ATVs. Many of those injured are not even ATV owners, are untrained and some are injured on their very first ride.

Dr. Andrew Bernard, Medical Director for the University of Kentucky's Level I Trauma Center, has experience managing injuries and deaths from ATV's. As an academic faculty member in UK's College of Medicine, he has read manuscripts and been audience to research presentations at national meetings on the topic of ATV injury. These publications and investigations largely focused on cataloging injuries and reporting clinical outcomes. Most of these works concluded that ATV's should somehow be restricted, especially from children. However, a scientific explanation why children could not safely operate an ATV had never been established. Rider biomechanics had not been studied relative to ATV operation or injury. Dr. Bernard contacted the Department of Biomedical Engineering at the University of Kentucky seeking collaboration to answer the question, "can children safely operate all-terrain vehicles?' and was connected with engineers Professor David Pienkowski and Graduate Student James Auxier.

1.2 Extent of the Problem

To determine the magnitude of the issue of injuries from ATVs, a publicly accessible US government database was located that incidentally collects data on the same topic. The CPSC collects injury information stemming from the use of ATVs (discussed further on page 9).

Below is a collection of charts that highlight the occurrence of ATV deaths and injuries for the population at large and for children younger than 16, from the beginning of reporting until the most recent reporting period. There are four clear inflection points in the charts, which remain even after normalization of the data for population growth, and which can be traced to events recorded in Table 1.1. The first is an uptick in injuries and deaths around 1984-6, which can be linked to when ATVs first became popular for recreational usage. The second is a decrease in injuries after 1986 when the CPSC issued consent decrees to the ATV industry (discussed on page 5). There is a second uptick after 1998, which is when the consent decrees expired. The last inflection point is a decrease in injuries and deaths after 2006, which is when updated regulations and design standards were proposed to the ATV industry by the CPSC.

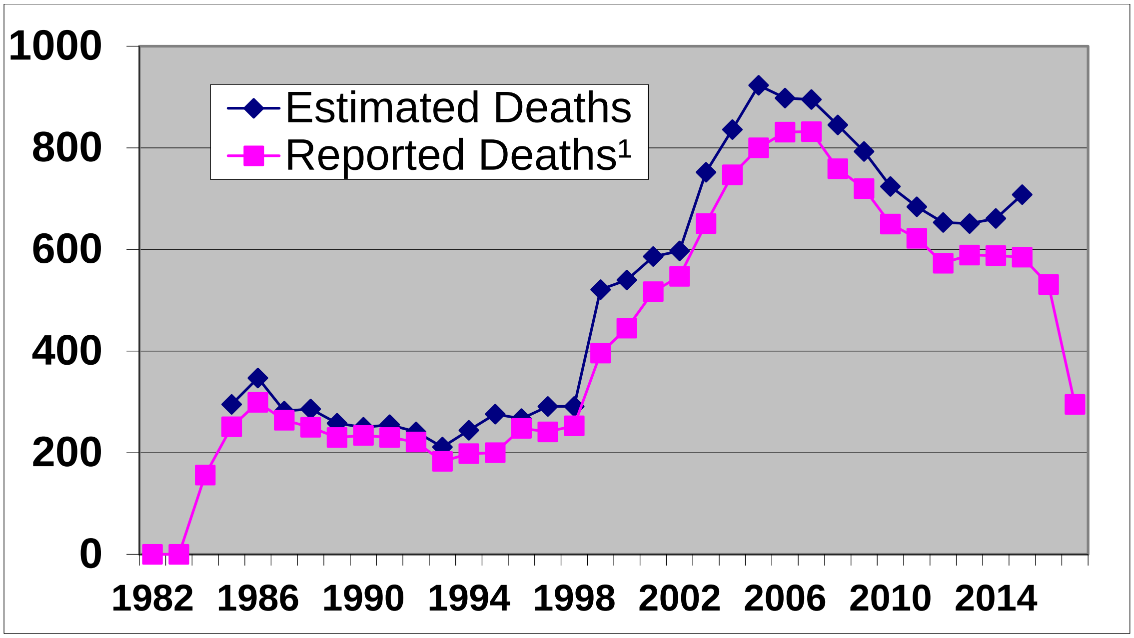

Figure 1.1 Total ATV-Related Fatalities (by Year), All Ages and Causes, Through 2017 (CPSC, 2019)

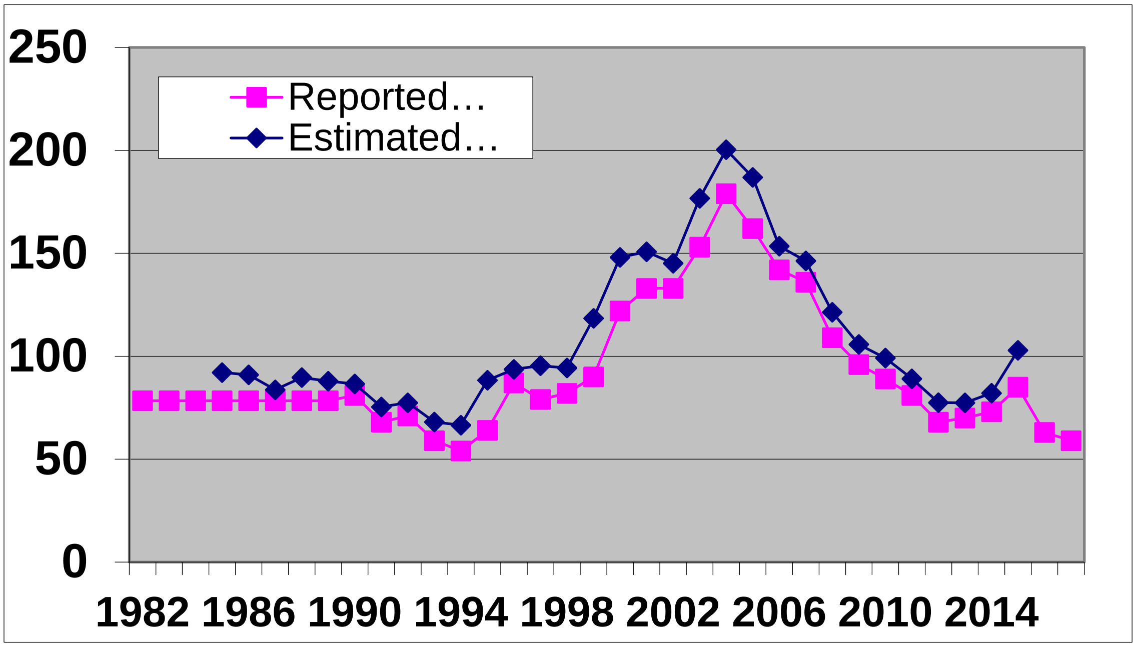

Figure 1.2 Total ATV-Related Fatalities (by Year), Children Younger Than 16 Years, Through 2017 (CPSC, 2019)

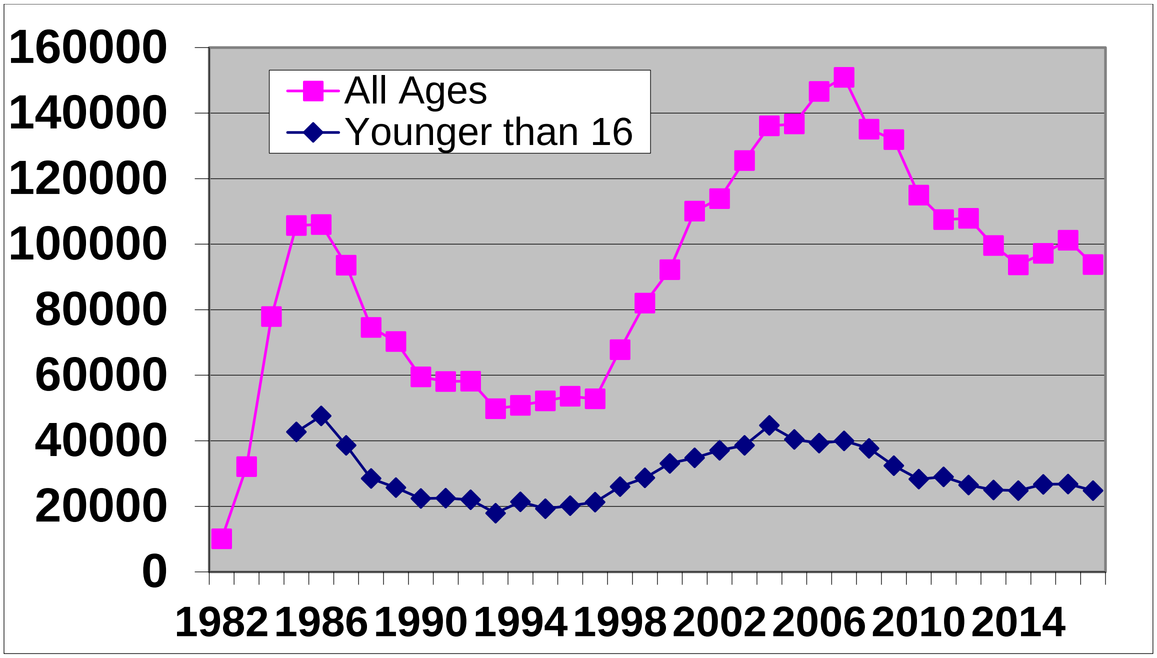

Figure 1.3 Estimated Total and Youth ATV-Related ER-Treated Injuries (by Year), Through 2018 (CPSC, 2019)

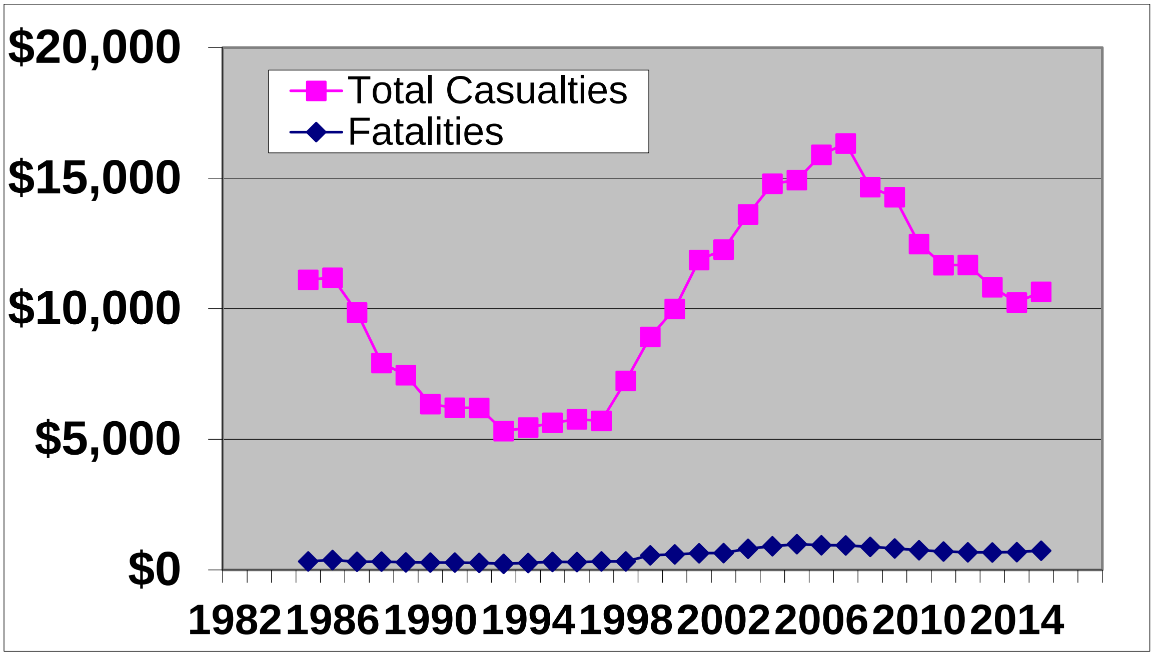

Figure 1.4 Estimated Total and Fatality-Related Societal Costs of ATV-Related Injuries (by Year), Through 2014, in $1M units (CPSC, 2019)

These injury statistics (Table 1.1 - Table 1.3) can be converted into monetary estimates for their societal impact, which includes cost of treatment, funeral expenses, legal fees, and lost wages. The impacts shown (Table 1.4) use the measure of $101,977 in 2013 dollars for non-fatal unintentional ED visit, and $980,516 / $1,409,467 in 2013 dollars per unintentional fatality for individuals over 15 and under 15, respectively. (Florence, 2013). The most recently reported (2015) societal cost of ATV injuries is $10.6 billion per year in

2013 dollars. When summed over the total reporting range of ATV-related injuries from 1985 to 2015, the sum of societal costs comes out to $316.5 billion in 2013 dollars.

From a US government epidemiological study of ER visits in 2010, 60.3 percent of ATV-related estimated injuries involve the vehicle overturning and were nearly statistically independent of any accompanying hazards (CPSC, 2014). The most commonly injured body part from an overturning event is the torso (41.7%); the inverse relationship shows that 73.8% of ATV-related torso injuries were from roll-overs, along with 52.9% of head injuries (Ibid). The only statistically significant relationships were the terrain slope (52.9% versus 43.4% on a measurable grade versus flat, respectively, $p < 0.0001$), and driver weight (36.8% / 66.1% / 65.5% for categories of <100 lbs. / 150-199 lbs. / 200+ lbs., $p < 0.0235$) (Ibid).

The correlations above will be shown to agree with the conclusions from this dissertation, that ATV rollover is predominantly a result of lateral instability due to a high center of gravity in relation to the vehicle wheelbase and track width. Poor ATV-rider fit, terrain slope, turn yaw rate, and number of riders are all strongly contributing factors from a vehicle dynamics perspective.

1.3 Prior Major Injury Abatement Efforts

As an issue recognized at multiple levels, the reduction in the incidence of ATV-related injuries has been the intent of a number of interest groups, both public and private. The actions taken to attempt to mitigate this problem have ranged from provision of information and training programs to setting laws and standards. A Systems Engineering approach to the study of the problem of ATV-related injuries entails not only analysis of the kinematics of ATV ridership, but also scrutiny of the extrinsic requirements affecting usage of the vehicles and how the two may relate.

Highlighted below are the various interest groups with focus on ATV usage-related injuries.

1.3.1 American Academy of Pediatrics (AAP)

The AAP is the official board certification group for pediatricians in the US, and their official academic journal is Pediatrics, among the top 100 most-cited journals in all of science and medicine (AAP, 2019). Their stated position since November 1987 has been the advocacy for an outright ban on ATV usage for individuals under 16 years old, and a recall of all ATV models intended for that same age range (Montgomery, 1987). The organization has rejected publication of ATV research, including from this author, not based on technical merit but whether or not the research topic / message supported their mantra of a complete ATV ban.

1.3.2 4-H ATV Safety Program

Established in 1902, 4-H is a private organization advocating for youth education, health, and safety, particularly in rural areas and on agricultural topics, that enjoys special Congressional protection of its emblem and logo (18 USC 707, 4-H History Preservation Program). They were one of the first organizations to provide guidelines for safer ATV ridership that included quantified criteria for proper ATV-rider fit. Since the mid-2010s they have aligned their ATV education programs with the ATVSI.

1.3.3 ATV Safety Institute (ATVSI or ASI)

A not-for-profit division of the Specialty Vehicle Institute of America (SVIA), which is the lobbying arm of the ATV and ATC industry. The ATVSI’s stated mission is “to promote the safe and responsible use of ATVs, thereby reducing accidents and injuries that may result from improper ATV operation by the rider." It was formed in 1988 as a condition of consent decrees negotiated between the Department of Justice and the SVIA, adjudicated by the CPSC (described in detail in section 1.3.4 below) (CPSC, 1988).

1.3.4 Consumer Product Safety Commission (CPSC)

The Consumer Product Safety Commission was formed in 1972 as an independent agency of the US government via the Consumer Product Safety Act (CPSA), and is authorized by this act to develop standards, recalls, and bans. A refresh of the 1972 law was signed in 2008, the Consumer Product Safety Improvement Act (CPSIA), which enables the CPSC to impose new product testing and documentation requirements and address acceptable levels of certain substances, particularly lead (additional discussion of the CPSC's differentiation from the FDA in Chapter 4). This latest legislation imposed new rules for ATVs, along with various children's products.

The CPSC tracks ATV-related injuries and deaths and issues reports on an annual basis with both reported figures and epidemiologically estimated figures (see Figure 1.1 - Figure 1.4). They maintain an All-Terrain Vehicle Deaths database (ATVD), and nearly all reported ATV-related fatal accidents are investigated by CPSC field staff (Garland, 2014), although not to the same rigor as an NTSB accident investigation (not being a federal agency with regular access to the resources of the FBI) unless a particular incident triggers the NTSB, for instance an ATV striking and rupturing a natural gas pipeline.

The CPSC has argued that a complete ban on youth ATV model sales and ridership is not warranted, and an action to do so would be counterproductive. In effect, the genie is out of the bottle and there is now a public need for ATVs both for recreation and for work. To illustrate the point quantitatively, as of 2008 there were an estimated 6.9 million ATVs operating in the U.S (USDA, 2008), which is of the same order of magnitude as motorcycles with an estimated 12.2 million operational in 2018 (MIC, 2019). Rules and standards encouraging safe ridership by empowering the market to find solutions have been shown via correlations of injury statistics to various levels of rule enforcement to be more productive (CPSC, 2006) and places power in the hands of the consumer and the parent.

1.3.5 American National Standard Institute, Inc. (ANSI)

Formed in 1918, this private organization functions by "supporting the US voluntary standards and conformity assessment system and strengthening its impact, both domestically and internationally." It was a founding member of the International Organization for Standardization (ISO) and is the official US representative within that organization.

ANSI authored their first ATV-related standards in 1985 and has issued updates as recently as 2018. The latest version, ANSI/SVIA 1-2017, has been incorporated by reference (IBR) into the US Code of Federal Regulations (CFR) by the CPSC in section 1420. It is reviewed every 5 years for updates (Yager, 2015).

1.4 CPSC ATV Regulations / Consent Decrees

1.4.1 Evolution of Regulations Involving the CPSC

Table 1.1 below summarizes changes to regulations, standards (mandatory and voluntary), and various communications issued by the CPSC.

Table 1.1 History of CPSC Regulations Pertaining to ATVs

Year	**Type**	**Description**
1984	Directorate Communication	Proposed stop sale of 3-wheel ATVs
1985	Proposed Rulemaking & Action Plan	• ATV Task Force established • Hazard and other analyses ordered • Monitor voluntary standard development • Monitor ATV industry's education and training efforts • Hold 5 public hearings to solicit input
1988	Consent Decree	• Stop sale of 3-wheeled ATVs • Training free of charge • Public awareness campaign • Improved labeling and documentation • Hotline for ATV-related consumer inquiries • Outreach program for safety materials to consumer groups • Age recommendations to prevent riding the wrong-sized ATVs, based on engine size Applies only to Honda, Yamaha, Suzuki, Kawasaki, and Polaris Compliance monitored through distributor surveillance
1996	Consent Decree Update	Arctic Cat joins the Consent Decree
1998	Consent Decree Expiration	
1998	ATV Action Plan	Voluntary extension of 1988 Consent Decree by SVIA. Applies only to Yamaha, Kawasaki, Suzuki, Polaris, and Arctic Cat.
1999	ATV Action Plan Update	Bombardier joins the voluntary extension
2006	Proposed Rulemaking	• Universal ban of 3-wheeled ATVs • Age guidelines based on speed • Lights either required or barred • Separate tandem ATV class • Brake performance • Pitch stability • Required labeling and documentation

Table 1.1 History of CPSC Regulations Pertaining to ATVs (continued)

Year	Type	Description
2008	CPSIA Requirements for ATVs	• Mandates the ANSI/SVIA 1-2007 standard • Each ATV manufacturer and distributor must file an Action Plan (ATV safety-related actions) similar to Consent Decree. • Manufacture, import, and sale of 3-wheeled ATVs banned • CPSC must consult with NHTSA for multiple-factor categorization of youth ATVs
2008	CPSIA Requirements for ATVs (cont.)	• GAO required to calculate costs associated with ATV-related accidents and injuries
2012	CPSC Rulemaking	Updated vehicle standard to ANSI/SVIA 1-2010
2018	CPSC Rulemaking	Updated vehicle standard to ANSI/SVIA 1-2017

In 2005, Polaris was ordered to pay $950,000 for a violation of the voluntary ATV Action Plan and federal law regarding immediate disclosure of suspected product defects. It had failed to report in a timely manner two issues: an issue where a defect in the throttle control would result in the throttle becoming stuck in the open position, and a second issue with the oil line bursting and spraying hot pressurized oil. Polaris had learned of 88 incidents of throttle sticking between 1998 and 2000, which resulted in 19 reported crashes and 7 reported injuries. For the oil line issue, they received 1450 incident reports between 1999 and 2001 with 18 reported injuries (CPSC, 2005). The throttle sticking issue is shown in Chapter 3 to be extraordinarily dangerous, as depending on the terrain in the immediate vicinity of the incident it may become difficult or impossible to avoid an unsafe operating condition before a rider is able to safely turn off the ignition or dismount / abandon the vehicle.

1.4.2 Initial 1988 Consent Decree Age Recommendations

Table 1.2 Initial (1988) CPSC Age-Related ATV Guidelines

Age Range	Engine Size	Other Factors
Under 12	Not recommended	None
12 to 15	70cc	None
16 and Older	90cc	None

1.4.3 Current CPSC Regulations

Summarized below in Table 1.3 and Table 1.4 are the current ATV design regulations enforced by the CPSC, which are encoded in 16 CFR § 1420. As mentioned in section 1.3.6, the details are incorporated by reference from ANSI/SVIA 1-2017. There are four bike size categories (Y6, Y10, Y12, and Y14) and two levels of top speed regulations.

The governed speed is permitted to be device-limited, but the max speed must be controlled mechanically (i.e. through an engine redline) should the governor fail or be removed.

Table 1.3 Current (2017) CPSC Age-Related ATV Guidelines

Age Range	**Engine Size**	**Top Speed (Governed / Max)**
6 to 9 (Y6)	No limit	10 mph / 15 mph (6.71 m/s)
10 to 11 (Y10)	No limit	10 mph / 15 mph
12 to 13 (Y12)	No limit	15 mph / 30 mph (13.41 m/s)
14 to 15 (Y14)	No limit	15 mph / 30 mph
16 and Older	No limit	No limit

Table 1.4 Current (2017) CPSC ATV Design Guidelines (CPSC, 2006) (ANSI/SVIA 1-2017)

Factor	**Requirement**
Max speed	Limited by engine/transmission, not governor
Operator foot environment	Sufficient to reduce inadvertent contact with ground or the wheels
Pitch stability	45 degree minimum tilt for single-rider ATV without rider, and with highest recommended tire pressure
Lateral stability	None
Labeling	
Headlights	Mandatory for adult ATVs to accommodate nighttime riding. Two each for ATV width over 1.5m. Headlamps and forward-facing DRLs disallowed on youth ATVs to discourage nighttime riding.
Tail lights	Recommended for youth ATVs
Speed limiting devices	Child models must require the simultaneous use of two different tools to adjust or remove
Transmission	Child models automatic only
Number of wheels	Three-wheeled ATVs banned from manufacture, import, or sale
Handlebars	Minimum edge radius >3.2mm. Crossbars must be padded.
Brakes	Minimum 0.6g average from max speed, after fade Both front and rear brakes operated by either a pedal near the right footrest or by a single level on the left side of the handlebar and operable without removing the hand from the handlebar or by both
Seats	Child models feature single rider only Adult tandem capability specially designated

1.5 Limitations of Current Governance

The basic issue with the current governance / regulation structure over ATVs in the US is that poor problem identification begets incomplete solutions. It is a commonly encountered dilemma in engineering where the response to a problem is based on an incomplete root cause analysis, followed by poorly executed generation of corrective actions. Also, the response surface is complicated in that the CPSC can enforce rules for manufacturers, but only states can drive improved rider behavior.

1.5.1 Lack of Fit Requirement versus Speed Requirement

While it is important to limit, as the CPSC has done, the speed and power available for inexperienced riders (as shown in Chapter 3), this does not address the equally important parameter of fit (as shown in Chapter 2). On the matter of fit, the CPSC relies on hope and optimism: “By eliminating the engine size restriction, manufacturers will be able to produce a variety of ATV models that meet speed restrictions but are more appropriately sized to account for the wide variation in physical dimensions of young people. By having the option of riding better-fitting ATVs that are not performance-limited by undersized engines, CPSC believes that more youth will ride age-appropriate and speed-restricted ATVs rather than gravitating toward adult ATV models.” (CPSC, 2006).

The CPSC did note more study was merited on the technical issues surrounding possible ATV design changes in order to address dynamic stability, rollover propensity, and individual rider fit (Ibid). Hence, original research documents such as this one play an important role in influencing the discovery of the root cause of problems and suggesting corrective actions both for manufacturers and usage regulations.

1.5.2 Lack of Uniform Accidental Injury Reporting System

As stated in section 1.3 on page 4, among US governmental agencies, the CPSC carries the responsibility of oversight for the regulation of commerce (supporting the power of the US Congress per Article 1 Section 8 of the US Constitution) for consumer goods which as defined in US Code 16 CFR 1420 includes ATVs, and therefore even though they are vehicles, ATVs do not fall under the realm of the federal Department of Transportation. As such, ATVs do not ordinarily benefit from the comprehensive recordkeeping system and investigative capability of the NHTSA.

For the benefit of the public the CPSC operates an open-access database that is built upon the records from a representative survey of emergency departments in the United States, the National Electronic Injury Surveillance System (NEISS). While the reach of the NEISS is broad and by CPSC’s own estimate a “statistically valid” sampling (CPSC, 2019), the data gathered is fairly generic and limited in scope. Each record (CPSC, 2018) consists of:

- Treatment date
- Product(s)
- Sex
- Age
- Race
- Location where the injury occurred
- Intentional infliction
- Fire involvement
- Work related
- A brief narrative/commentary describing the incident

- Affected body part(s)
- Diagnosis
- Disposition

All fields except for the narrative are numerically coded, which again limits the specificity of the data gathered where it may concern an ATV-related injury versus, for argument's sake, a chainsaw-related injury. As an example, the location of injury has only 10 entries: Home, Farm/Ranch, Street or highway, Other public property, Manufactured home, Industrial place, School, Place of recreation of sports, or Not recorded. For ATV-related injuries, these location entries are not particularly enlightening; this imprecision is a missed opportunity to home in on details pertinent to ATV ridership and usage. Suggestions for improvement are highlighted in Chapter 4.

1.5.3 State Guidelines Inconsistent

The CPSC has maintained a non-answer to the concern of inconsistency in state regulations, only noting the "critical role [state and local legislation has] to play in any strategy to address the risk of injury and death associated with ATVs." (CPSC, 2006) This statement is in recognition of the limitations of the CPSC in respect to the 10th Amendment to the US Constitution, where in the US's republican model the individual states have the final authority of setting regulations for usage (but not import or inter-state sale) of ATVs within the bounds of that state. By analogy, this model of regulation is in line with state-based licensure for operation of automobiles on public roads.

Chapter 4 goes into further details of the various levels of inconsistency, but the net effect is that there is no steady signal to the ATV industry or the Congress/CPSC for setting a new, safer direction for ATV design or usage. To date no state or group of states as represented by their attorneys general has been willing to step up to the plate to significantly challenge any manufacturer, contravene any other state, or contest any CPSC-overseen regulation (or gap therein).

1.6 Apparatus Design, Sourcing, and Construction

In order to tie together the methods sections of Chapter 2 and 3, some exposition is required. An ATV tilt table was originally constructed as part of Chapter 2 to examine the effects of inclination and declination on ATV rider fit parameters. Unexpectedly, no statistically significant results were found that directly related the forward-backwards tilt of the ATV to rider fit. Unlike Chapter 2, Chapter 3 was primarily enabled through the usage of the tilt table, upon which the author relied to measure several physical properties of ATVs.

The design schematic for the tilt table is contained in section 2.4.5 on page 19. The apparatus was designed by James Auxier according to the requirements in Table 1.5.

Table 1.5 Design requirements for the ATV tilt table.

Design Requirement	**Metric**
Minimum load capacity	1500 lbs. (680.4 kg)
Tilt angle range	0 to 30°
Angular resolution	0.1°
Tie down axial adjustment	1 in. (2.54 cm)
Overhead clearance	7 ft. (213.36 cm)
Width	4 ft. (121.92 cm)

The bill of materials for the studies in Chapters 2 and 3 is contained in section 2.4.4 on page 15. Lumber and common building materials were procured and delivered by Dr. Andrew Bernard. Less common materials were procured through McMaster-Carr by James Auxier and delivered via UPS / FedEx. ATVs were rented and transported by Dr. Andrew Bernard and Bradley Griffits. Medical devices were provided by the Kentucky Clinic and administered by Jennifer Forman.

Construction was performed in the UK Wenner-Gren Biodynamics Lab by James Auxier and Jerry Fields. Construction equipment was property of James Auxier.

2. Chapter 2 – Pediatric Anthropomorphic Interaction with ATVs

2.1 Preface

The majority of the text below is extracted from the author's 2010 publication in Accident Analysis & Prevention (Bernard, 2010) with formatting changes to fit this dissertation as well as several additions to the Methods section. The author of this dissertation was the primary contributor to the methods, results, and conclusion sections. It is of note that this original research was submitted for publication at the end of 2009, so as a snapshot in time subsequent minor changes to regulatory information and injury statistics as described in Chapter 1 since the 2010 publication have occurred.

2.2 Abstract

Background/purpose: This study sought to establish objective anthropometric measures of fit or misfit for young riders on adult and youth-sized all-terrain vehicles and use these metrics to test the unproved historical reasoning that age alone is a sufficient measure of rider-ATV fit.

Methods: Male children (6–11 years, n = 8; and 12–15 years, n = 11) were selected by convenience sampling. Rider-ATV fit was quantified by five measures adapted from published recommendations: (1) standing-seat clearance, (2) hand size, (3) foot vs. foot–brake position, (4) elbow angle, and (5) handlebar-to-knee distance.

Results: Youths aged 12–15 years fit the adult-sized ATV better than the ATV Safety Institute recommended age-appropriate youth model (63% of subjects fit all 5 measures on adult-sized ATV vs. 20% on youth-sized ATV). Youths aged 6–11 years fit poorly on ATVs of both sizes (0% fit all 5 parameters on the adult-sized ATV vs 12% on the youth-sized ATV).

Conclusions: The ATV Safety Institute recommends rider-ATV fit according to age and engine displacement, but no objective data linking age or anthropometrics with ATV engine or frame size has been previously published. Age alone is a poor predictor of rider-ATV fit; the five metrics used offer an improvement compared to current recommendations.

2.3 Introduction

All-terrain vehicle (also ATV and quad-bike) recreation is one of the fastest-growing motorsports in the United States, but ATV crashes are associated with significant morbidity and mortality (Concerned Families for ATV Safety, 2007; Consumer Product Safety Commission, 2007). ATV crash-related deaths have risen from less than 300 in 1998 to almost 900 annually (Streeter, 2008b). Children are an important subset of this population and ATV use by youths under 16 years is increasing (Consumer Product Safety Commission, 2007; Streeter, 2008a).

Reliable information regarding the incidence and mechanism(s) of ATV crashes is lacking because unlike automobiles, no uniform reporting system exists for ATV incidents. Existing ATV crash information has been obtained from sporadically collected arbitrarily reported incidents recovered from the lay media. Available injury and fatality data are therefore believed to be lower level estimates due to under-reporting. A national estimate indicated that more than 35,000 children visited the Emergency Department annually in the period 2001–2003 (Shults et al., 2005). Current data for the number of children injured are likely greater because this injury rate estimate increased 25% over the 3-year period noted. Similarly, the reasons by which youths are injured are also largely unknown. The few publications that exist attribute youth-related ATV crashes to lack of physical or mental ability to safely operate ATVs (Brandenburg et al., 2007; Graham et al., 2006). Some of the factors associated with unsafe operation include poor terrain choice, lack of protective gear, riding tandem and inability to have complete control of the ATV under the prevailing conditions (Brandenburg et al., 2007). Safe operation of an ATV depends upon many factors which include; training, experience, supervision, developmental stage, vehicle condition, and rider-vehicle fit. Fit of the operator to any vehicle, motorized or not, is considered by most to be the first step in promoting safe operation. Fit of the rider to the ATV is no exception. Significant mismatch between the dimensions of the rider and the ATV reduces the rider's ability to control the ATV. Rider-ATV fit relationships; however, have not been scientifically determined or published in the peer-reviewed literature. Rider-ATV fit thus appears subjective, often illogically influenced by vehicle availability.

Some argue that logic, rather than rider-ATV fit, should be the first order of safe ATV operation. If individuals always based their decisions on logic, then "Danger No Trespassing" signs would be all that is needed to prevent injury at electric power substations. Clearly, tall chain-link fences and barbed wire accompany those signs and are effective physical reminders that one should not ignore reason. Similarly, ATV frame sizes and designs provide a physical impediment to vehicle operation that to some may be more persuasive than logic. Because youths will ride ATVs regardless of regulations, information regarding proper rider-ATV fit, and its relationship to ATV control, is needed to educate the public and minimize the frequency or severity of mishaps due to differential size-related loss of ATV control. As with every human conveyance, including ATVs, the first rule of safe operation is that the operator should fit the configuration of the vehicle so that safe operation, through complete control of the vehicle, has been enabled (National 4-H Council, 2005).

Current recommendations for ATV fit are based upon youth age and ATV engine size guidelines from the Consumer Product Safety Commission (2009) and All-Terrain Vehicle Safety Institute (2009; ATVSI is a division of the Specialty Vehicle Institute of America). These recommendations have been adopted and expanded by safety advocacy organizations, including the National 4-H Council (2005). These include: (1) minimum of 3–6 in. clearance between seat and inseam which permits "posting" (vertical elevation of the pelvis from the seat) and helps the rider retain vehicle control while traversing rough terrain, (2) thighs roughly horizontal while sitting (allows range of motion for "posting"), (3) distal metatarsal joints ("ball of foot") should rest comfortably on the foot–brake, (4) hand size and grip strength should be sufficient to enable throttle control and brake lever actuation, and (5) elbow angle should exceed 90◦, but should not be "too straight" (permits adequate steering range and thus obstacle avoidance).

The ATVSI (2009) recommends that children aged 6–11, 12–15 and≥16 years should be limited to ATVs with engine displacements of <70cc, <90cc, and unlimited, respectively. Objective standards for the fit of these children on ATVs are confounded by size variability among youngsters in these age categories as well as actual ATV frame sizes (engine size only approximately correlates with frame dimensions). Although no objectively validated engine size metric for proper rider-ATV fit has been published, these seemingly arbitrary age–engine displacement recommendations have been largely accepted as fact and have been incorporated into the policy statements of some prestigious organizations (American Academy of Orthopaedic Surgeons, 2009) and become incorporated into law in some states, e.g. Texas (Texas Department of Public Safety, 2000) and Pennsylvania (Operation of ATVs by Youth, 2009). Therefore, the present study sought to determine if these age–engine displacement recommendations are valid for predicting whether a child of a given age category can properly fit (as a driver in full control) of a youth- or adult-sized ATV.

2.4 Methods

2.4.1 Study design

A prospective, interventional three-variable (age group, ATV size, and ATV inclination angle) laboratory study was used to quantify the anthropometric fit of male children to youth- and adult-sized ATVs. No prior studies were available from which a sample size could be calculated; therefore, an estimated 10 subjects per age group was targeted at the commencement of the study.

2.4.2 Study subjects

Subjects were recruited over a 3-month period while school was in recess for the summer by using printed and oral advertisements promulgated via faculty and staff of the study institution's medical center. Because of the predominance of young males in a study of Emergency Room visits (Shults et al., 2005), the inclusion criteria were: males; 6–15 years old who were able to participate in physical education without restriction. Subjects were separated into two age groups, 6–11 years (hereafter the young subjects) and 12–15 years (hereafter the older subjects), based on previously established age categories pertinent to rider-ATV fit (National 4- H Council, 2005). None of the study subjects were experienced ATV riders, but subjects had some knowledge of ATVs. All study procedures were approved by the authors' Institutional Review Board. One or both parents of the subjects were present during the study. Written informed consent was obtained from the patient or guardian and an assent from the subject was obtained prior to the commencement of any study procedures. A modest time-effort reimbursement was provided to subjects.

2.4.3 Description and operation of experimental apparatus and ATVs

One youth-sized ATV (Kawasaki KFX90, 89cc engine) and one adult-sized ATV (Honda TRX500FM, 475cc engine) were used. The frame size of the Kawasaki KFX90 (89cc engine) was also used on the Kawasaki KFX50 (49.5cc engine) and thus the KFX90 served as a single relevant test frame for both the young and older subjects (Specs for the Kawasaki, 2008; Martin-Du-Pan, 2008). ATV's were each fitted with 13 retroreflective markers placed on the left and right: front/rear wheel axles; lateral point of handlebars, front/rear fenders and foot–brake pedal, and midpoint of the handlebars. A custom-designed and built wooden inclination/declination platform was used to evaluate rider position as a function of ATV riding (static) angle (Figure 2.4, Figure 2.5, and Figure 3.1). This platform had U-shaped bolts at each of the four corners of this platform. These U-shaped bolts were connected to lever-actuated strong nylon "ribbon" hold-downs that had "S"-shaped hooks on each end. The other end of the hold-downs was connected to the front suspension arm or rear axle of the ATVs so that the ATV was secured to the platform and did not move regardless of the angle of inclination. The platform was designed and constructed to securely hold the rider and ATV throughout a range of angles from −30° (inclined) to 30° (declined).

2.4.4 Experimental Apparatus bill of materials

1) All-Terrain Vehicle #1 (Adult)

Figure 2.1. Adult-Sized ATV Honda TRX500FM Foreman 2WD

Manufacturer: Honda
Year: 2008
Model: TRX500FM Foreman 2WD
Mass (dry): 281 kg
Quantity: 1
(Image Courtesy: Honda Motor Corporation)

2) All-Terrain Vehicle #2 (Youth)

Figure 2.2. Youth-Sized ATV Kawasaki KFX90

Manufacturer: Kawasaki
Year: 2008
Model: KFX® 90
Mass (dry): 115.2 kg
Quantity: 1
(Image Courtesy: ATV.com)

3) Precise position lifting winch, 1200-2000 lb. rating
Vendor: McMaster-Carr
Item: 3732T15
Quantity: 1

4) Wire rope with hook
Vendor: McMaster-Carr
Item: 3307T57
Dimensions: 5/16” diameter x 25’ length
Quantity: 1

5) Pulley with removable wheel
Vendor: McMaster-Carr
Item: 3099T21
Quantity: 2

6) Hardened AISI 1566 steel solid shaft
Vendor: McMaster-Carr
Item: 6061K85
Dimensions: 1” OD x 60” length
Quantity: 1

7) Base-mount steel rotary shaft bearings
Vendor: McMaster-Carr
Item: 5913K44
Quantity: 9

8) U-bolts
Vendor: McMaster-Carr
Item: 8880T37
Dimensions: 1/2”-13 thread x 3” thread length
Quantity: 10

9) Hex carriage bolts, Grade 5
Vendor: McMaster-Carr
Item: 91247A241
Dimensions: 3/8”-24 x 5.5”
Quantity: 8

10) Eye bolts, 2600 lbs. rating
Vendor: McMaster-Carr
Item: 3014T913
Dimensions: 1/2"-13 thread
Quantity: 3

11) Hex lag screws
Vendor: McMaster-Carr
Item: 91478A640
Dimensions: 3/8” thread x 3” length
Quantity: 100 (2 boxes of 50)

12) Hex lag screws
Vendor: McMaster-Carr
Item: 91478A732
Dimensions: 1/2" thread x 5”
Quantity: 30 (3 boxes of 10)

13) Hex nuts, Grade 5
Vendor: McMaster-Carr
Item: 95505A613
Dimensions: 3/8”-24 thread
Quantity: 200 (2 boxes of 100)

14) Hex nuts, Grade 5
Vendor: McMaster-Carr
Item: 95045A033
Dimensions: 1/2"-13 thread
Quantity: 50

15) Washers, zinc-plated
Vendor: McMaster-Carr
Item: 90126A031
Dimensions: 3/8” ID
Quantity: 280 (2 boxes of 140)

16) Washers, zinc-plated
Vendor: McMaster-Carr
Item: 90126A033
Dimensions: 1/2” OD
Quantity: 110 (2 boxes of 55)

17) Digital angle indicator
Vendor: McMaster-Carr
Item: 3353A77
Quantity: 1

18) 2x4 dimensional lumber
Vendor: Lowe’s
Specifications: Pressure-treated pine, square-edge, 8 ft. length
Quantity: 8

19) 3/4" plywood
Vendor: Lowe’s
Specifications: Decking-rated, 5 ft. x 8 ft.
Quantity: 3

20) 4x4 dimensional lumber
Vendor: Lowe’s
Specifications: Pressure-treated pine, square-edge, 8 ft. length
Quantity: 10

21) 4x6 dimensional lumber
Vendor: Lowe’s
Specifications: Pressure-treated pine, square-edge, 8 ft. length

22) Post caps
Vendor: Lowe’s
Manufacturer/Brand: Simpson Strong-Tie
Item: LCE4
Quantity: 4

23) Post caps
Vendor: Lowe’s
Manufacturer/Brand: Simpson Strong-Tie
Item: AC4
Quantity: 2

24) Wood drill bit
Vendor: Lowe’s
Dimensions: 1” cutter
Quantity: 1

25) Fastening screws
Vendor: Lowe’s
Manufacturer: Simpson Strong-Tie
Dimensions: 2” length
Quantity: 1 box

26) #2 Pencils
Vendor: Lowe’s
Quantity: 2

27) Variable-size grip dynamometer

Figure 2.3. Grip Dynamometer, Image for Example Purposes Only (Image Courtesy: Amazon.com)
Usage provided by University of Kentucky Medical Center
Quantity: 1

2.4.5 Experimental Apparatus Design Layout

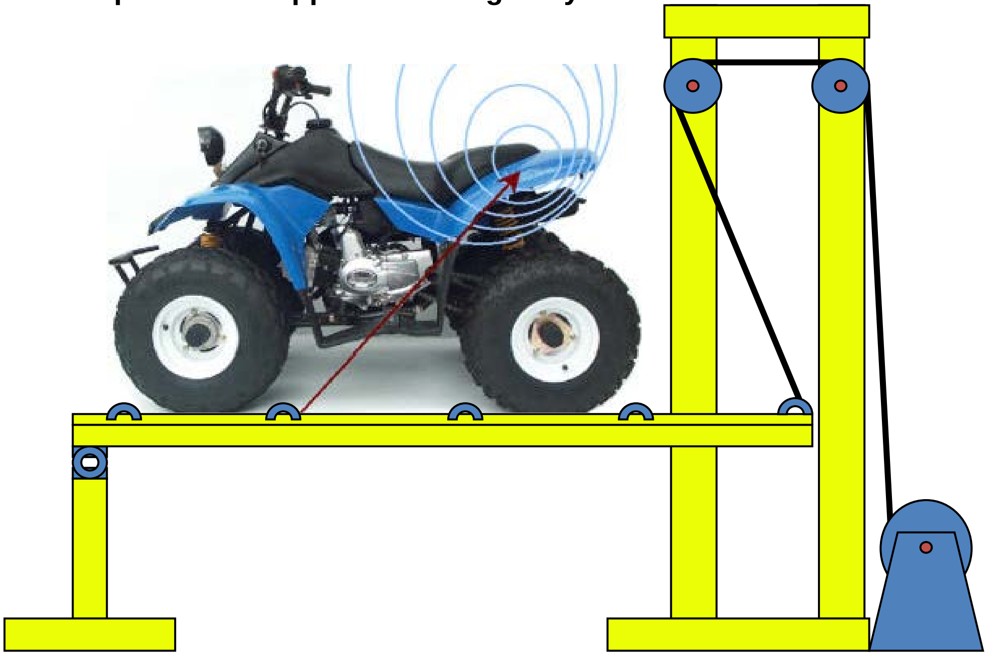

Figure 2.4. Simplified Schematic of Assembled Lift Table, Side View.

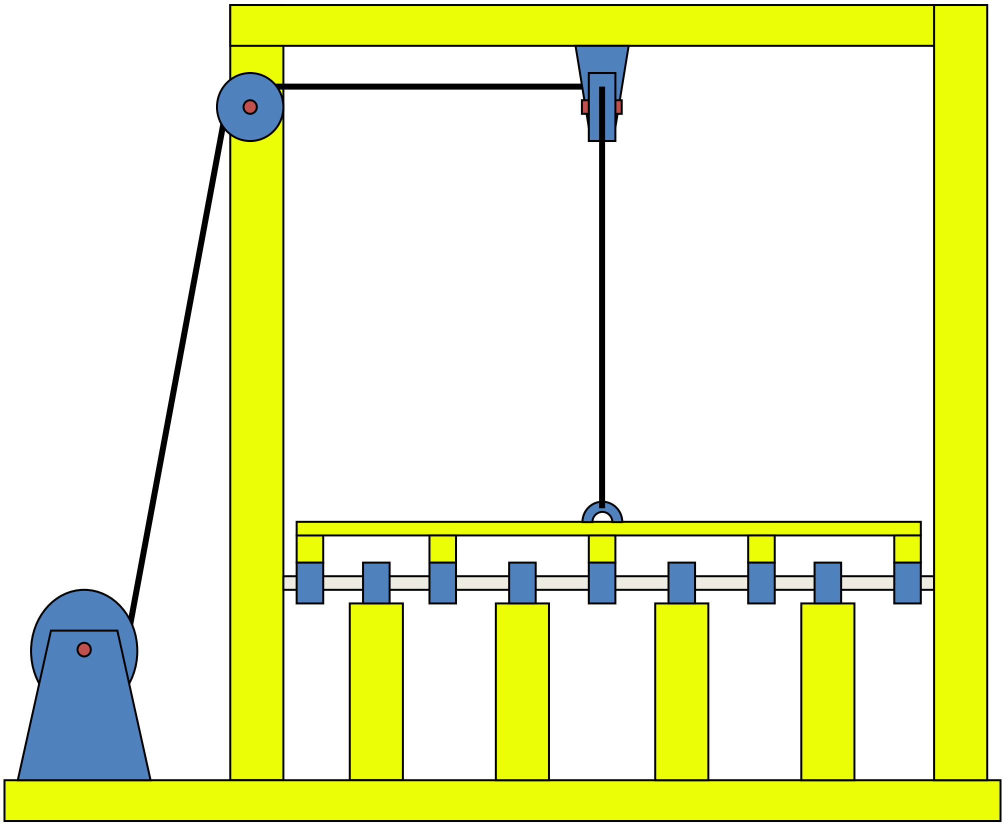

Figure 2.5. Simplified Schematic of Assembled Lift Table, Front View.

2.4.6 Experimental procedures

To quantify the anatomical position and anthropometrics of each subject as they sat on each of the two different sized ATVs, a total of twenty-three round (12.5mm diameter) retroreflective optical markers were placed on each subject according to the Helen Hayes recommended anatomical landmarks (fore-foot, hind-foot, ankle, knee, hip, pelvic wing, hand, wrist, elbow, shoulder, lumbar spine, front and back of head) (Kadaba et al., 1990).

Subjects were asked to mount the ATV, assume a normal riding position, and sit with hands and feet comfortably placed in their proper positions as if they were preparing to ride the ATV. Subject safety was a major concern, and to this end, all subjects wore an appropriately sized motorsports helmet and a chest harness that was connected to a safety line. This safety line was routed through an overhead pulley to a study assistant whose full-time study assignment was to monitor the position of the subject and provide slack, or belay the rope, as necessary for subject safety and proper experimental conduct.

The custom-designed and built wooden inclination/declination platform was used to evaluate rider position as a function of static ATV riding angle (Figure 2.4, Figure 2.5, and Figure 3.1). Inclination or declination of this platform was varied from−30° (inclined) to 30° (declined), in 5° increments, for each rider and ATV frame size. Three-dimensional body segment positions and angles were measured by using 12 Eagle and Eagle-4 digital motion capture cameras with Cortex v1.0 software (Motion Analysis Corporation, Santa Rosa, CA).

2.4.7 Quantification of fit and data analyses

The three-dimensional anthropometric and position data of the subjects and ATVs were analyzed by using a commercially available numerical computing software platform that allowed ready data manipulation (Matlab, v2008b; Mathworks, Natick, MA). The objective standard for rider-ATV fit was determined from the National 4-H Council (2005) guidelines. These guidelines consisted of five anthropometric measures of fit: (1) handlebar–knee distance, (2) hand size compared to ATV brake grip-size, (3) brake–foot position, (4) standing-seat clearance and (5) elbow angle. Fit “success” criteria for each parameter were: (a) handlebar–knee distance >200mm, considered necessary to reach the handlebars and steer around obstacles; (b) hand size versus ATV grip-size was based upon the ability of the rider to grip a variable-size hand strength dynamometer (grip length was set to the average distance from the rear of the handlebar grip to the front of the brake lever – if the rider’s hand size was insufficient for this grip dimension and no force could be exerted on the grip dynamometer, then a binary “no-fit” (0%) score was assigned – a score of 100% was given to each subject if they could exert any force on the grip dynamometer); (c) brake–foot position ratio was calculated as the percentage distance from the “ball” of foot (at its most rearward position in the ATV’s foot well) to the brake pedal divided by the length of the foot—a brake–foot position score greater than 105% indicates an excessive distance between the foot and the foot–brake and thus a risk for ineffective foot–brake operation; (d) standing-seat clearance was measured from the inseam—a value greater than 150mm allows the rider to raise the torso up from the ATV seat (posting) to maintain balance and avoid distracting longitudinal torso impacts that occur when the ATV traverses rough terrain; and (e) elbow angle of 90–135° (<90° indicates excessive arm flexion and the rider’s torso is too close to the handlebar; >135° indicates the arms are excessively straight due to the grips being too far apart which in turn requires the youthful rider to lean the torso to the outside of the turn to achieve an adequate range of handlebar turning).

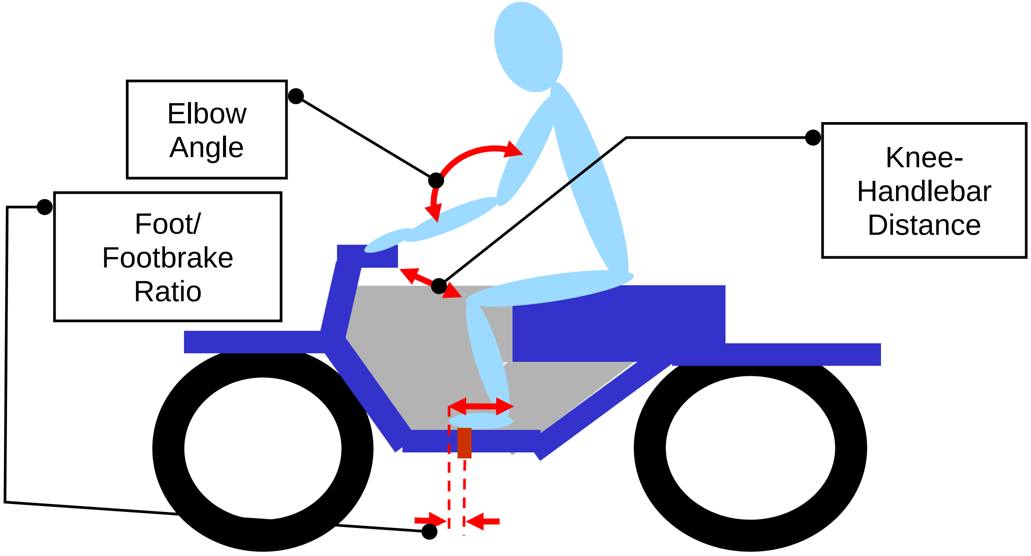

Figure 2.6. Visual Depiction of ATV-Rider Fit Measures for Elbow Angle, Foot/Footbrake Ratio, and Knee-Handlebar Distance.

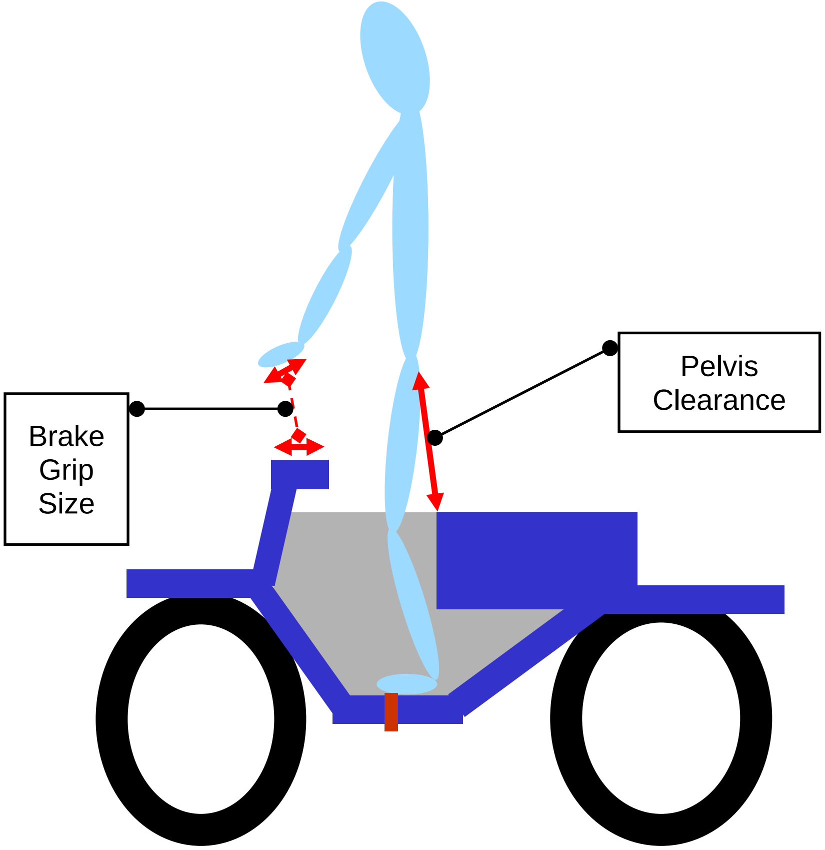

Figure 2.7. Visual Depiction of ATV-Rider Fit Measures for Brake Grip Size and Pelvis Clearance.

2.4.8 Statistical Analyses

The Shapiro–Wilks test was used to test for data normality. Parametric data were analyzed by using a three-way (vehicle size, age group, incline/decline angle) repeated measures ANOVA and comparisons were made between groups using Welch's t-test. P-values less than 0.05 were considered indicative of significant differences.

2.5 Results

2.5.1 Subject weight and height variability

Subject weight and height varied within each age group. The young subjects (n=8) had a mean ± standard deviation weight of 40.6 ± 16.9 kg (range 22.6 – 65.8 kg), and a mean height of 139.8 ± 16.7 cm (range 118.1 – 157.5 cm); the older subjects (n=11) weighed 60.4 ± 17.2 kg (range 36.3 – 88.5 kg) and were 166.8 ± 9.5 cm (range 153.7 – 181.6 cm) tall. The young subjects were 32.7% lighter (p=0.0095) and 16.2% shorter (p=0.0008) than older subjects. Weights and heights also varied more within the young subjects than within the older subjects: coefficients of variation (standard deviation / mean) of subject weight and height were 41.6% and 11.9% in the young group as compared with the corresponding weight and height values of 28.5% and 5.7% in the older group.

2.5.2 Fit of the young subjects on youth and adult-sized ATVs

Handlebar-knee distance was inadequate for 2 of the 8 (25%) young subjects when they were seated on the youth-sized ATV: this was attributed to the exceptional height of these subjects. Five of the 8 young subjects (62.5%) were able to exert a force on the grip dynamometer (width matched the dimensions of the youth-sized ATV's hand brake grip); the other 3 subjects (37.5%) were unable to properly grip the brake lever and thus could not exert any braking force on the age-recommended youth-sized ATV (Table 2.1). Brake-foot position and pelvic-seat clearance were within the recommended range for 6 of the 8 (75%) young subjects when seated on the youth-sized ATV. Mean elbow angle (150 ± 25°) observed from 7 of the 8 subjects (88%) young subjects seating on the youth-sized ATV was greater than the recommended 90 - 135°.

Table 2.1 Fit of Younger (6-11 Years) Test Subjects on Youth and Adult-Sized ATVs.

	Steering	**Braking**		**Body Control**	
	Handlebar-Knee Distance	**Hand Size**	**Brake-Foot Position**	**Pelvis Clearance**	**Elbow Angle**
Criteria	**>200mm**	**100%**	**< 105%**	**> 150mm**	**90 - 135°**
Youth ATV	224 ± 55mm	62.5%	94 ± 20mm	230 ± 102mm	150 ± 25°
	75%	62.5%	75%	75%	12.5%
Adult ATV	377 ± 41mm	62.5%	116 ± 58mm	133 ± 79mm	149 ± 22°
	100%	62.5%	25%	25%	0%

None of the young subjects met all of the size parameters for the adult-sized ATV. The handlebar-knee distance was the only anthropometric fit parameter that fell within the acceptable range when all of the young subjects were seated on the adult-sized ATV. Given their shorter (compared to the older subjects) leg lengths, this finding was unsurprising. Adequate foot position and posting clearance were each met by only 2 of the 8 (25%) young subjects when seated on the adult-sized ATV.

2.5.3 Fit of the older subjects on youth and adult-sized ATVs

Only 2 of the 11 (18%) older subjects met all of the anthropometric fit criteria on the youth-sized ATV: failure of the other 9 subjects was primarily due to inadequate handlebar-knee distance (Table 2.2). All of the older subjects met the hand size and pelvis clearance guidelines for both ATVs. Only one, particularly small-statured subject of the 11 older subjects failed to meet the elbow angle criterion on the adult-sized ATV. Foot position was more consistent on the foot pedal of the youth-sized ATV but was still adequate in the majority of the older subjects when seated on the adult-sized ATV. As a group, the older subjects fit the adult-sized ATV in every category better than the youth-sized ATV.

Table 2.2 Fit of Older (12-15 Years) Test Subjects on Youth and Adult-Sized ATVs.

	Steering	Braking		Body Control	
	Handlebar-Knee Distance	**Hand Size**	**Brake-Foot Position**	**Pelvis Clearance**	**Elbow Angle**
Criteria	**>200mm**	**100%**	**< 105%**	**> 150mm**	**90 - 135°**
Youth ATV	197 ± 21mm	100%	94 ± 7mm	374 ± 64mm	112 ± 30°
	20%	100%	91%	100%	100%
Adult ATV	343 ± 29mm	100%	102 ± 24mm	257 ± 84mm	123 ± 26°
	100%	100%	64%	100%	91%

The angle of the ATV tilt had no relationship to any of the measured anthropometric fit parameters, and thus the data were not stratified by angle. All data shown were obtained from the mean of 13 different angles of youth and adult-sized ATV tilt angles.

2.6 Discussion

Table 2.3 Percentage of Subjects in Each Age Group Fitting Each Category of ATV.

Fit	Age 6-11	Age 12-15
Youth ATV	13%	18%
Adult ATV	0%	64%

2.6.1 Key findings

The key findings of this study were: (1) according to the anthropometric size parameters adapted from the National 4-H Council (2005), only one of eight 6-11-year-old children and two of eleven 12-15-year-old children fit the age-recommended ATV, (2) as a group, the older subjects (youths aged 12-15 years) fit the adult-sized ATV in every category better than the recommended youth-sized ATV, and (3) none of the 6-11-year-old children met all fit criteria on an adult-sized ATV.

2.6.2 Discussion of key findings

Rider-ATV misfit is important because children suffer a disproportionately large mortality rate relative to adults in ATV crashes (Altizer, 2008; Sue et al., 2006). The reasons for this discrepancy are unknown and are only slowly emerging as studies become sporadically available (Consumer Product Safety Commission, 2007; Moore and Sabella, 2007). Such studies have shown that rollovers on flat and uneven surfaces are more common in children (Brandenburg et al., 2007; Helmkamp et al., 2008) and that fractures are the most common injury observed in young riders (Shults et al., 2005; Kirkpatrick et al., 2007). Fracture sites in young ATV riders also appear to vary with age category: older (age 13-15 years) youths were more likely to sustain pelvic fractures while children 12 years and younger were more likely to sustain lower extremity fractures (Kellum et al., 2008; Thompson et al., 2008). Because crash mechanisms and injury types are functions of rider age category and other factors, the dynamics of youth-ATV accidents are likely complex but possibly predictable.

Industry guidelines recommend against use of ATVs by youths less than 6 years or operation of adult ATVs by youths aged 6-15 years. The first recommendation is supported by the present findings, but the latter is only partially supported because some youths aged 6-15 years fit upon an adult-sized ATV better than a youth-size ATV. Although the present data showed that older youths (12-15 years) may have a better anthropometric fit upon and adult-sized ATV frame, this can create a potentially dangerous sense of security given their lack of maturity and (likely) limited ATV riding experience. In this regard, engine displacement (power) restrictions may serve a useful role. Clearly, the definition of rider-ATV fit is more complex than previously realized and this has implications for ATV design, manufacturing, marketing, sales, and training.

Guidelines based upon engine size have the advantage of simplicity, but there is only a loose associate between engine size and frame size. This already loose association is further complicated by lack of standards and ensuing variation in ATV size by model and year. Fit of rider to ATV is further confounded by varying height and body weight among young males of similar ages. Clearly there are children that may fit all, some, or none of these or other to-be developed anthropometric parameters. The results of the present study clearly show that rider-ATV recommendations must be based on parameters other than age alone.

Two unexpected observations were made regarding ATV design. First, handlebars on the youth and adult-sized ATVs tested were nearly identical in size, and this was supported by the data showing elbow angles that were similar on the two ATV frames when studied with the young subjects. Large observed elbow angles (straight arms) may have been accentuated by the more rearward seat position (greater longitudinal handlebar-center of seat distance) on the adult-sized ATV. Regardless of cause, excessive arm angles impair turning ability, even on the youth-sized ATV. This can compromise safe operation due to an inability to provide adequate steering angles (without excessive body leaning) that are needed to avoid obstacles. The importance of steering angle range increases with an increasing off-road terrain heterogeneity.

Second, a wide distance was observed between the handlebar grip and the brake lever on both ATV frames. Although this wide distance reduces the grip strength required for braking and allows gradual predictive brake force application, it prevents a young person with small hand size from rapidly applying the brakes (due to the need to release a secure purchase on the handlebars and rotate the hand to enable the upper extremity's naturally powerful "hook grip" to engage the brake lever). This problem has not been solved in the youth-sized ATV and remains a major reason why young riders (less than 6 years of age) or those with inadequate hand size should never ride any ATV.

2.6.3 Study limitations

This study has several noteworthy limitations. The anthropometric fit parameters used to quantify fit were only a first approximation, developed by using suggestions from the

Consumer Products Safety Commission (2009), the National 4-H Council (2005), as well as industry standards for rider-bicycle fit. Relationships among these parameters, rider-ATV fit, and safe ATV control are unproven. Also, rider-ATV fit was quantified based upon their fit on stationary vehicles; no aspect of riding dynamics was incorporated into the fit assessment protocol. While the experimental protocol used was an important first step in quantifying rider-ATV fit, it is incomplete. Additional parameters which arise from the dynamics of actual ATV riding must be considered.

Some may argue that the experimental protocol used, with numerous investigators and study assistants, clinical monitors, supervising parents, etc. may have confounded the reported measures of fit due to the Hawthorne effect (observer's paradox) whereby subjects act differently when in the laboratory under observation. Arguments against are based upon the objective parameters used to quantify fit; however, it is recognized that close supervision (particularly parental) may have inhibited subjects from adopting other body postures that would have mitigated against the usefulness of the fit parameters employed.

Sample size is frequently a subject of criticism, but the 19 subjects brought to endpoint were adequate to prove the conclusion that age alone is an inadequate metric for gauging rider-ATV fit.

Though some organizations (American Academy of Orthopedic Surgeons, 2009; Consumer Product Safety Commission, 2002; Department of Federal Affairs, 2009) and authors advocate a universal ban on ATV operation by youth, ATVs have arguably irreversibly leapt from the Pandora's box of powersports equipment. Focus group studies have shown that age limits are unlikely to reduce ATV use (Aitken et al., 2004) and therefore new knowledge regarding proper rider-ATV fit may offer a more efficacious method for improving the safety of those who decide to ride and ATV (Curran and O'Leary, 2008; Trauma Committee of the Canadian Association of Pediatric Surgeons, 2008). Additional measures may also be needed, beyond those of simple rider-ATV anthropometrics, to more accurate assess rider skill and appetite for risk, among other behavioral factors., in gauging who is safe to ride which ATV. Section 107 of the Consumer Product Safety Improvement Act of 2008 (Text of H.R., 2009) requires study of reportable injuries and deaths in minority children; given the use of ATVs by American Indians and Pacific Islanders, there exists further motivation for continuing studies.

2.7 Conclusions

2.7.1 Conclusions

Assessment of youth-ATV fit is amenable to quantitative study of anthropometric rider-ATV parameters. Additional opportunities exist to improve upon the metrics used to gauge which rider can safely operate which ATV (if any). Although the five metrics presently employed to quantify the ability of a youthful rider to steer and brake an ATV are unproven, they offer a point of departure for a tested set of metrics that improves upon the current age-engine displacement recommendations. A widespread evaluation of rider-frame fit, in addition to age-power limitation guidelines, should be studied and potentially implemented before ATV purchase or usage by any riders. Power limitations seem intuitively useful, but the present data clearly show that the current guidelines based solely upon age and ATV engine size are inadequate for determining whether or not a child under 16 years of age has the correct anthropometric dimensions that would allow them to safely operate an ATV.

2.8 Funding Source

Funds for this study were obtained from the University of Kentucky’s Center for Clinical and Translational Sciences in 2008 and 2009.

3. Chapter 3 – Interactions Among Human Factors and Vehicle Dynamics in Mechanics of ATV Rollovers

3.1 Preface

The text below for this chapter is from a draft manuscript (Auxier, 2020) with formatting changes to fit this dissertation. The author of this dissertation is the lead author of said manuscript and the primary contributor to all sections.

3.2 Abstract

Abstract pending final manuscript preparation for journal submission.

3.3 Introduction

All-terrain vehicle (ATV) injuries trigger more than 115,000 annual emergency department visits, 12,000 hospital admissions and 800 deaths (Breslau 2012; Helmkamp Pub H Rep 2009). Total annual costs of ATV injuries exceed $165 million (Breslau 2012). Males are injured twice as frequently as females and the adolescent age group, 11-15 years, accounts for 2/3 of all hospitalizations (Shults 2013).

The common, morbid nature of ATV collisions combined with their prevalence among youth has attracted attention aimed at developing preventive measures. Riding while intoxicated, riding on paved roadways, and riding without a helmet have been associated with increased risk of dying if involved in an ATV-related crash (Krauss 2010; Denning 2013). These data have led to pertinent cautions and new safety practices. Other injury mechanisms; however, remain problematic due to lack of study and information dissemination that offers the potential for changing rider behavior (Brann 2012; Aitken 2004). An improved understanding of the specific mechanics of these hitherto ignored ATV accidents and injury mechanisms may be useful in educating the relevant population, changing behavior, and significantly reducing the frequency and extent of ATV injuries (Shults 2013).

ATV rollover is an unappreciated injury mechanism that is responsible for significant morbidity and mortality. Moreover, rollovers account for 63% of ATV crashes, making them the most prevalent type of ATV injury mechanism. Youth are more likely than adults to roll sideways on flat terrain, but adults are more likely to roll backwards while riding uphill (Brandenburg J Trauma 2007). Due to the static weight of the ATV and the kinetics of the rollover incident, this mechanism most commonly results in severe crush injuries to the chest and abdomen (Hall 2009). Considerable variability in the location and severity of injuries has been observed for backwards rollover injury, occurring due to variability in the component of the ATV which strikes the chest (handlebars, fuel tank, etc.). This variability is a consequence of current industry standards for ATV fit based upon age alone because rider size and shape vary widely within the age groups recommended for 'youth-size' ATVs versus 'adult-size' ATVs (Bernard 2010).

Expanding upon prior laboratory research defining rider-ATV 'fit' and contrasting fit on 'youth-size' ATVs versus 'adult-size' ATVs in youth of different ages, we hypothesized that additional variables, notably surface inclination and operator commands have dramatic effects on the likelihood for ATV rollovers. Thus, the objective of this study was to quantify the effect of terrain angle, rider morphology, and engine throttle input on the threshold for sideways and rearward rollover of youth- and adult-sized ATVs.

3.4 Methods

3.4.1 Study Design

Empirical laboratory testing and virtual mathematical simulation were used to prospectively evaluate the relationship between threshold for sideways and backwards rollovers of the following variables: 1) ATV frame size (youth and adult), 2) type of rider (adult and child), 3) number of riders, 4) ATV speed or rider-applied ATV engine throttle and 5) terrain incline angle. No human subjects were involved in this study.

3.4.2 Experimental Procedures

Two ATV types: one new unused youth-sized ATV (Can-Am P5-90; 89cc engine,

Table 3.1) and one new unused adult-sized ATV (Yamaha Grizzly 700F1; 686cc engine,

Table 3.1) were acquired for this study and manually positioned on a level concrete floor. Each ATV tire was positioned atop a load cell and the normal force (weight) over each tire and axle were measured.

Each ATV type was then manually rolled onto the test platform of a custom-made inclination/declination device that simulated the pitch (defined according to the customary aeronautical sense) of an ATV on non-horizontal terrain. Each ATV was securely fastened to tracks secured to this platform by two lever-actuated cam-lock tie-down straps that mated to these tracks. This constrained ATV motion by securing both left and right sides of the ATVs front axle to the test platform.

After each ATV was securely fastened to this platform (maintained initially in the horizontal (0°) pitch orientation) the normal force under one rear wheel was measured using a load cell. Then the platform was inclined to an angle of 15° with the horizontal, and then to an angle of 25° to the horizontal. Load cell measurements were repeated for each angle and ATV type (Figure 3.1).

Figure 3.1 ATV and tilt platform inclined to pitch angle of 25 degrees declination relative to the horizontal.

The mean acceleration capabilities of each ATV type were measured by using a stopwatch and a level portion of grassy terrain, on which a distance of 45.73 m was marked. An experienced adult driver of known weight accelerated each ATV at full throttle from a full stop and piloted this vehicle to the endpoint while a second observer measured the time required to traverse the known distance. This was repeated three times and the mean acceleration capabilities for each ATV type were calculated. This mean value was used to calculate the maximum sustained torque that could be applied to the driving wheels of each ATV type.

To measure the effective spring rate of each axle, the same driver was placed upon the seat of each ATV and the vertical displacement of a fixed point on the ATV chassis located directly over each axle was measured. Pertinent ATV vehicle parameters, i.e., wheelbase, front and rear track widths, front and rear axle heights, seat height, seat axial position, footwell height, footwell to rear axis distance, handlebar width, and rear wheel & tire radius, were also acquired from each ATV type.

3.4.3 Simulation and Data Analysis

ATV parameters were defined via the convention created by TD Gillespie and embodied in SAE specification J670E as shown for a passenger automobile (Figure 3.2). Frame measurements for each ATV type were entered into an Excel (Version 2010; Microsoft Corporation, Bellevue, WA) spreadsheet, along with the wheel normal force measurements obtained from each tilt angle as previously noted.

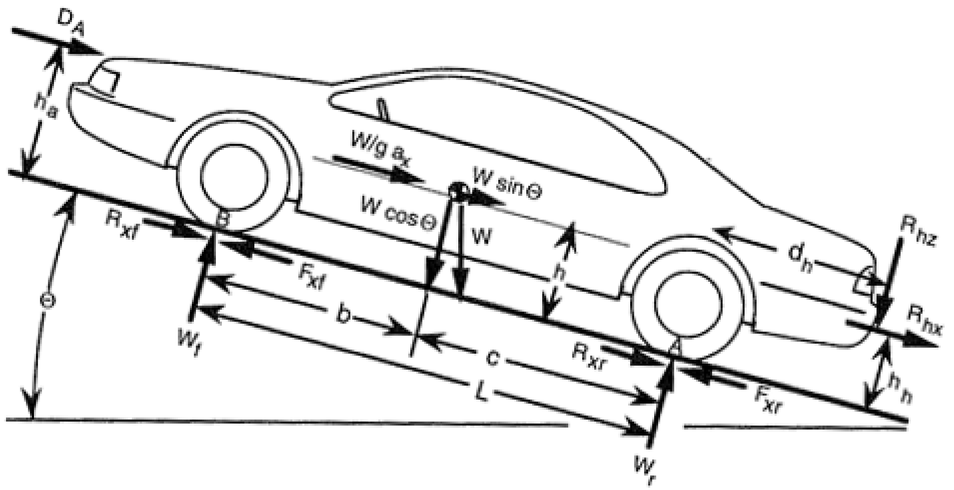

Figure 3.2 Convention for Vehicle Kinematic Parameters. Reprinted with permission from “Fundamentals of Vehicle Dynamics” (R-114) Copyright © 1992 SAE International. Further use or distribution is not permitted without permission from SAE.

The axial position of the center of gravity was computed (Equation 3.1) from the fore-aft weight balance on level ground.

$$c = \frac{W_f}{W} L, b = \frac{W_r}{W} L, L = b + c$$

Equation 3.1 Fore-aft vehicle center-of-mass balance

Using this value for the computed axial center of gravity and the measurement of the rear axle normal force at each angle of tilt, the ATV center of gravity height was computed (Equation 3.2). Although only one tilt angle was needed for this computation, the measurements at 15° and 25° for each ATV were used to double-check the result.

$$W_r = W\left(\frac{b}{L}\cos(\theta) - \frac{h}{L}\sin(\theta)\right), W_f = W\left(\frac{c}{L}\cos(\theta) - \frac{h}{L}\sin(\theta)\right) \Rightarrow \tan(\theta_{f0}) = \frac{c}{h}$$

Equation 3.2 Center-of-mass balance on an incline

Next, spring rates of each axle were computed using Hooke's law based upon the weight applied by the rider distributed over each axle (per Equation 3.1) and the resultant frame-to-axle displacements. The resulting calculated spring rates were then used to calculate the displacement of the height of the center of gravity for each ATV type with the simulation of additional riders.

Given this calculated center of gravity height of the ATV and rider, the computed lateral (sideway) rollover threshold was calculated (Equation 3.3). The suspension roll height term (h_r) in Equation 3.3 would normally be determined by the suspension geometry and compliance, but for the purposes of this simulation a quasi-static approximation was used, i.e., the roll rate (R_φ) was set to zero. In actual practice, the tripped sideway rollover threshold is typically less than the quasi-static sideway rollover value, owing to non-zero roll rates and that the roll height is almost always less than the center of gravity height; in other words, the results in this paper for rollover thresholds may be considered anti-conservative. It is worthy to note that the t/2h term (Equation 3.3) is also referred to as the Static Stability Factor (SSF) and is used by the National Highway Traffic Safety Administration as part of their rollover stability measurement used in their New Car Assessment Program (NCAP) and subsequently reported in the "star" rating system found on new automobiles.

$$\frac{a_y}{g} = \frac{t}{2h}\frac{1}{1 + R_\varphi\left(1 - {}^{h_r}\!/_{h}\right)} \Rightarrow \frac{a_y}{g} = \frac{t}{2h}$$

Equation 3.3 Tripped side rollover critical lateral acceleration

Derivation of the rearward roll threshold is based upon the axial force balance and its effect on the ATV weight distribution (Equation 3.4 – Equation 3.7).

$$M_r = r_A \cdot F_{xr}\frac{h}{r_A} = F_{xr} \cdot h$$

Equation 3.4 Bike moment and rear ground reaction force balance

$$F_{By} = \frac{M_r}{b}\frac{b}{L} = \frac{M_r}{L} = F_{xr}\frac{h}{L}$$

Equation 3.5 Front axle normal force and rear ground reaction force balance

$$F_{xr}\frac{h}{L} = W\left(\frac{c}{L}cos(\theta) - \frac{h}{L}sin(\theta)\right) \Rightarrow \frac{F_{xr}}{W} = \frac{c}{h}cos(\theta) - sin(\theta)$$

Equation 3.6 Static rear ground reaction force at an incline

$$\frac{W + W_r}{g} a_x = \frac{T_e N_{tf} \eta_{tf}}{r} - R_x - D_A - R_{hx} - W\,sin(\theta) = F_{xr} - R_x - D_A - R_{hx} - W\,sin(\theta)$$

Equation 3.7 Axial force balance at an incline including d'Alembert (virtual) acceleration forces

The critical inclination angle (θ) is determined by solving for the point where the weight over the front axle drops to zero. In the case of an accelerating ATV, or at least one with power applied to the rear wheels, this critical point also occurs when the mass moment of the ATV-rider system about the rear axle equals the torque input. [This practice is known in the vernacular as "…popping a wheelie" and involves precarious balancing of engine torque with ATV-rider-related torque. Risk of ATV rider injury inherent in this maneuver is evident.] As such, in an ATV with non-zero throttle applied, the threshold inclination angle for rearward roll is less than that of a stationary ATV.

ATV "riders" were simulated in the model by considering them as point weights whose centers of gravity were located at defined points on each ATV type. Simulated rider weights were chosen to be 54.55 kg located at the center of gravity. This weight was chosen as a conservative mid-point between a 50th percentile 12-year-old youth (40.9 kg) and a 50th percentile adult (86.4 kg) male rider. The center of gravity of a simulated single ATV rider (driver) was located at the nominal seat position axially and 25.4 cm above the saddle height of each ATV type. The center of gravity of a simulated second ATV rider (passenger) was located 30.48 cm axially behind the first rider and 30.48 cm above the saddle height of each ATV type. The center-of-mass locations were chosen based upon the approximate navel-to-rump distance of a 50th percentile adult male for height, and an abdomen-to-back placement of a second rider for axial location.

$$a_c = \frac{v^2}{r} = a_y = \frac{tg}{2h}$$

Equation 3.8 Relation between threshold lateral acceleration in a turn and angular velocity

$$v = \pm\sqrt{\frac{rtg}{2h}}$$

Equation 3.9 Threshold rollover velocity for a given turn radius on flat terrain

By balancing the relation between speed and centripetal acceleration versus the equation for tripped rollover critical lateral acceleration from Equation 3.3, we are able to derive the maximum speed in a turn before inducing a rollover on flat terrain in Equation 3.8 and Equation 3.9.

$$v = \pm\sqrt{rg\frac{t}{2h\cos\phi} + \tan\phi}$$

Equation 3.10 Threshold rollover velocity for a given turn radius on angled terrain

After applying trigonometric relations to the force balance of a vehicle in an angled turn (again with infinite friction as in Equation 3.3), the relation between threshold rollover velocity, static rollover acceleration threshold, turn radius, and camber angle (ϕ) is derived in Equation 3.10.

3.5 Results

Data are presented showing the height of the center of gravity of unloaded (for reference only), single rider (driver) and dual riders (driver and passenger) centers of gravity for youth-sized and adult-sized ATVs (

Table 3.1). These values provide perspectives for information presented below regarding thresholds for sideways and backwards ATV rollovers.

Table 3.1 Specifications for the representative Youth and Adult-sized ATVs used in this study.

	Youth ATV	Adult ATV
Gross Vehicle Weight (kg)	195.1	357.2
Spring Rate F/R (kg/m)	3730.5 / 914.3	1192.9 / 3391.2
Gross Vehicle Weight (kg)	195.1	357.2
Displacement / *Power / *Torque (cc / kW / N-m)	89.8 / 6.7 / 9.5	686 / 34.0 / 47.7

3.5.1 Static Sideways Rollover

Linear acceleration thresholds are provided for youth-sized and adult-sized ATV with no riders (reference purposes only), one rider (the driver) and two riders (driver and passenger, Table 3.2). When ridden solely by a driver, youth-sized ATVs are slightly less susceptible to sideways rollover than adult-sized ATVs. Specifically, youth-sized ATVs can withstand 0.80 g lateral acceleration during a turn, but adult-sized ATVs can only withstand 0.77 g during a comparable turn. This is due to differences between youth-sized and adult-sized ATVs regarding their track width (Table 3.1) and center of gravity height (Table 3.2).

Table 3.2 Static and dynamic backwards rollover critical angles as well as static side rollover acceleration for 0, 1 or 2 riders on youth or adult-sized ATVs.

	Youth ATV	Adult ATV
CG Height 0 / 1 / 2 Riders (cm)	30.2 / 41.4 / 50.0	50.5 / 57.9 / 65.0
Static Side Rollover Lateral Acceleration Threshold 0 / 1 / 2 Riders (g)	1.09 / 0.80 / 0.66	0.88 / 0.77 / 0.69
Backwards Rollover Static Critical Angle 0 / 1 / 2 Riders (degrees)	56.4 / 45.7 / 34.7	48.5 / 43.2 / 36.9
Backwards Rollover Dynamic Critical Angle 0 / 1 / 2 Riders (degrees)	46.0 / 33.6 / 20.6	27.0 / 21.8 / 15.3

Adding a rider behind the driver reduces these values and inverts this relationship. Specifically, if a rider sits behind the ATV driver, then the adult-sized ATV can withstand a 0.69 g turn, but the youth-sized ATV can only withstand a 0.66 g turn. Thus, youth-sized ATVs are slightly <u>less</u> susceptible to sideways rollover than adult-sized ATVs for a <u>single</u> rider, but slightly <u>more</u> susceptible to sideways rollover than adult-sized ATVs for <u>2 riders</u>.

3.5.2 Static and Dynamic Backwards Rollover

Data are presented for backwards rollovers for youth-sized and adult-sized ATVs with zero, one or two riders for both static and dynamic circumstances (Table 3.2). Static circumstance refers to an ATV with zero forward motion and non-rotating engine. Dynamic circumstance refers to an ATV ready to launch forward using maximum torque applied to the rear wheels from a running engine.

Backward rollovers will occur when forward terrain inclination angles reach 45.7° and 43.2° for youth-sized and adult-sized ATVs. Note the substantial (nearly half) reduction in this critical backwards rollover angle (from 43.2° to 21.8°) when the driver-only adult-sized ATV has maximum torque applied to the rear wheels. Maximum torque at the rear wheels also reduces the critical backwards rollover angle for the youth-sized ATV from 45.7° to 33.6°, but this reduction is less (27%) than that which occurs in the adult-sized ATV because of the reduced torque generating capabilities of the youth-sized ATV and the altered centers of gravity (

Table 3.1 & Table 3.2).

Although Youth-sized ATVs are almost equally susceptible to static backwards rollover when only the driver is present (forward approaching static critical angle is 45.7° versus 43.2°), Youth-sized ATVs are less tolerant to “rider abuse” (adding a passenger behind the driver) than Adult ATVs. Specifically, when a rider mounts a Youth-sized ATV, a 38.7% reduction in the critical terrain angle occurs. This contrasts with a 29.8% reduction in the critical terrain angle for Adult-sized ATVs for the same circumstances.

If maximum throttle is applied when 2 riders are present on an ATV, the likelihood of backward rollovers increases still more as shown by the 15° to 21° critical inclination of forward approaching terrain angles. This reduction, from 36° to 15.3° (nearly 58%), is greatest for the case of an Adult-sized ATV with a second rider and maximum throttle.

The maximum calculated ATV speed during turning of adult and youth sized ATVs are shown as a function of turn radius for youth and adult sized ATVs with one or two riders for varying angles of terrain camber (Figure 3.2 – Figure 3.7). The curves shown represent the threshold speed value at which tip-over will occur for the turn radius and conditions indicated in the legend. The non-rollover zone of operation is denoted by the area to the right and beneath of these curves.

Legend for Figures 3.3-3.7:
The Effects of Rider number (one, or two) and ATV type (Large, Small) are shown. The area beneath and to the right of each curve represents the non-rollover zone of operation. The horizontal dotted line illustrates the Consumer Product Safety Commission-mandated maximum speed (30 mph) for Y12+ ATVs.

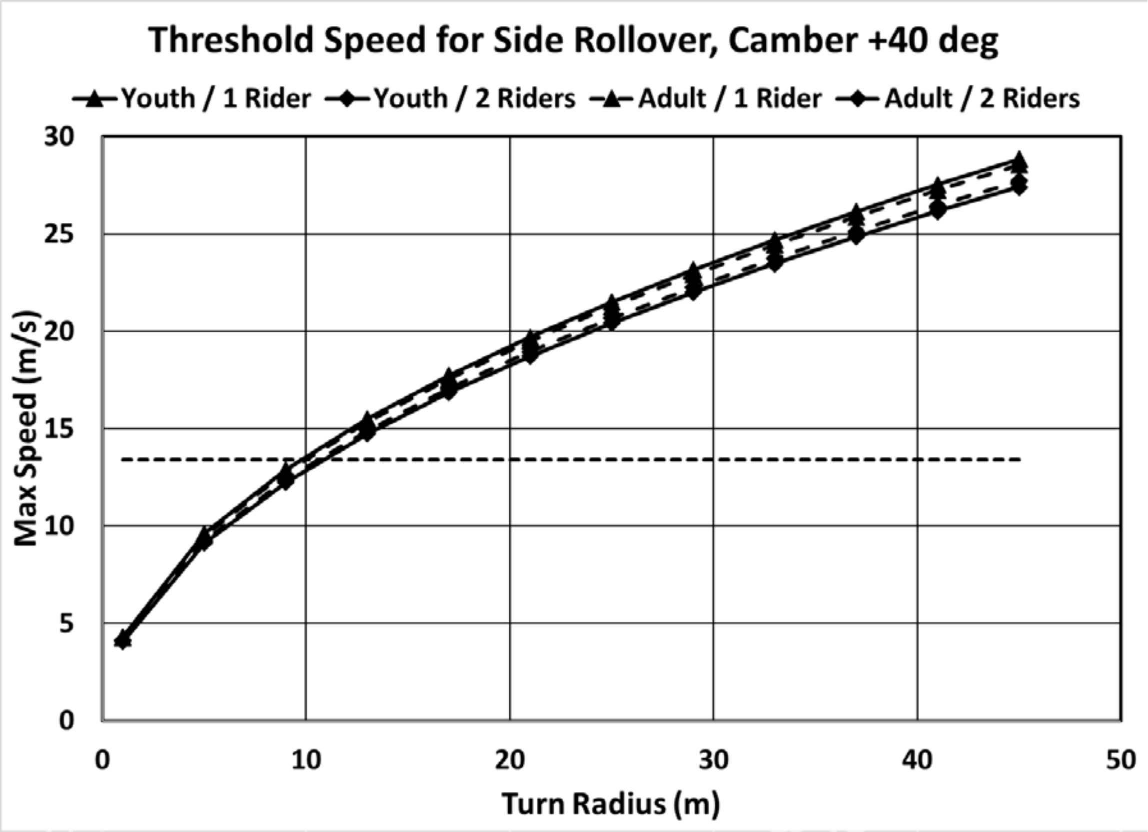

Figure 3.3 Maximum Calculated Speed in a Turn of Adult versus Youth-Sized ATV and Number of Riders Before Sideways Rollover on Terrain Angle of -40 Degrees of Camber

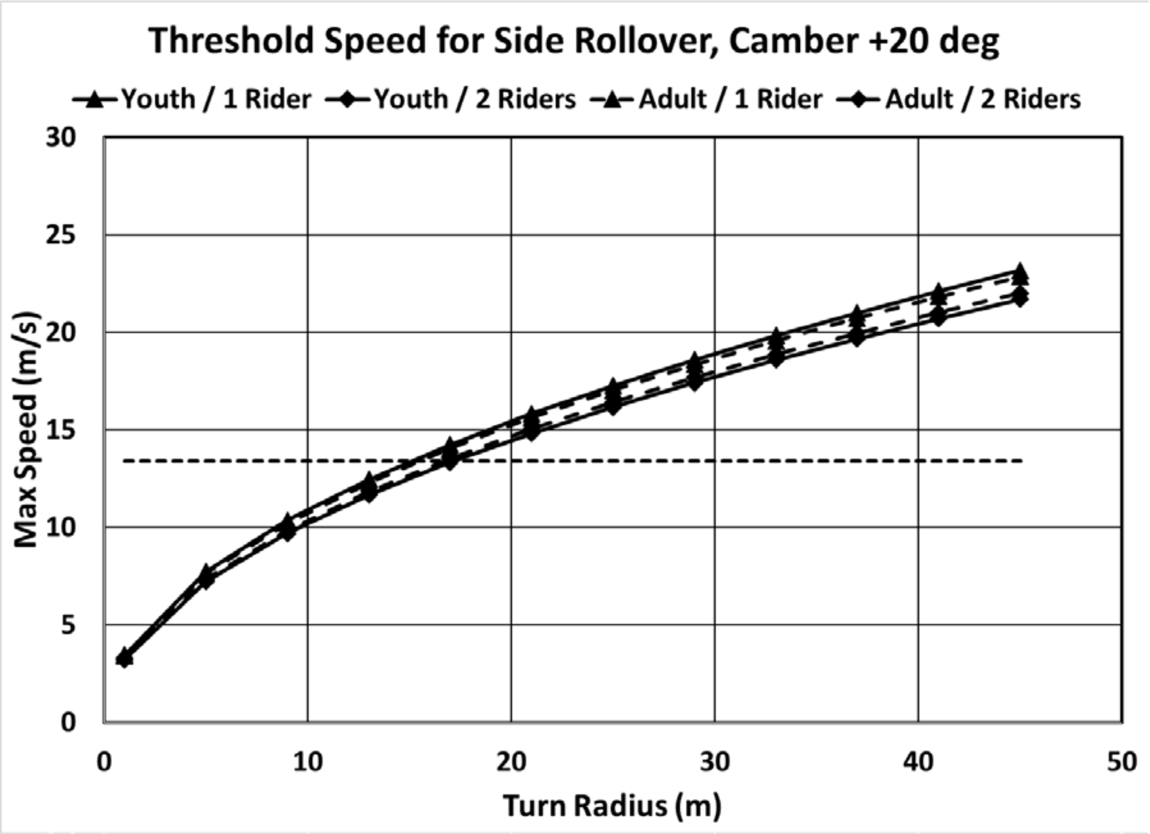

Figure 3.4 Maximum Calculated Speed in a Turn of Adult versus Youth-Sized ATV and Number of Riders Before Sideways Rollover on Terrain Angle of -20 Degrees of Camber

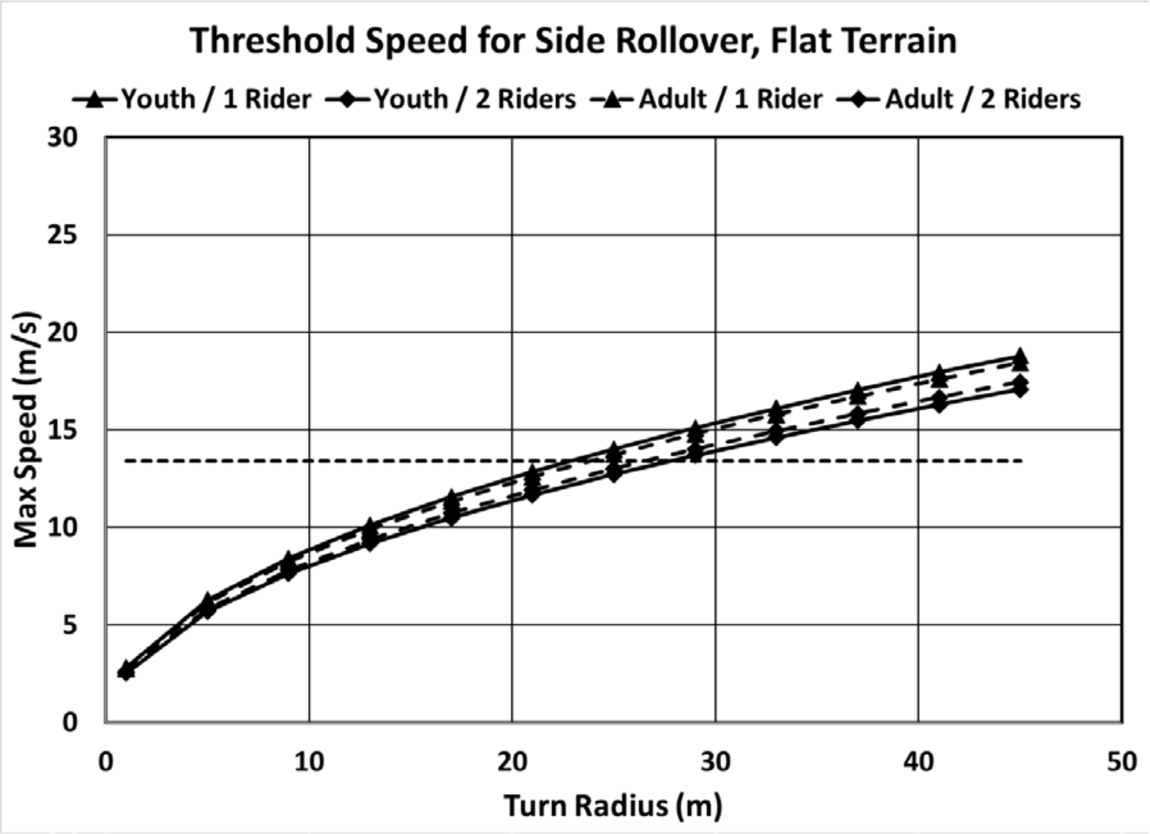

Figure 3.5 Maximum Calculated Speed in a Turn of Adult versus Youth-Sized ATV and Number of Riders Before Sideways Rollover on Terrain Angle of 0 Degrees of Camber

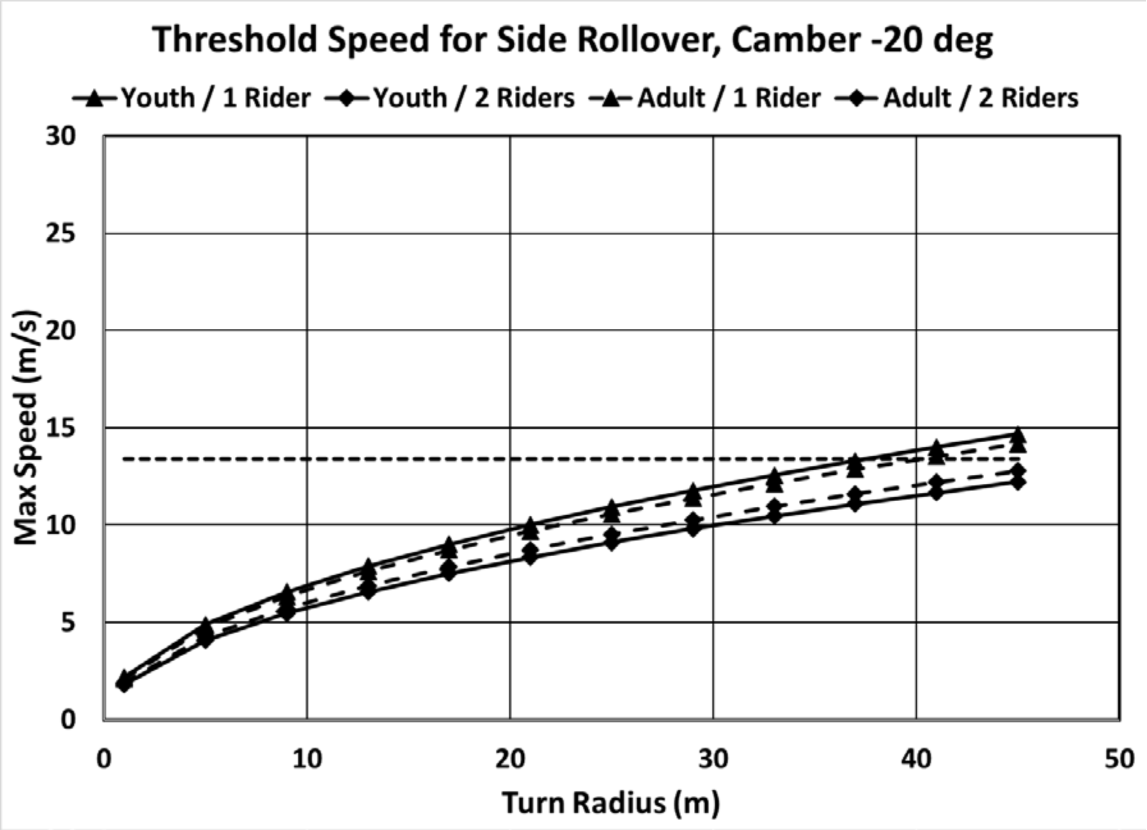

Figure 3.6 Maximum Calculated Speed in a Turn of Adult versus Youth-Sized ATV and Number of Riders Before Sideways Rollover on Terrain Angle of +20 Degrees of Camber

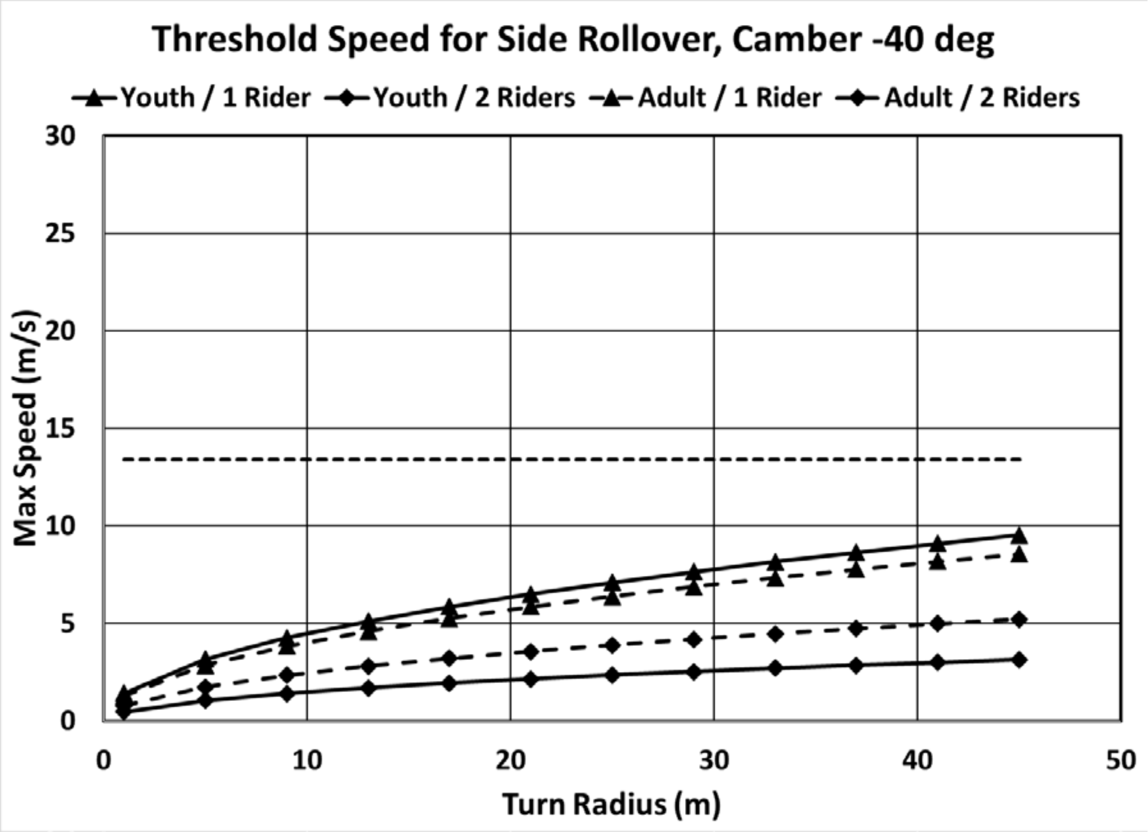

Figure 3.7 Maximum Calculated Speed in a Turn of Adult versus Youth-Sized ATV and Number of Riders Before Sideways Rollover on Terrain Angle of +40 Degrees of Camber

These data show that the maximum speed that Adult or Youth-sized ATVs can safely negotiate without risk of sudden tip-over, decreases sharply when turn radii decreases below approximately 6 meters. This relationship is most pronounced when a single rider makes increasingly tight turns on terrain with a 20-degree incline. Specifically, Youth or Adult ATV can endure a one-meter turn radius at low (2.8 m/s or 10.1 kph, or 2.7 m/s or 9.9 kph) speeds. This distance is almost the equivalent to the wheelbase of the ATV, i.e., the ATV can nearly pivot about a single rear wheel. Doubling the speed of the ATV to 6.0 m/s (21.6 kph) increases the safe minimum turn radius nearly 5-fold to 4.6 or 4.8 meters.

The likelihood of ATV tip-over with sharp radius turns substantially increases in the presence of inclined terrain. Specifically, a mild and commonly encountered 20° incline changes the minimum safe turn radius at youth or adult-sized ATV vehicle speeds of 10 m/s (36 kph) from 12.7 or 13.2 meters on flat terrain to 20.9 or 22.4 meters. A rider sitting behind the ATV driver further increases these safe minimum turn radii (at 10 m/s) to 30.1 and 27.5 meters. Alternatively, as terrain camber angle increases, the maximum safe speed during a fixed 10 m turn radius decreases from approximately 13.5 m/s to approximately 2.5 m/s.

Legend for Figures 3.8-3.9
The effects of terrain camber angle (+40 deg, +20 deg, 0 deg, -20 deg or -40 deg) are shown each for 1 and 2 riders. The area under each curve is the “safer” zone of operation. The horizontal dotted line illustrates the CPSC-mandated max speed (30mph) for Y12+ ATVs.

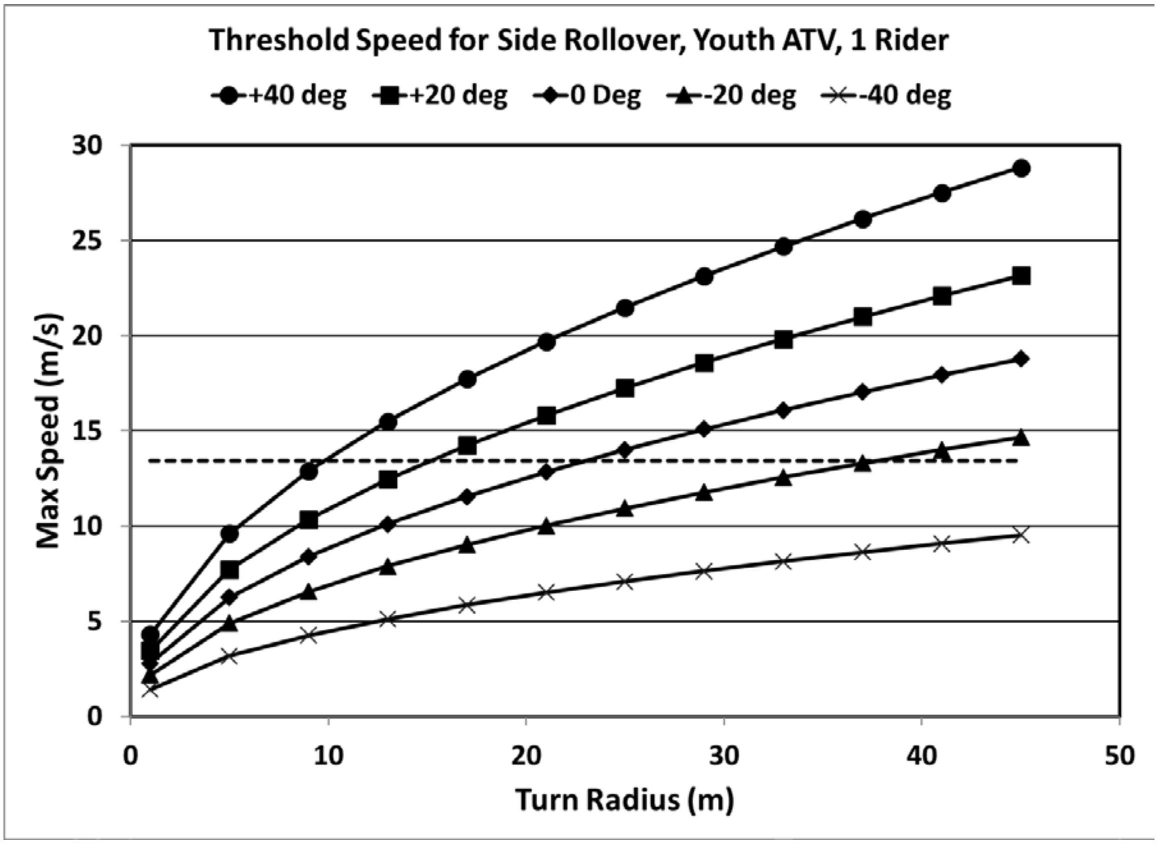

Figure 3.8 Maximum Calculated Speed of Youth-Sized ATV Before Sideways Rollover versus Radius of Turn. The effects of terrain camber angle (+40 deg, +20 deg, 0 deg, -20 deg or -40 deg) are shown for 1 rider.

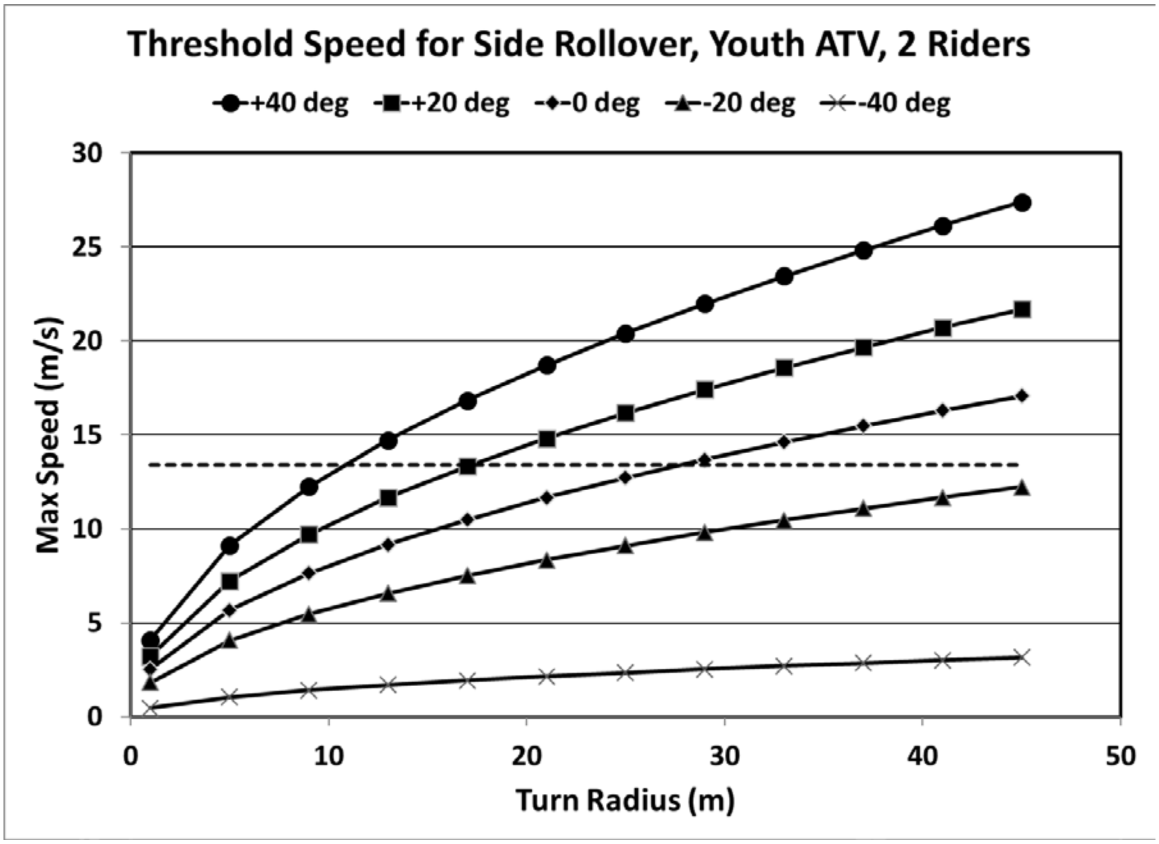

Figure 3.9 Maximum Calculated Speed of Youth-Sized ATV Before Sideways Rollover versus Radius of Turn. The effects of terrain camber angle (+40 deg, +20 deg, 0 deg, -20 deg or -40 deg) are shown for 2 riders.

Legend for Figures 3.10-3.11
The effects of terrain camber angle (+40 deg, +20 deg, 0 deg, -20 deg or -40 deg) are shown each for 1 and 2 riders. The area under each curve is the “safer” zone of operation.

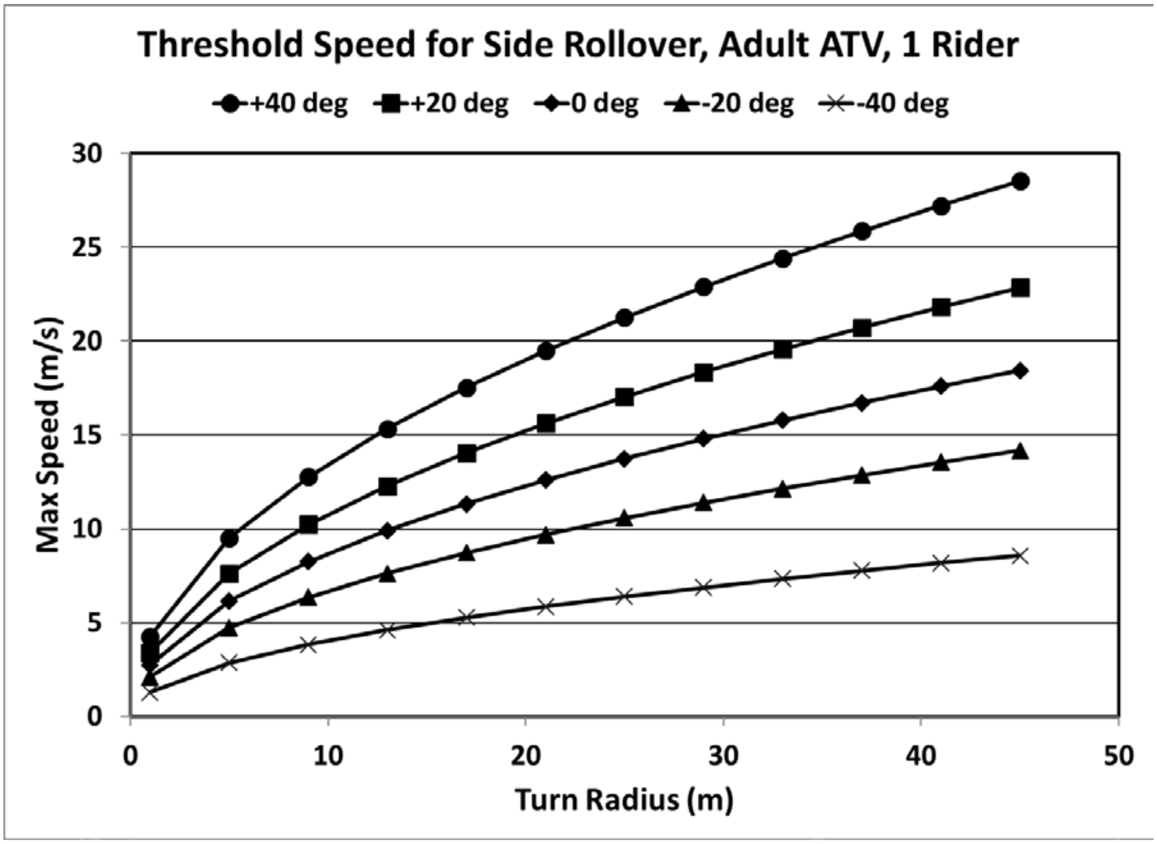

Figure 3.10 Maximum Calculated Speed of Adult-Sized ATV Before Sideways Rollover versus Radius of Turn. The effects of terrain camber angle (+40 deg, +20 deg, 0 deg, -20 deg or -40 deg) are shown for 1 rider.

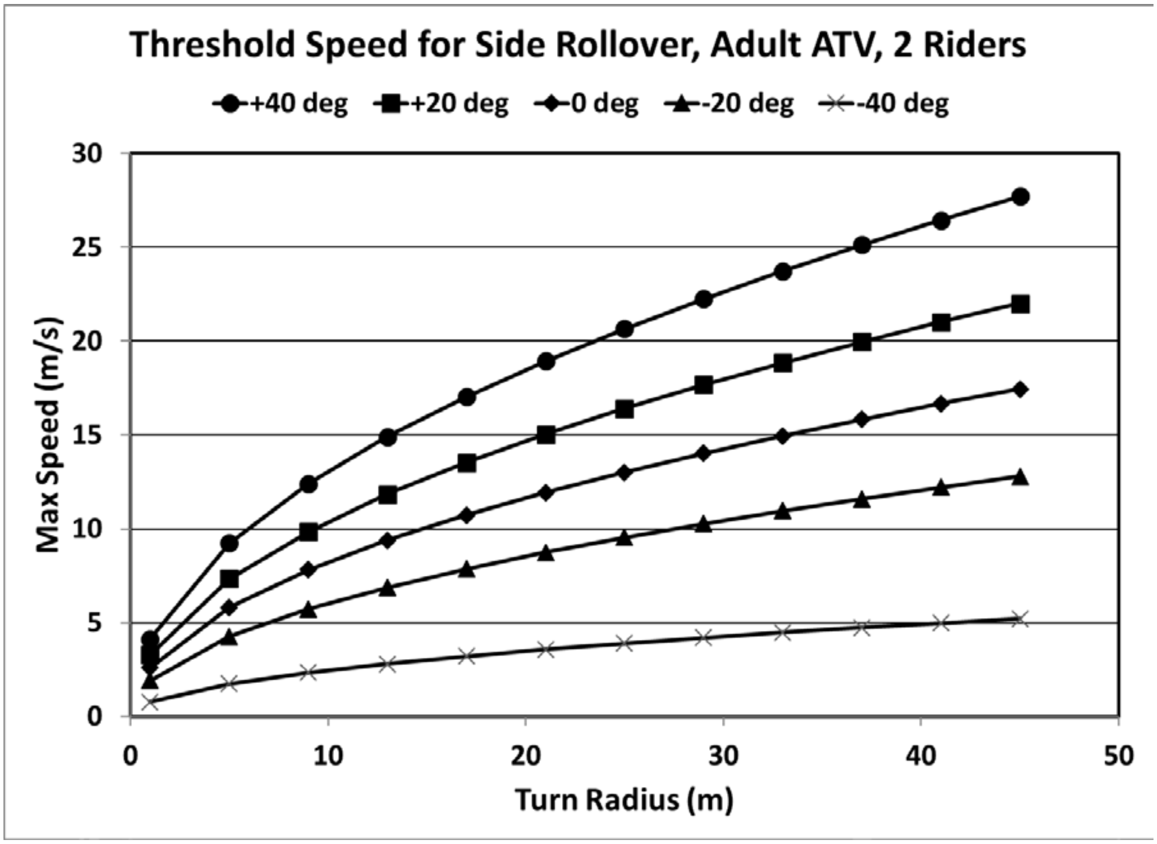

Figure 3.11 Maximum Calculated Speed of Adult-Sized ATV Before Sideways Rollover versus Radius of Turn. The effects of terrain camber angle (+40 deg, +20 deg, 0 deg, -20 deg or -40 deg) are shown for 2 riders.

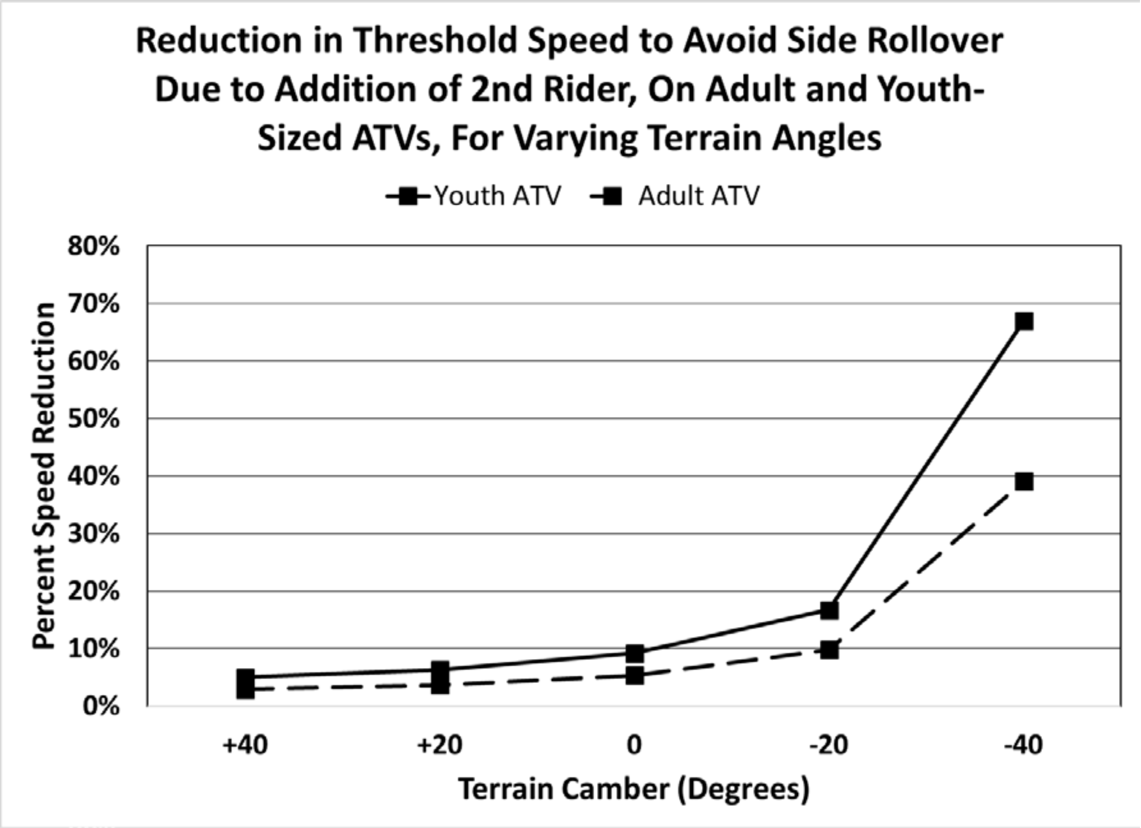

Figure 3.12 Reduction in Threshold Speed Required on Adult and Youth-Sized ATV to Avoid Sideways Rollover, Due to Addition of Second Rider. The effects of terrain camber angle (+40 deg, +20 deg, 0 deg, -20 deg or -40 deg) are shown.

3.6 Discussion

ATV rollover (both sideways and backwards) is a major injury producing mechanism. This study provides quantitative new information indicating the threshold for such rollovers and the factors that increase the likelihoods of such rollovers in Youth and Adult-sized ATVs. The major findings of this study are the comparative 'ease' with which ATVs can rollover given a variety of commonly found riding conditions, including specific values for terrain angle, ATV speed, turn radius, engine throttle, and number of riders.

The large reduction (nearly 50% to a value of 22°) in safe forward approaching terrain inclination angles for fully revved engines of Adult-sized ATVs is attributable to their higher (approximately 5X) horsepower engines. For this reason, Youth-sized ATVs are at significantly less risk for maximum throttle assisted backward rollover due to their substantially reduced engine power output. The lesser weight of the Youth-sized ATV is of little concern given that its absolute value (nearly 200 kg) is sufficient to cause injury given its static value alone on the chest of a child who suffers a backward rollover.

Backwards rollovers with maximum throttle input and rider abuse can occur at forward-approaching terrain angles of as little as 15° – 21°. Such angles can often be found on the side of roadways adjoining farm fields. Such rollovers pose a significant risk of injury due to the combination of high forces from the static weight of the ATV on top of the now-supine driver plus additional forces on the driver due to the ATV rotating about the rear

axle and contributing dynamic force to driver (and rider). Responsible parties should caution children "accustomed" to riding Youth-sized ATVs who suddenly change and ride an Adult-sized ATV. Such children used to revving the throttle of a Youth-sized ATV to gain maximum performance, who now do so on an Adult-sized ATV, even on a small terrain angle, have a substantially increased risk of injury due to backward rollover due to increased engine torque and ATV weight)86% greater) considerations.
Youth-sized ATVs were found to be slightly <u>less</u> (by 0.03 g) susceptible to sideways rollover than Adult ATVs for a <u>single</u> rider, but slightly <u>more</u> (by 0.03 g) susceptible to sideways rollover than Adult ATVs for <u>2 riders</u>. The actual significance of these (0.03 g) differences is unknown. While some may consider Youth-sized ATVs "safer" than Adult-sized ATVs, this is not true when sideways rollover propensity is considered in the presence of "rider abuse", i.e., adding a second rider behind the driver. Then, the propensity for side rollover is almost twice as risky as occurs with an Adult-sized ATV, in terms of the percentage reduction in speed needed due the addition of a second rider to avoid rollover on any given incline (Figure 3.12).

Concern for sideways tip-over while turning, particularly on an incline, is especially relevant when rider abuse occurs. In this case, the analyses show that the Youth-sized ATV poses greater risk than the Adult-sized ATV. This is because the second rider causes the minimum safe turn radius of the Youth-sized ATV to increase absolutely (6.7 m, 50% more) and proportionately more than in the Adult -sized ATV (4.0 m or 17% increase). Riders having an above-average body mass, as quantified by an above average Body Mass Index (BMI) are also at elevated risk of sideways ATV tip-over, especially on inclines. "Copycat" ATV riding by those of increased BMI is dangerous, particularly if those with higher BMI attempt to take turns on ATVs at the same radius and speed as those with substantially lower BMI.

Sideways ATV rollover is a concern when negotiating turns at any speed. Sharp ATV turns at speed on inclined terrain are particularly dangerous due to the widespread presence of such inclines and the common failure to appreciate the hazards of such inclines. Specifically, it is not uncommon to ride parallel to a roadway elevated above that of the adjacent field. It is also not uncommon for an ATV driver to enter such an embankment when avoiding obstacles or passing by other ATVs. ATV drivers attempting to cross roadways must first negotiate the incline between the field and the roadway and may be tempted to do so at elevated speed with a turn radius below the safe value. Sideways tip-over, driver ejection, and serious injury or death are then more likely to occur.

Stable terrain slope angles of up to 40 degrees are not uncommon, being within the range of angles for embankment construction with rock riprap support (USDA, 1989) which itself is modeled on the pedology and geology of naturally occurring hillside formations. The maximum ungoverned speed allowed for Y12 and Y15 ATVs (most similar to the model tested) is 30 mph (13.41 m/s) (Cornell, 2019). As shown in Figure 3.7 and Figure 3.8, at this speed there is less room for safe operation, especially when negotiating inclined terrain. A turn into a 40-degree incline can only be safely executed at 13.41 m/s with one rider on the Youth ATV by maintaining a turn radius of greater than 89.3 m. With two riders, this radius increases to 815.8 meters, which for all intents and purposes means such a turn cannot be safely executed at that speed.

Reading more into the CPSC speed limit on youth ATVs, an examination of Figure 3.3 through Figure 3.6 show that even moderate turn radii can induce an unsafe condition at that speed. On flat terrain at 13.41 m/s a turn radius of 22.9 m will induce a rollover for a youth ATV with one rider, and turning into a bank of 20 degrees, a radius as large as 37.6 m can induce a rollover. As ATV riders are often required to navigate between obstacles such as trees and fence posts, a turn radius of over 20m would be considered large. Therefore, for conditions encountered in everyday use, a youth ATV can quickly become unsafe if not operated with caution. This is particularly so given that the results above are anti-conservative and do not account for additional instability from dynamic influences such as roll rates induced by alternating steering inputs, steering step functions (rapid overcorrections), suspension bounce, or terrain impacts.

The frequency of rollover reported in literature is supported by the results of this study. At least 60.6% of fatal accidents were associated with an overturned ATV, and of those fatal accidents for riders under 16, at least 64.6% were linked to an overturned ATV (Garland, 2014). Overturning events were most commonly associated with terrain types of "forest/woods" and "field/pasture/farmland," as opposed to more flat terrain types such as beaches and paved roadways (ibid), supporting the argument above that even moderate turn radii into inclined terrain, especially enhanced by elevated speeds, can lead to unsafe conditions.

Unexpectedly, the reported number of riders linked to injury-causing ATV accidents is not supported by these results. At least 23.0% of fatal accidents and 31.5% of injury-causing accidents featured at least one passenger, however, in an alternate analysis the number of riders linked to fatal overturning events showed similar proportions (62.5% for one rider and 58.8% for multiple riders) (Garland, 2014). It is the author's suggestion that while the rollover propensity has significantly increased due to the multiple riders as shown in the results above, a behavioral response of more cautious driving while carrying a passenger counteracts the increased danger.

3.6.1 Study Limitations

This scope of this study was limited because the risk of injury inherent to ATV rollover. Thus, the study was limited to theoretical calculations without any empirical verification of the findings. Within these calculations, first-order simplified dynamic models assumed riders were rigid lumped masses. No consideration was given to moments of inertia or the complexity of the ATV suspension system. The terrain was modeled simply as unchanging angles of pitch or roll / camber. No rider input was simulated besides acceleration and the rider position was maintained constant, without changes that may affect the center of mass such as leaning or elevating their body above the ATV seat.

3.7 Conclusions

Considering sideways rollover performance, youth and adult ATVs operate nearly equivalent with one rider, having rollover thresholds that are respectively 0.80 g and 0.77 g; these values are easily exceeded by turning too sharply even at moderate speeds. Connectedly, in examining the effect of terrain angles on rollover, current CPSC speed limits for youth ATVs are inconsistent with safe operation for common operating conditions in avoiding sideways rollover, which supports the results of prior ATV accident epidemiological analyses. Similarly, the critical angle for backwards rollover under full throttle is also within common operating conditions, particularly for an adult ATV and by extension a youth ATV with an oversized engine that may be speed limited by a governor. Finally, the addition of a second rider on a youth ATV decreases both sideways and backwards rollover thresholds significantly more than a second rider on an adult ATV.

3.8 Funding Source

Funds for this study were obtained from the University of Kentucky’s Center for Clinical and Translational Sciences in 2011.

4. Chapter 4 – Engineering for Safer ATVs

4.1 Directions Based on Results

Chapter 2 has shown that age is not an appropriate measure in place of stature for fit on a particular ATV model. Chapter 3 has shown that conditions that precipitate both sideways and rearward rollover are well within the common operating ranges of youth and adult ATVs. This chapter will explore the surrounding issues and root causes behind the problems uncovered in the previous two chapters, building upon the groundwork exposed in Chapter 1 of the state of the industry and the regulatory landscape, and suggest ways to further explore and possibly improve both situations.

- Improvements to US state guidelines
- Development and installation of rollover-limiting fail-safe devices
- Design iterations to better accompany high variability in sizes of riders

4.1.1 Survey of US State ATV Usage Guidelines

Table 4.1 below surveys the current US state guidelines for ATV usage (SVIA, 2017). Whereas the CPSC has the authority to regulate sales of ATVs, they do not have any authority when it comes to how the ATVs are actually used after purchase.

Table 4.1 Summary of ATV usage laws enforced in US states and DC (51 total)

Usage Guideline	States with Requirements	Requirements on Public Land Only	Notes
Operator's License	13	12	7 of 13 only require for crossing a highway. Only 1 (North Dakota) applies for all usage
Safety Education Certificate	24	11	19 of 24 are age specific
Minimum Age	36	35	North Dakota applies for all usage
Age vs. Engine Size	5	5	
Rider Fit	1	1	Oregon has the only requirements
Passengers	22	22	16 limit to tandem models only; 4 to certain ages
Helmet	37	21	

Whereas Table 4.1 might seem to suggest that several states have similar requirements, they are instead inconsistent from state to state. There are no two states with exactly matching ATV usage requirements, and some of the greatest disparities are between states that share a border. For example, North and South Dakota are at opposing ends of the spectrum in their enforcement landscapes.

-Least restrictive states: Alabama, DC, Georgia, Hawaii, South Dakota
-Most restrictive states: North Dakota, Massachusetts

4.1.2 Improvements to US State ATV Usage Guidelines

The survey results in Table 4.1 indicate that there is a lot of white space when it comes to practical usage regulations that could have substantial impact considering the results of Chapters 2 and 3. It was shown that the presence of a passenger has a substantial impact on the sideways and rearward rollover stability, and that fit on an ATV is not guaranteed by only matching a rider's age to a particular youth model.

Suggestions ATV regulations have been offered beginning 1984 (the inception of CPSC recordkeeping and national attention to ATV-related injuries), which are:

- More stringent training requirements w/ licensure to buy & rent (as the risk of injury and death per mile is far greater than for cars)
- Consistent matrix of speed, engine size, fit, and age requirements nationally
- Safety equipment always
- Require insurance
- Federal penalties for injury/death from operation outside requirements, even on private property
- Required reporting and in-depth investigations for accidents, similar to traffic accidents
- Certification system and testing requirements for new ATV models, a la FMVSS

Within the scope of the analyses provided by Chapters 2 and 3, and without the capability of performing a thorough legal analysis the author can only suggest these two requirements be consistently applied across the US:
1) Replace or augment age guidelines with fit guidelines, modeled after legislation enacted in Oregon.
2) No passengers allowed on Youth ATVs, modeled after legislation enacted in Connecticut.

4.1.3 Rollover-Limiting Devices

As shown in Chapter 3, conditions that precipitate both sideways and rearward rollover are well within the common operating ranges of youth and adult ATVs. It is inexperience and overconfidence of youth riders that can lead them into such situations, and therefore having features on an ATV that may be able to partially compensate for their lack of judgement could save the population from numerous injuries per year.

It is the combination of throttle / brake input, terrain angle, ATV pitch (from suspension reaction), and ATV loading (including rider position / posture) that can lead to the center of gravity extending beyond one of the axles or the track, which will cause a rollover if a mitigating dynamic input is not applied. Inexperienced, particularly pediatric riders may not be able to supply the proper series of inputs in time to counter a rollover event.

Utilizing the flexible Design-to-Value methods (McKinsey, 2020) for innovating effective solutions to meet customer requirements, several potential design changes with increasing levels of complexity are explored below and distilled into a product roadmap for technology insertion. A full Design to Value workshop would likely reveal and refine additional potential solutions.

4.1.3.1 Rollover Prevention Strategy: Cut Power to Engine

Basis: Stop flow of fuel when out-of-bounds event is detected, in order to reduce either or both a) overpower on an incline, b) over speed during a turn.
Technology readiness: Dependable and widely deployed on a variety of vehicles.

Sensors, control system, and actuator easily adaptable to ATV scope.
Cost: The cost of the components required for this system has been reduced to commodity-level, due to their commonality between numerous industries and availability from numerous suppliers. Only a limited number of new components to design. $15-20 per ATV.
Effectivity: Moderately effective at preventing rearwards and over speed-induced side rollover and mitigating unsafe conditions, acknowledging there would be some elapsed time between event detection, fuel cut, engine cut-off, power reduction, and speed decrease. No effect on frontwards or tripped side rollover.
Drawbacks: None identified.
Patent Space: Fairly busy, but not with major manufacturers of ATVa

4.1.3.2 Rollover Prevention Strategy: Smart speed governor

Basis: Reducing speed reduces propensity for rollover; employ accelerometer/gyro tied to governor to limit top speed. Early version of stability control. This solution would be intended to limit speed on inclines & declines, as well as during yaw by detecting steering and terrain camber angle.
Technology readiness: Widely available. Sensors and actuator easily adaptable. Control system would need to be tuned and validated for off-road yaw scope.
Cost: Cost curve well burned down by auto and construction vehicle industries. Several new components easily fit to existing designs. $50-100/vehicle (lower end of spectrum for vehicles equipped with electronic throttle)
Effectivity: Quite effective at preventing unsafe rearward and side rollover conditions, minimally effective for avoiding front rollover conditions. Small capability to help recover from an unsafe condition. No effect for sudden, terrain-induced rolls.
Drawbacks: None identified.
Patent Space: Fairly busy, covering wide range of vehicle OEMs

4.1.3.3 Rollover Prevention Strategy: Smart weight limit (for # riders)

Basis: Disable ignition if weight carried by ATV, or weight balance, exceeds specified limits on either or both axles, in order to discourage tandem ridership on ATVs designed for just one rider as well as significantly undersized riders on larger ATV models.
Technology readiness: Some invention and component down selection required for ATV scope.
Cost: Several new components that are widely available, easily fit to existing designs.
Effectivity: When used as intended, can detect either undersized riders (for older Youth or Adult ATV models), additional riders, or otherwise overloaded ATVs.
Drawbacks: Can be fairly easily defeated by clever children.
Patent Space: Fairly busy, particularly with largest ATV market players.

4.1.3.4 Rollover Prevention Strategy: Active stability control

Basis: Computer-controlled independent brake inputs combined with throttle control to counter out-of-bounds dynamic state in real time, particularly to mitigate the impact of inappropriate speed during turns. Similar to a Mercedes-Benz ESP (electronic stability program) or Mitsubishi Active Yaw Control real-time traction control and braking system. Not in scope: Audi Quattro or BMW Active M-style torque vectoring, which are controlled through a series of up to 6 differentials and as such not as easily adapted or scalable to ATVs.
Technology readiness: Widely available. Sensors and actuators easily adaptable from automotive applications. Control systems for off-road use proven in rally events; would need to be tuned and validated for wider side rollover scope of ATVs.

Cost: Relatively large number of new or more elaborate parts to design, but if able to reuse automotive components and leverage that supply chain, then $150-200 per vehicle.
Effectivity: Moderate level of prevention and recoverability; the best application is to avoid speed-related (more than tripped) side rollover.
Drawbacks: Increased brake wear and addition of electromechanical components will decrease reliability and increase maintenance cost.
Patent Space: Fairly busy, but few ATV major players

4.1.3.5 Rollover Prevention Strategy: Active suspension

Basis: Implement independently computer-controlled dampers, roll bars, and other suspension members to counter out-of-bounds dynamic state in real time. Such a system can work to extend the rollover threshold for both front/rearward and side rollover, providing an opportunity for recovery during the rider behaviors of overpower or harsh braking going up or down hills, respectively, and of turning at too tight of a radius for the combination of speed and terrain camber angle.
Technology readiness: Limited availability. Has been deployed in auto sports for 40+ years with increasing level of sophistication, particularly in Formula 1, but few applications to date in non-supercar production vehicles beyond adjustable ride comfort settings. Also used in some high-rise elevator systems to overcome bounce at top or bottom of shaft. The two most common system types are servo-actuated and magnetorheological.
Cost: Relatively large number of new or more elaborate parts to design, but if able to downgrade/simplify high-end automotive components and leverage that supply chain, then $300-500 per vehicle.
Effectivity: Moderate level of prevention, very effective for recoverability.
Drawbacks: Durability and reliability. Real-time control in a small volume and light weight requires high-output electromagnetic components and high-pressure fluidic seals, both of which need regular maintenance as they wear with use. Off-road usage would impact component durability. The performance of both the servo-actuated and magnetorheological components are also degraded in cold weather. Lastly, such a system could backfire by encouraging riders to operate closer to a “ten tenths” limit rather than leaving a reasonable safety margin for unpredictable situations.
Patent Space: Extremely busy and increasingly active in recent years for off-road applications.

4.1.3.6 Rollover Prevention Strategy: Gyroscopic stabilizer

Basis: Provide ATV stabilizing torque from a flywheel’s angular momentum and precession oscillation rate, or from a vibrating bar. Such a system can supply extra margin to prevent rollover on the order of 75-92% of max roll angle reduction, based on sea craft applications (VEEM, 2019). The errant rider behaviors addressed by this system match those for an active suspension system.
Technology readiness: Widely available for sea craft, submarines, tank turrets, drone aircraft, satellites, strategic missiles, and cruise missiles. An ATV application would be most similar to sea craft.
Cost: Typically used only when extreme performance or comfort is required due to poor ROI. $500-1000 each at ATV scale.
Effectivity: At current technology level, such systems provide ~40-45 Nm / kg (VEEM, 2019). Based on requirements for counteracting the moment between the COG of the bike-rider system and the ground, 1013.6 Nm Youth 1 rider → 25 kg device and 2338.0

Nm Adult 1 rider → 59 kg device.

Drawbacks: Noise, weight, size, durability, power draw, start-up time. Moment may still be exceeded with extreme roll event. Would need at least one stabilizer for each desired roll axis. Due to the limited space in the frame of an ATV versus the volume of this device, placement of this mass could raise the COG height and shift it more towards one axle, both of which would have negative consequences on basic stability measures (see section 4.1.4.2 on page 53).

Patent Space: Very quiet. Most publicly accessible applications, particularly in foreign filings are for weapons systems.

4.1.3.7 Rollover Prevention Strategy: External stabilization

Basis: External mechanical ATV balance supports that deploy in real time when needed to supply lever arm to resist a rollover. This system would function essentially as real-time, as-needed training wheels, addressing rollover conditions after a rider has already exceeded the front, rear, or sideways rollover threshold through harsh braking, applying too much power, or turning too sharply for the combination of speed and terrain camber angle, respectively.

Technology readiness: Utilizes similar control system as active suspension.

Cost: Requires not a large number but fairly complicated electromechanical, pneumatic, or hydraulic components, not dissimilar from active aerodynamic elements on automobiles. $250-500 per vehicle.

Effectivity: Best in class for recoverability; able to absorb large aberrations. No capability for dangerous situation prevention.

Drawbacks: Response rate of mechanical components, possibility of interaction with rider

Patent Space: Fairly busy, but mostly with construction equipment OEMs and aerospace

Table 4.2 Proposed Design Solution Versus Customer Value Comparison Matrix for Rollover Limiting Devices.

Scoring Criteria: Mistake proofing ●, Recoverability ○

Technology	**Rearward Roll**	**Frontward Roll**	**Side Roll – Terrain Induced**	**Side Roll - Overspeed**	**Technology Readiness Level**	**Cost**
Power Cut	●○	-	-	●○	●●●●	●
Smart Governor	●●○	●○	-	●●○	●●●	●●
Smart Weight Limit	●○	●○	●	●○	●●●	●●
Active Stability Control	●○	●○	●○	●○○	●●●	●●
Active Suspension	●○○	●○○	●○○	●●○○	●●●	●●●
Gyroscopic Stability Control	●○○	●○○	●○○	●●○○	●●	●●●●
Deployable Stabilizers	○○	○○	○○	○○	●●	●●●

CPSC recommends 36 degrees tilt (73% slope) before static rearward lift-off (§ 1410.18 Pitch stability requirements for tandem ATVs). It's not clear upon what engineering methodology this specific rollover threshold requirement was based.

Below in Table 4.3 is a top-level patent search loosely indicating the business of each patent space and potential freedom to operate.

Table 4.3 Proposed Design Solution Patent Space Summary for Rollover Limiting Devices

Technology	**Patents**	**Major Assignees (>1%)**	**Prolific Firms**
Power Cut	1142	3	Jaguar Land Rover, Ford, Raytheon
Smart Governor	1275	8	Caterpillar, GM, Cummins, GE, Yamaha, Zonar, Peloton
Smart Weight Limit	1942	9	LG, Bombardier, Polaris, Kawasaki, Toyota, Yamaha, Yanmar
Active Stability Control	2380	8	Ford/Mazda, Polaris, Jaguar Land Rover, Lockheed Martin
Active Suspension	6875	17	Polaris, Bombardier, Jaguar Land Rover, Ford, Mitsubishi, John Deere
Gyroscopic Stability Control	105	5	No prolific firms
Automated Deployable Stabilizers	1673	8	X Development, Urban Aeronautics, Oshkosh Truck, Wing Aviation, Google, Bamford Excavators

4.1.3.8 Product Roadmap Summary

In order to best achieve the customer values evaluated above, the most suitable use cases for this trade space would be the combination of an **active stability control** with a **smart governor**. These two solutions for addressing the complex biomechanical and human behavioral problem of ATV rollover are cost effective, reliable, and utilize proven technologies.

As an area for potential further exploration, conceptual-level Systems Engineering analysis and design study to further refine the selected solutions would be advised. A full patent search and landscape analysis in order to develop an IP strategy is encouraged to be performed prior to moving forward with any implementation of the chosen technologies above.

4.1.4 Physical Design Iterations for Fit

What are the problems?
- Handlebars do not fit smaller children
- Brake levers do not fit smaller children
- Handlebar-knee distance inadequate on youth ATVs for older children
- Pelvis clearance for smaller children, for posting

Recalling the fit guidelines for ATVs discussed in Chapter 2:
- Knee-handlebar distance >200mm

- Posting seat clearance > 150mm
- Elbow angle 90-135 degrees
- Max footbrake distance < 105%

Evoking the results of Chapter 2, it is clear that a) children cannot safely continue to ride the same smaller ATV throughout their childhood years without their fit function declining, and conversely b) children cannot be expected to safely ride a larger ATV so that the fit function will eventually be minimized (“grow into it”).

Simplifying pubertal growth spurts, the growth curve of children between 6 and 16 years of age can be approximated with a straight line with a slope of 5.9 cm per year, between the points of 115 cm at 6 years and 173.5 cm at 16 years for the 50th percentile for boys (CDC, 2000). Breaking this figure down further and in account of body proportion changes before and after puberty, both boys’ legs and arms lengthen at a rate of about 3.5 cm per year, and the torso growing in length at roughly 2.5 cm per year (Nwosu, 2008). From the age of 16 for boys, the 50th percentile has only 3.5 cm more in growth to the full adult stature of 177 cm by 20 years (CDC, 2000).

Children’s bicycles (for the purpose of this discussion, the author means “mountain bikes” and not high-speed road bikes which are more exacting and involve far more personal preference) and ATVs have similar fitment guidelines, given the similarity in their construction and operation. The main difference is that long ago the bicycle industry responded to the need to better optimize fitment to the wide range of rider sizes by offering frame sizes that vary by only 2-3 cm and have several adjustable features. These features include sliding seat posts and either sliding or interchangeable handlebar stems (with a variety of forward extensions, as well). Modern mass-produced bicycles have a proportional sized frame: that is, their top tubes are longer or shorter in proportion to the seat and head tubes. The frame size of a bicycle generally refers to the length of the seat tube (or an equivalent vertical measure, depending on the frame construction).

The maximum ATV frame size (i.e. for an ATV that is not too big for the rider) is primarily determined by the ability to post above the saddle; in a bicycle, the analogous reference for posting fit is the ability to both stand on one’s heels above the top tube and place the balls of both feet (heads of the metatarsal bones) on the ground while seated in the saddle. A secondary maximum measure is the fit to the handlebars, where on a children’s bicycle one should have a comfortable 10-degree forward tilt of the torso while the arms are nearly straight while gripping the handles. The minimum size for both an ATV and bicycle frame (i.e. for a bike that is not too small for the rider) is limited primarily by the elbow angle in this same 10-degree forward torso tilt, which on a bicycle is controlled by the combined length of the top tube and exposed handlebar stem.

Youth bicycles are most often offered in 2” / 5 cm increments of frame size. Threading the needle of the fit guidelines in the above paragraph and in light of the adjustable features on the frame allowing taller riders to adjust to slightly smaller-than-intended frames, it is recommended to update the frame size no greater than every 4” / 10 cm in growth. Following this update frequency over 58.5 cm of growth between 6 and 16 years of age would cross 11-12 steps in frame size and 6 new bicycle frames to avoid potential ergonomic misfits at any given age.

All youth ATVs on the market known to the author have no means for adjustment (either in height or longitudinal position) of handlebars, hand brake levers, seat / saddle, or footrests. In light of the recommended frequency of bicycle frame size adjustment / update, it is of little surprise to find how few subjects in Chapter 2 fit their age-appropriate youth ATV.

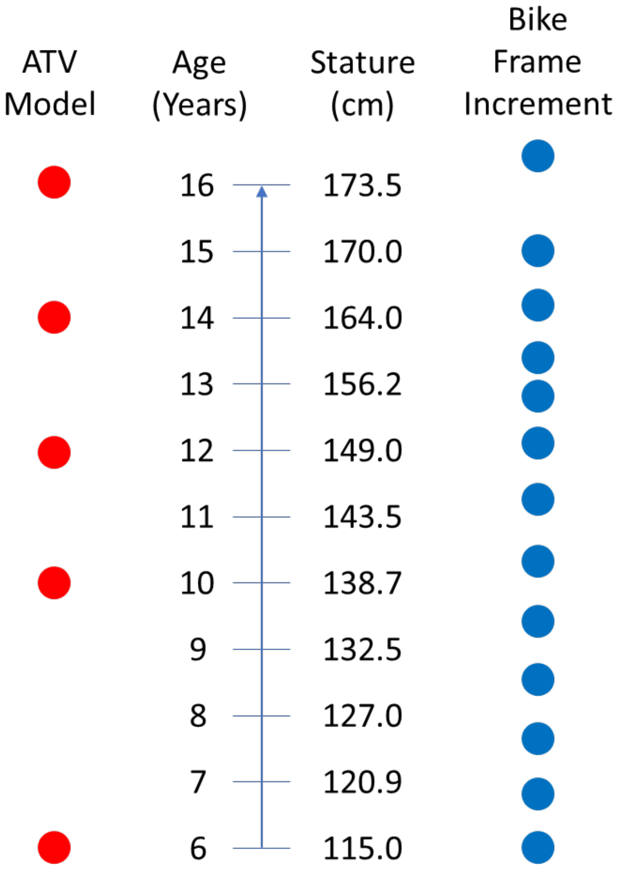

Figure 4.1 Graphical Comparison Between Age, Stature, Recommended Increments of Bike Frame Size, and CPSC-Mandated Youth ATV Model Offering Requirements

The figure above illustrates the how many increments of bike frames are available versus ATV models for children between 6 and 16, based on the growth curve for a 50th percentile boy, as well as how much increase in stature occurs between each successive youth ATV model. The greatest increase between any two subsequent ATV models is between Y6 and Y10 where 23.7 cm of growth has occurred, equivalent to a 20.6% increase in height. This is the same percentage difference in height between two individual standing 6 feet (183 cm) and 7 feet 5 inches (220.7 cm) tall.

Following the same Design-to-Value procedures as 4.1.3 on page 49, the sections below review several proposed safety-related design changes to ATVs that could address an improvement in fit for children on ATVs that may also secondarily benefit a reduction in rollover potential.

4.1.4.1 Fit & Design Improvement Strategy: Increase ATV track width

During the CPSC ATV safety public hearings in 2006, one suggestion that was given serious consideration was to mandate increasing track widths on youth ATVs by 2" (5.08cm) (CPSC, 2006). For the adult-sized ATV tested in chapter 3 using the relationship in Equation 3.4, this wider track would increase the rollover threshold by 5.67%, and for the youth-sized ATV the threshold would similarly increase by 7.69%. The percentage changes are independent of the number of riders. While these may seem like small numbers, the effect on the performance of the youth ATV is equivalent to the difference in cornering stability (measured on a skidpad) between a Ferrari 488 GTB (1.02g) and a base model Audi A6 (0.95g), with a 5x difference in list price (Car and Driver, 2019).

Table 4.4 Effect of Increased ATV Track Width on Side Rollover Threshold for Adult and Youth ATVs.

	Adult ATV Side Rollover	Youth ATV Side Rollover
Nominal	0.77g	0.80g
+2” Track	0.81g	0.86g
% Diff.	+5.67%	+7.69%

4.1.4.2 Fit & Design Improvement Strategy: Lower COG

Similar to 4.1.4.1, a reduction in the center of gravity would affect not only the side rollover potential but also the front & rear rollover propensities (neglecting any dynamic effects in altering of the moment of the COG versus the roll center height). Thus, a 2” reduction in the height of the center of gravity is proposed.

There are two basic ways to accomplish a lower COG without changing the height of the seat(s) (which may have a negative impact to terrain visibility) or the suspension design (which may have a negative impact on ground clearance): alter the engine design, or abandon the combustion engine entirely. Most ATV motors and their mountings mimic motorcycles; going to a flat (boxer) style cylinder arrangement would be an efficient way of reducing the COG height without a substantial design challenge or increase in cost. Shifting to an electric vehicle has been shown on occasion in automobiles to significantly reduce the COG height, although the curb weight does typically increase as the delta weight owing to the low specific energy density of the batteries versus gasoline far outweighs the lighter electric motors (+23% in the case of the Mercedes SLS AMG Electric Drive versus the SLS AMG GT, 3800 lbs. versus 4700 lbs.) (Car and Driver, 2013). The batteries are usually placed within the floorboard structure, and the electric motors and transaxles typically sit even in height with one or both wheel axles, particularly when the motors are located within the wheel-hub.

Table 4.5 Effect of Decreased Center of Gravity on Side and Rear Rollover Thresholds for Adult and Youth ATVs, with 1 and 2 Riders Each.

		Adult ATV		Youth ATV	
		Side	Rear	Side	Rear
1 Rider	Nominal	0.77g	43.22°	0.80g	45.67°
	-2” COG	0.85g	45.85°	0.91g	49.42°
	% Diff.	+9.62%	+6.09%	+14.03%	+8.19%
2 Riders	Nominal	0.69g	36.87°	0.66g	34.71°
	-2” COG	0.75g	39.13°	0.73g	37.62°
	% Diff.	+8.47%	+6.13%	+11.28%	+8.40%

Compared with increasing the track width in 4.1.4.1, lowering the COG height has a greater inch-for-inch impact on ATV rollover stability. For the youth ATV, the improvement is nearly double for side rollover stability versus increasing track width (+7.69% / track width versus +14.03% / COG height). Increasing the track width also has no direct effect on front or rearward rollover stability, whereas reducing the COG height has a substantial impact between +6.09% and +8.40% (depending on the ATV type and number of riders) as shown in Table 4.5.

4.1.4.3 Fit & Design Improvement Strategy: Custom handlebar width

Supply a greater array of handlebar sizes to address both ends of the fit spectrum, with smaller riders currently being too far outstretched and lacking the range of motion to turn the wheels lock-to-lock, and larger riders being too hunched and unable to supply a proper turning moment to the handlebars.

4.1.4.4 Fit & Design Improvement Strategy: More ATV sizes

Addressing the conundrum in Figure 4.1, increase the number of ATV frame offerings to mimic bicycles frame sizes (every 2”). Due to the cost and hassle of buying a new ATV roughly every 1-2 years, users are unlikely to comply with increasing the frequency of their frame updates.

4.1.4.5 Fit & Design Improvement Strategy: Adjustable ATV frame

Also addressing the conundrum in Figure 4.1, as children grow, so too should their vehicles. Increases possible space of size combinations without necessarily increasing the number of ATV frames or substantially increasing the complexity of the ATV system design through additional components and interfaces. Puts power in the hands of the consumer.

4.1.4.6 Fit & Design Improvement Strategy: Modular ATV

A variation of 4.1.4.5, this functionality would enable the exchange of pre-fabricated components to minimize the error in a rider’s specific fit function. Again, due to cost and hassle, consumers are unlikely to comply with increasing the frequency of their frame updates.

4.1.4.7 Fit & Design Improvement Strategy: Smart fit detection and interlock

This functionality would operate in the same fashion as gesture control for cell phones or user detection and tracking for building security systems. One high-TRL implementation would utilize millimeter wave radiofrequency energy (also known as ultra-wideband) from a sensor mounted in the center of the handlebars to measure a rider and subsequently perform a high-level analysis of the acquired 3D shape to determine the sizes of their major body parts (torso, upper arms, shoulders). In this format, the cost has been commercialized to a $20 component that includes both the scanner and the processor, available both from Analog Devices Inc. and Texas Instruments.

4.1.4.8 Fit & Design Improvement Strategy: Biometric recognition and interlock

The best use case for a biometric interlock would be for Adult ATVs to prevent unauthorized small riders. The same technology that enables the smart fit detection in 4.1.4.7 could be employed for this function to detect major body segment sizes, where visual facial identification would not be recommended as the helmet would need to be removed at the time of rider identification.

Table 4.6 Proposed Design Solution Versus Customer Value Comparison Matrix for ATV Design Changes for Fit Improvement.

Scoring Criteria: Dynamic Mitigation ●, Prevention ○

	Rear/Front Roll	Side Roll	Brake	Turn	Post	Cost
Increase track by 2”	-	●●●	-	-	-	●
Decrease COG by 2”	●●●	●●●●	-	-	-	●●
Custom handlebar width	-	-	-	●●●	-	●
Increased frame sizes	-	-	●●●	●●●	●●●	●●●●
Adjustable ATV	-	-	●●●●	●●●●	●●●●	●
Modular ATV	-	-	●●●	●●●	●●●	●●●
Smart fit interlock	-	-	○○	○○	○○	●
Biometric interlock	-	-	○	○	○	●

4.1.4.9 Product Roadmap Summary

Based on the customer values presented above and within the scope of analyses in Chapters 2, 3, and 4, the most suitable use cases are to both **increase track width by 2”** and **COG height by 2”**, as well as introduce an **adjustable ATV frame** paired with **smart fit detection**. These design configurations and technology insertions are not only cost-effective solutions to the biomechanical problems presented above but also add significant value in line with user expectations in an increasingly digitally-enabled world.

4.2 Suggested Next Research Study Steps

4.2.1 Detailed Study Limitations

4.2.1.1 ATV is static during measurement; not dynamic

Except for measurement of acceleration to calculate the torque at the wheels, the ATVs were never in motion (relative to ground reference frame, straight-line or rotation).

4.2.1.2 Rider is not manipulating controls for effect

While the subject riders in Chapter 2 were asked to touch the ATV controls to measure their fit to the ATVs, time-varying control inputs and their dynamic effects were not explored, and neither were the responses of riders via the controls to any varying conditions.

4.2.1.3 Terrain is unchanging

Besides the ATV remaining static during both studies, there was no accounting for unsteady terrain in the modeling of rollover stability. The more common types of unsteady factors in terrain that were not explored were: varying friction (e.g. between sets of wheels or in transitions such as from mud to grass), bumps, and angle changes (incline, camber, or both).

4.2.1.4 Contribution from suspension not modeled or measured

The backwards and sideways rollover models in Chapter 3 did not include the suspension as a dynamic element, in effect simplifying the ATV to a rigid structure. As such the dynamic effects of the suspension and (if present) stability system were not measured or modeled.

4.2.1.5 Real-world accident contributors not well understood

While some likely scenarios were uncovered, this study did not place any ATVs with riders in dynamic motion to replicate or simulate possible accident-causing situations in a controlled environment. Furthermore, the actual details of injury-causes ATV accidents are not consistently investigated or documented in order to supply correlations to validate such a study.

4.2.2 Suggested research with detailed descriptions

A catalogue of potential further research directions is described below. For each of the study limitations listed above in section 4.2.1 above, a score is assigned versus each research direction according to its hypothetical ability to address each limitation in order to determine which combination of topics would be most appropriate to pursue. These scores are summarized in Table 4.7.

Table 4.7 Anticipated Effectiveness of Proposed Future Research Directions to Overcome Study Limitations.

Scoring Criteria: Utility ●

	ATV Static	Rider Not Manipulating Controls	Terrain Unchanging	Suspension Not Modeled	Real-world Accident Contributors	Cost
Dynamic Simulation	●●	●	●●	●●	●●	●
Active Monitoring / Lab Sim	●	●●●	●●●	●●●●	●	●●●
Active Monitoring / Test Track	●●●●	●●●●	●●●●	●●●	●●	●●
Active Monitoring / Untethered	●●●●	●●●●	●●●●	●●●	●●●	●●●
ATV Accident Data Mining	-	-	-	-	●●●	●
ATV Accident Investigations	-	-	-	-	●●●●	●●●●

4.2.2.1 Research Strategy: Demonstrate through a dynamics-based simulation how interactions with different terrains contribute to rollover and the sensitivity of changes to ATV dynamics for improving rider safety.

Utilize vehicle suspension parameters in constructing 3- and 5-mass linear systems as MIMO state space models. Collapse masses where appropriate to a "bike" form for simplicity. Develop output vectors to probe sprung mass. Embed several throttle and brake control logic behaviors. Build datasets for several terrain scenarios, and inputs for steering, throttle, and brake, and feed through state space models to simulate behavior of ATVs traversing roadways (for instance, using MATLAB's LSIM utility). The value of this research would be enabling the ability to predict ATV response to simulated real-world conditions, and placing a simulated rider behavior in the control loop, although physical benchmarking would still be needed for falsification.

Cost: 1 FTE graduate student, software licenses (MATLAB, Simulink, and SysML)

4.2.2.2 Research Strategy: Active monitoring of ATVs with simulated conditions.

Amongst the proposed studies actively involving human subjects, this one would be the most likely to receive IRB approval for children. Instrument both ATVs and riders in a laboratory setting for kinematic measurements, with servo-controlled suspension displacements to mimic controls and terrain. Either supply a large rear-projected screen or AR/VR goggles with a live video simulation of the terrain. This setup would function in the same style as an immersive vehicle simulator. By providing the proper safety equipment, children would be able to participate in this simulation. The value of this research would be to analyze how riders respond to simulated real-world conditions and how their fit upon the ATV may interact with those responses.

Cost: 1.5 FTE graduate student, 4 force plates, motion controller (i.e. National Instruments), linear actuators, data acquisition & processing system, software licenses (LabVIEW, MATLAB)

4.2.2.3 Research Strategy: Active monitoring of ATVs and riders on controlled course.

Instrumented ATVs and riders with sensors connected via CAN-Bus to recording device, using the ATV test track at the Transportation Research Center in East Liberty, OH. As an IRB would not be likely to approve children to participate in this study, or possibly even adult volunteers, professional ATV riders would need to be employed as the test subjects for this study. The value of this research would be to record an analyze how the ATV-rider system responds to a limited sampling of real-world conditions.

Cost: 0.5 FTE grad student, 10 x 0.01 FTE professional riders, 3 day track rental, sensors, long-range wireless data acquisition & processing system (i.e. NI mmWave), software licenses (LabVIEW, MATLAB, Simulink).

4.2.2.4 Research Strategy: Active monitoring of ATVs (long-term) on uncontrolled courses.

This program would instrument ATVs and rider helmets with sensors connected via CAN-Bus or wirelessly to a CPIB to measure, process, store, and upload kinematic data to a cloud-based platform. Various data acquisition and cloud-based sensor data handling platforms are commercially available that could be leveraged to enable the system at a reasonable price point and without a great deal of up-front electronics or software design work. The value of this research would be to record and analyze how the ATV-rider system responds to a potentially wider variety of real-world conditions.

Cost: 1 FTE grad student, 10 sets of sensors and cloud-based data acquisition & processing systems (i.e. NI IIoT, McLaren Applied Technologies), software licenses (LabVIEW, MATLAB, Simulink)

4.2.2.5 Research Strategy: ATV accident data mining, including state-by-state comparison.

As shown in section 1.5.2 on page 9, the CPSC NEISS ATV injury coding system is lacking in resolution as to important details that would increase its analytical utility. The NHTSA NCSA (CrashStats) program could have augmented the data set with many pertinent details, but it only records incidents and publications relevant to involvement with motor vehicles. This value of this proposed program would be to expand the data set by querying sources with vested interests in expanded analyses related to ATV accidents such as insurance companies and law firms for their accumulated data.

Cost: 1 FTE graduate student

4.2.2.6 Research Strategy: ATV accident reporting & investigation program.

Going one step further than 4.2.2.5, this proposed program would perform trauma center follow-ups and ATV accident reconstructions upon incident reporting in the CPSC NEISS system. The value of this proposed research would be to collect a richer dataset to provide a level of analysis that has not been reported in academic or governmental literature to date for ATV-related injuries.

Cost: 2 FTE graduate students, 100 – 2 day business trips (domestic airfare, car rental, hotel room, meals), DSLR camera, surveying equipment.

4.2.2.7 Research Roadmap Summary

In the interest of supplying maximal coverage of all the prior study limitations not just in Chapters 2 and 3 but also in the broader literature in the most efficient manner, the author recommends following a phased approach with three of the suggested research methods. First, the performance of a **dynamics-based simulation** followed by validation of this simulation through **active monitoring of ATVs and riders on controlled courses** will address limitations 4.2.1.1 through 4.2.1.4 on page 48. To baseline both of these studies against the real-world accident contributors from limitation 4.2.1.5 , a 1-year program of **ATV accident investigation** is recommended.

4.3 Final Summary

Returning to the original question posed by Dr. Bernard, can children safely operate ATVs?

The answer is not a clear-cut yes or no, but instead points to parents' and society's tolerance for and management of risk. And as always, greater knowledge of a system can help those who want to be helped to reduce the risk involved. This dissertation has examined the ATV-rider system, characterizing two major risks of youth ATV ridership and suggesting several associated mitigation methods.

The ability to fit properly on an ATV was the first risk to be examined. The key take away from that study was that age is not a reliable indicator of fit on an ATV. The lack of correlation due to variability in stature and a limited number of youth ATV frame sizes is most pronounced in pre-adolescent children. This finding also applies to adults on either end of the bell curve for stature.

The second key risk to be examined was the propensity of ATVs to overturn. It was determined that both sideways and backwards rollover are possible within normal operating conditions for speed, turn radius, and terrain angles. The rollover propensity is aggravated by adding additional riders or other loads.

From the risks that were revealed in the above studies, directions were shown for improving design and legislation, as well as conducting further research to refine the risk analyses. These directions were determined by performing gap analyses paired with a Design-to-Value approach. The key recommendations were: better fit through more adjustability of ATV frames, adding safety-oriented electronics / smart features, simple ATV design changes for improving stability, reading across existing best-in-category legislation between the states regarding youth ATV fit and tandem ridership, executing improved dynamic modeling and benchmarking via controlled field testing, and finally conducting a limited program of ATV accident investigations. The constellation of biomechanically-derived solutions above can improve the ability of the ATV system to compensate for possible or actual errant rider behavior and in so doing reduce the risk of ATV injuries.

Appendix

This dissertation follows formatting guidelines from The Mayfield Handbook of Technical & Scientific Writing, http://www.mit.edu/course/21/21.guide/home.htm

APA parenthetical citation and reference listing formatting guidelines have been followed.

References

Aitken ME, Graham CJ, Killingsworth JB, Mullins SH, Parnell DN, Dick RM (2004). All-terrain vehicle injury in children: strategies for prevention. Injury Prevention, 10, 303-7.

Altizer, L.L. (2008). All-terrain vehicle safety: a long-standing issue! Orthop. Nurs, 27(4), 243–245.

All-Terrain Vehicle Safety Institute (2009). ATV Safety Institute. URL: http://www.atvsafety.org/ (accessed 2009, December 29).

American Academy of Orthopaedic Surgeons (2018, September). All-Terrain Vehicle Safety. URL: http://orthoinfo.aaos.org/topic.cfm?topic=A00265 (accessed 2020, February 12).

American Academy of Pediatrics (2019). Journals & Publications. URL: https://www.aap.org/en-us/professional-resources/publications-and-journals/Pages/Publications-and-Journals.aspx (accessed 2019, October 25).

American Academy of Pediatrics, Department of Federal Affairs (2009). Testimony of the American Academy of Pediatrics, Committee on Energy and Natural Resources, American Academy of Pediatrics. Oversight Hearing on Off-Highway Vehicle Management on Public Lands, 5 June, 2008. Available from: http://www.aap.org/advocacy/washing/Testimonies-Statements-Petitions/06-05-08-ENR-ATVTestimony.pdf.

Auxier JT, Bernard AC, Griffits B, Chang E, Novitski T, Pienkowski D (2020). The Mechanics of All-Terrain Vehicle Rollovers. Unpublished manuscript, University of Kentucky, Lexington, KY.

Bernard AC, Mullineaux DR, Auxier JT, Forman JL, Shapiro R, Pienkowski D (2010). Pediatric anthropometrics are inconsistent with current guidelines for assessing rider fit on all-terrain vehicles. Accident Analysis and Prevention, 42, 1220-5.

Brandenburg MA, Brown SJ, Archer P, Brandt EN, Jr (2007). All-terrain vehicle crash factors and associated injuries in patients presenting to a regional trauma center. J Trauma, 63(5), 994-9.

Brann M, Mullins SH, Miller BK, Eoff S, Graham J, Aitken ME (2012). Making the message meaningful: a qualitative assessment of media promoting all-terrain vehicle safety. Injury Prevention, 18, 234-9.

Breslau J, Stranges E, Gladden M, Wong H (2012, May). Emergency Department Visits and Inpatient Hospital Stays for All-Terrain-Vehicle-Related Injuries, 2009: Statistical Brief #130. Healthcare Cost and Utilization Project (HCUP) Statistical Briefs [Internet]. Agency for Health Care Policy and Research (US). Rockville, MD.

Tingwall E (2013, April 4). Mercedes-Benz SLS AMG Electric Drive. Car and Driver. URL https://www.caranddriver.com/reviews/a15116128/2014-mercedes-benz-sls-amg-electric-drive-first-drive-review/ (accessed 2019, November 17).

U.S. Centers for Disease Control (2000, November 21). 2 to 20 years: Boys, Stature-for-age and Weight-for-age percentiles. URL:

https://www.cdc.gov/growthcharts/data/set1clinical/cj41c021.pdf (accessed 2019, November 17).

Code of Federal Regulations, 16 CFR Part 1420 (2017). Requirements for All Terrain Vehicles. URL: https://www.law.cornell.edu/cfr/text/16/part-1420 (accessed 2019, October 25).

Concerned Families for ATV Safety (2007). Facts about ATV's and Children. URL: http://www.atvsafetynet.org/ (accessed 2009, December 2).

Consumer Federation of America (2017). ATV Fatalities Report. URL: http//consumerfed.org/2017 (accessed 2019, October 1).

U.S. Consumer Product Safety Commission (1985, April 3). CPSC Approves Action Plan For All-Terrain Vehicle Accidents. Release number: 85-015.

U.S. Consumer Product Safety Commission (1988, March 14). CPSC Approves Consent Decrees for All-Terrain Vehicles. Release number: 88-016.

U.S. Consumer Product Safety Commission (2002). Petition requesting ban of ATVs sold for the use of children under 16 years of age. URL: http://www.cpsc.gov/BUSINFO/frnotices/fr03/atvban.pdf (accessed 2009, December 29).

U.S. Consumer Product Safety Commission (2005, January 13). Polaris to Pay $950,000 Penalty for Failing to Report Hazards with ATVs. Release number: 05-086.

U.S. Consumer Product Safety Commission (2006, August 10). Standards for All Terrain Vehicles and Ban of Three-Wheeled All Terrain Vehicles; Notice of Proposed Rulemaking. CPSC-2006-0043-0001. Federal Register Number: 06-06703. CFR: 16 CFR 1307, 1410, 1500, 1515. URL: https://www.regulations.gov/document?D=CPSC-2006-0043-0001 (accessed 2019, October 25).

U.S. Consumer Product Safety Commission (2007). 2005 Annual Report of Deaths and Injuries-Amended. URL: http://www.cpsc.gov/library/atv2005.pdf (accessed 2009, December 2).

U.S. Consumer Product Safety Commission (2009). ATV Safety Messages. URL: http://www.atvsafety.gov/safetytips.html (accessed 2009, December 29).

U.S. Consumer Product Safety Commission (2014, May). ATV-Related Fatalities from 2005 through 2007. URL: https://www.cpsc.gov/s3fs-public/pdfs/ATVSpecialStudyReport.pdf (accessed 2019, October 28).

U.S. Consumer Product Safety Commission (2018, January). NEISS Coding Manual. URL: https://www.cpsc.gov/s3fs-public/2018%20NEISS%20Coding%20Manual.pdf?2pAQeGAhfK4oMyg6q_aeLrGCpMP.3tDD (accessed 2019, December 20).

U.S. Consumer Product Safety Commission (2019, February). 2017 Annual Report of ATV-Related Deaths and Injuries. URL: http://cpsc.gov/s3fs-public/atv_annual%20Report%202017_for_website.pdf (accessed 2019, October 27).

U.S. Consumer Product Safety Commission (2019). National Electronic Injury Surveillance System (NEISS). https://www.cpsc.gov/Research--Statistics/NEISS-Injury-Data (accessed 2019, December 20).

Curran J, O'Leary C (2008). Paediatric trauma associated with all-terrain vehicles. Ir Med J, 101(2), 55–57.

Denning G, Jennissen C, Harland K, Ellis D, Buresh C (2013). All-terrain vehicles (ATVs) on the road: a serious traffic safety and public health concern. Traffic Inj Prev, 14, 78-85.

U.S. Department of Agriculture (1989, July). Loose Riprap Protection. URL: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_022577.pdf (accessed 2019, December 1).

U.S. Department of Housing and Urban Development (1990, March). Site Grading and Drainage Guidelines. 4145.1 Rev-2 Appendix 8. March 1990. URL: https://www.hud.gov/sites/documents/41451X8HSGH.PDF (accessed 2019, November 20).

Florence C, Haegerich T, Simon T, et al (2015). Estimated lifetime medical and work-loss costs of emergency department–treated nonfatal injuries—United States, 2013. MMWR Morb Mortal Wkly Rep, 64, 1078–82.

Florence C, Simon T, Gaegerich T, Luo F, Zhou C (2015). Estimated Lifetime Medical and Work-Less Costs of Fatal Injuries – United States, 2013. MMWR Morb Mortal Wkly Rep, 64, 1074-1077.

Garland S (2014, May). National Estimates of Victim, Driver, and Incident Characteristics for ATV-Related, Emergency Department-Treated Injuries in the United States from January 2010 – August 2010 with an Analysis of Victim, Driver and Incident Characteristics for ATV-Related Fatalities from 2005 through 2007. U.S. Consumer Product Safety Commission. URL: https://www.cpsc.gov/s3fs-public/pdfs/ATVSpecialStudyReport.pdf (accessed 2019, October 28).

Gillespie, Thomas D. (1992). Fundamentals of vehicle dynamics. Warrendale, PA: Society of Automotive Engineers, Inc.

Graham J, et al (2006). Clothesline injury mechanism associated with all-terrain vehicle use by children. Pediatr Emerg Care, 22(1), 45–47.

Hall AJ, Bixler D, Helmkamp JC, Kraner JC, Kaplan JA (2009). Fatal all-terrain vehicle crashes: injury types and alcohol use. Am J Prev Med, 36, 311-6.

Helmkamp JC, et al (2008). All-terrain vehicle-related hospitalizations in the United States, 2000–2004. Am J Prev Med, 34(1), 39–45.

Helmkamp JC, Aitken ME, Lawrence BA (2009). ATV and bicycle deaths and associated costs in the United States, 2000-2005. Public Health Rep, 124, 409-18.

U.S. House of Representatives (2009). Text of H.R. 4040 [110th]. Consumer Product Safety Improvement Act of 2008. URL: http://www.govtrack.us/congress/bill.xpd?bill=h110-4040 (accessed 2009, December 28).

Kadaba MP, Ramakrishnan HK, Wootten ME (1990). Measurement of lower extremity kinematics during level walking. J Orthop Res, 8(3), 383–392.

Kawasaki (2009). Specs for the Kawasaki 2008 KFX90. URL: http://www.powersportstv.com/2008/Kawasaki/KFX/90/ATV/24594/ (accessed 2009, May 25).

Kellum E, et al (2008). Age-related patterns of injury in children involved in allterrain vehicle accidents. J Pediatr Orthop, 28(8), 854–858.

Kirkpatrick R, Puffinbarger W, Sullivan JA (2007). All-terrain vehicle injuries in children. J Pediatr Orthop, 27(7), 725–728.

Krauss EM, Dyer DM, Laupland KB, Buckley R (2010). Ten years of all-terrain vehicle injury, mortality, and healthcare costs. J Trauma, 69, 1338-43.

Martin-Du-Pan, RC (2008). Invisible LH syndrome and the Hawthorne effect: when the analysis device affects the observed phenomenon. Rev Med Suisse, 4(172), 2064.

McKinsey & Company (2020). Design-to-Value. McKinsey & Company, New York, NY. URL: https://www.mckinsey.com/business-functions/operations/how-we-help-clients/product-development-procurement/design-to-value (accessed 2020, February 12).

Montgomery WC (1987). ATVs: Ban, recall needed. AAP News, 3(11), 22.

Moore, S, Sabella, J (2007). Young riders: all-terrain vehicle use in north Texas. J Trauma Nurs, 14(4), 203–205.

Motorcycle Industrial Council (MIC) (2019). 2019 Statistical Annual. Irvine, CA.

National 4-H Council (2005). 4-H ATV Safety. URL: http://www.atv-youth.org/ (accessed 2019, April 4).

National Highway Traffic Safety Administration (2013). Laboratory Test Procedure for Rollover Stability Measurement for New Car Assessment Program (NCAP): Static Stability Factor (SSF) Measurement. Washington, DC.

Nesteruk, HEJ (2015, May 1). CPSC Response to SVIA concerning ATV activities for ANSI/SVIA-1-2010. URL: https://www.cpsc.gov/s3fs-public/pdfs/blk_media_SVIA-ANSI-Comment-Letter.pdf (accessed 2019, October 28).

Nwosu BU, Lee MM (2008, Sep 1). Evaluation of Short and Tall Stature in Children. Am Fam Physician, 78(5), 597-604 .

Pennsylvania Department of Conservation & Natural Resources (2009). Operation of ATVs by Youth, 2009. Summary of Pennsylvania's All-Terrain Vehicle Law. URL: http://www.dcnr.state.pa.us/Forestry/atv/ATVBrochure.pdf (accessed 2009, December 29).

Shults, RA, et al (2005). All-terrain vehicle-related nonfatal injuries among young riders: United States, 2001–2003. Pediatrics, 116(5), e608–e612.

Shults RA, West BA, Rudd RA, Helmkamp JC (2013). All-Terrain Vehicle-Related

Nonfatal Injuries Among Young Riders in the United States, 2001-2010. Pediatrics, 132(2), 282-9

Skidbike Inc (2019). Skidbike adjustable rider training device. URL: https://www.skidbike.com/about/ (accessed 2019, November 4).

Specialty Vehicle Institute of America (2017, November). State All-Terrain Vehicle Requirements. Irvine, CA.

Streeter, A (2008). Marketers must advocate for patients. Mark Health Serv, 28(4), 9.

Streeter, R (2008). 2007 Annual Report of ATV-Related Deaths and Injuries. CPSC, Washington, DC. URL: www.cpsc.gov/library/atv2007.pdf (accessed 2009, December 2).

Strohecker KA, Gaffney CJ, Graham J, Irgit K, Smith WR, Bowen TR (2017). Pediatric all-terrain vehicle (ATV) injuries: An epidemic of cost and grief. Acta Orthop Traumatol Turc, 51(5), 416-9.

Su W, Hui T, Shaw K (2006). All-terrain vehicle injury patterns: are current regulations effective? J Pediatr Surg, 41(5), 931–934.

Texas Department of Public Safety (2000). All-Terrain Vehicle Operator Education and Certification Program. URL: http://www.txdps.state.tx.us/msb/atv.htm (accessed 2009, December 29).

Thompson TM, et al (2008). Foot injuries associated with all-terrain vehicle use in children and adolescents. Pediatr Emerg Care, 24(7), 466–467.

Trauma Committee of the Canadian Association of Pediatric Surgeons (2008). Canadian Association of Pediatric Surgeons' position statement on the use of all-terrain vehicles by children and youth. J Pediatr Surg, 43(5), 938–939.

U.S. Department of Agriculture, Forest Service (2008, February). Off-Highway Vehicle Recreation in the United States and its Regions and States. National Survey on Recreation and the Environment. URL: https://www.fs.fed.us/recreation/programs/ohv/IrisRec1rpt.pdf (accessed 2019, October 31).

VEEM Gyro (2019). URL: https://veemgyro.com/stabilizer-models/vg120/ (accessed 2019, November 3).

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Auxier JT, Bernard AC, Griffits B, Chang E, Novitski T, Pienkowski D. *The Mechanics of All Terrain Vehicle Rollovers.* In journal submission (Accident Analysis and Prevention), 2020.

Bernard AC, Mullineaux DM, Auxier JT, Forman J, Shapiro R, Pienkowski D. *Pediatric Anthropometrics are Inconsistent with Current Guidelines for Assessing Rider Fit on All Terrain Vehicles.* Accident Analysis and Prevention, 2010. 42 (4): 1220-5.

"Evaluation of Pediatric Fit and Safety Guidelines for All-Terrain Vehicles," presented at *36th International Workshop on Human Subjects for Biomechanical Research*, Stapp Conference, San Antonio, Texas. November 2, 2008. Sponsored by NHTSA.

"Carbon Composite Box Girder Bridge Formed via Soluble Cores," exhibited at *49th International SAMPE Symposium and Exhibition*, Long Beach, California, May16-20, 2004.

"A Novel Approach to Sleep Apnea by Facilitating Normal Nasal Breathing," presented at *Stanford Biomechanical Engineering Distinguished Lecture*. Stanford University, 2002.

"High Performance Prosthetic Foot for Pediatric Reverse Symes Amputee," presented at *Stanford Biomechanical Engineering Distinguished Lecture*. Stanford University, 2001.

Granted Patents (Public / Non-Classified)

US9453419B2 Gas turbine engine turbine blade tip cooling
US10104313B2 Method for turbine component qualification
US10226812B2 Additively manufactured core for use in casting an internal cooling circuit of a gas turbine engine component
US10273819B2 Chamfered stator vane rail
US10300526B2 Core assembly including studded spacer
US10307816B2 Additively manufactured core for use in casting an internal cooling circuit of a gas turbine engine component
US10337121B2 Separate vessel metal shielding method for magnetic flux in directional solidification furnace
US10337332B2 Airfoil having pedestals in trailing edge cavity
US10364683B2 Gas turbine engine component cooling passage turbulator
US10406596B2 Core arrangement for turbine engine component
US10456831B2 Detection of blockage in internal passages of gas turbine engine components
US10465530B2 Gas turbine engine component cooling cavity with vortex promoting features
EP3088100B1 Core arrangement for turbine engine component
EP3127631B1 Core with radiopaque material
EP3170979B1 Turbine component including mixed cooling nub feature
EP3196414B1 Dual-fed airfoil tip
EP3241992B1 Internally cooled airfoil
EP3262440B1 System and process to provide self-supporting additive manufactured ceramic cores

35 additional public patent applications pending

Academic & Professional Awards

National Merit Scholar, 1995
Palm Beach Post Pathfinder Awards, Finalist – Computer Science, 1996
AP Scholar with Distinction, 1996
The Benjamin School Frederick M. Busse Memorial Scholarship, 1996

James F. Lincoln Arc Welding Foundation, Division V National Silver Award, 2001.
SAMPE Composite Lightweight Bridge Competition, 2nd Place, 2004.
UTC Leadership Award Nominations – 2015, 2018 (twice), 2019; Finalist – 2018, 2019.
UTC Luke Hobbs Award for Technical Innovation – Finalist – 2018, 2019
Pratt & Whitney Hot Section Engineering Special Award – 2018, 2019