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Agricultural All-Terrain Vehicle Safety

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ABSTRACT

Farmers need more than a single trusty tractor to handle most of the jobs and tasks on their property. Tractors are useful for tasks that require high power such as seeding and plowing. However, for some daily-farm tasks that need lower power, tractors are being replaced with All-Terrain Vehicles (ATVs). While ATVs cannot match up the strength of tractors, their versatility and relatively lower costs allow farmers to efficiently perform some of the jobs and tasks in a farm that do not require high power, such as transporting supplies, mowing grass, checking fences, herding calves, and carrying firewood. However, the increasing use of ATVs as a utility vehicle adds a heavy burden to the American public health system. The U.S. Consumer Product Safety Commission (CPSC) estimates that in the past ten years, ATV-related incidents have resulted in over 6,500 deaths and 925,000 hospitalizations. In addition, the annual cost of lives and health care from ATV-related incidents has increased almost five times in the past decade, reaching $22 billion dollars spent in 2016. ATVs have engineering features such as low-pressure tires, narrow wheelbase, and high center of gravity that make them prone to rollover when riding on rough and uneven terrains, or steep slopes (all common scenarios in farms and ranches). Indeed, agriculture is the major contributor for incidents involving ATVs, accounting for 50% and 65% of all occupational-related injuries and deaths, respectively.

Based on data from the CPSC, youth younger than 16 years old are the leading victims of ATV incidents. Furthermore, a previous study found that ATVs are one of the primary sources of vehicle injury for youth on farms, causing 63% of the vehicle-related injuries. Moreover, according to “AgInjuryNews.org” in 2021 the number of reported fatalities and nonfatal injuries in the U.S. among youth caused by ATV were 52 and 26, respectively. Data from the 2019 National Electronic Injury Surveillance System revealed that youth younger than 18 accounted for 36.8% of all ATV-related injuries. Over 15% of those injuries occurred on farms or ranches. Furthermore, several studies identified a correlation between ATV-related injuries of children and their readiness to ride, including their strength and anthropometry, among other characteristics.

For these reasons, two studies of this dissertation focused on evaluating the capabilities and limitations of youth operating utility ATVs.

Furthermore, previous studies showed that crash location is an important risk factor for ATV-related incidents. Most ATV crashes on farms and ranches result in traumatic injuries where the rider needs immediate care but is unable to seek help because they are severely injured. Further compounding the issue, most of these crashes occur in isolated areas of hard access and without reliable and constant cellular service. Thus, making it challenging to contact emergency medical services (EMS) promptly and receive first-aid care in a timely manner. Therefore, one study in this dissertation aimed at developing and testing a low-cost, ATV crash-prediction-and-detection device (AgroGuardian) that immediately alerts EMS, even when the rider is unable to do so, and there is no cellular service available.

In the first study, potential discrepancies between the required activation forces of eight controls of fifty-four utility ATVs and the strength of youth of varying ages (6-20 years old), genders (males and females), and strength percentiles (5^{th}, 50^{th}, and 95^{th}) were evaluated. In addition, we also assessed if youth strength is enough to push the ATV off if they are pinned underneath it, which is a common post-rollover scenario that can result in death by mechanical asphyxia. A handheld force gauge, a button load cell, and a pressure glove were used to measure the activation forces of the main controls (handbrake, footbrake, handlebar, throttle lever, ignition switch, headlight switch, hand gearshift, and foot gearshift) of the utility ATVs. The activation forces of the ATVs' controls were compared with the corresponding strength of youth found in previous reports. The results of this first study demonstrated a physical mismatch between the forces required to operate ATV controls and youth's strength. Turning the handlebar, pressing the footbrakes, and pushing the ATV off were the most difficult tasks for ATV operation. For instance, youth aged 6-10 would be able to activate the footbrake of only 64% of the evaluated ATVs. The inability to depress the footbrake affects the youth's ability to reduce the speed or stop the ATV and can prevent the operator from diverting from obstacles or potential bystanders. The results were even more striking when considering the ability of a youth operator to push the ATV off if pinned underneath it. Less than 13% of all evaluated vehicles could be pushed off by male operators aged 16-20 years old of the 95th strength percentile, the strongest subjects of this study. These discrepancies compromise the youth's ability to ride ATVs, increasing their risk of crashes.

In the second study, potential inconsistencies between the operational requirements of utility ATVs and the anthropometric dimensions of youth were evaluated through virtual simulations in an ergometric software (SAMMIE CAD). The simulations were performed to assess eleven reach-based ATV fit guidelines proposed by several ATV safety advocacy organizations (National 4-H council, CPSC, IPCH, and FReSH). In total, seventeen utility ATVs along with male-and-female-youth of nine different ages (8 – 16 years old) and three height percentiles (5th, 50th, and 95th) were evaluated. The results demonstrated a physical mismatch between ATVs' operational requirements and youth's anthropometry. For example, male-youth aged 16 years old of the 95th height percentile failed to pass at least one out of the eleven fit guidelines for 35% of all vehicles evaluated. The results were even more concerning for female operators. Female youth 10 years old and younger (from all height percentiles) failed to pass at least one fit guideline for all (100%) ATVs evaluated. As such, youth should not ride utility ATVs.

The results from these first two studies provide quantitative and systematic evidence to modify/update current ATV safety guidelines. Furthermore, youth occupational health professionals could use the present findings to prevent ATV-related incidents in agricultural and other settings.

Lastly, in the third study, a device (AgroGuardian) was developed to make online predictions of the likelihood of an ATV rollover based on the ATV characteristics (e.g., length, width, height) and riding conditions (e.g., speed and attitude) and alert the rider in real-time if this likelihood is above a pre-set threshold. In addition, AgroGuardian automatically notifies EMS and emergency contact(s) when a rollover is detected even though no cellular service is available, and the rider is unable to take action.

AgroGuardian includes an embedded data logging system, a smartphone application, and a remote database. The embedded system includes a 3-axis Inertial Measurement Unit (IMU) for attitude (roll, pitch, and yaw) estimation, a low-cost Global Positioning System (GPS) for position estimation, and a Rock7 modem for

off-board communication. To reduce the system's attitude error, a Madgwick filter was implemented to fuse the data from the sensors of the IMU (accelerometer, gyroscope, and magnetometer). Similarly, GPS and IMU data were fused through an Unscented Kalman Filter (UKF) to improve the ATV's position estimate. The smartphone application was developed to receive inputs from the users regarding their machines (e.g., make, model, and characteristics such as width and length), to log information about emergency contacts, and to allow them to interact with their ATV data. The ATV's riding data collected by the sensors in the embedded system along with the ATV characteristics inputted from the user via the smartphone app are fed to a deep neural network to make online rollover predictions. An emergency signal along with the ATV's coordinates are sent off-board through the Rock7 modem and received in the remote database when a rollover is detected by the system. This emergency signal is then processed and sent to EMS and emergency contact(s). The performance of the proposed device was assessed through experimental tests simulating rollover incidents and normal riding conditions. The results indicate that: (1) the device has a rollover prediction system with an accuracy superior to 99%; (2) the device has a rollover detection system with an accuracy superior to 99%; (3) the device has a fast EMS notification time (40.70 s); (4) ATV localization presented an accuracy of 2 m.

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ABBREVIATIONS AND ACRONYMS

Name	Abbreviation
All-terrain vehicle	ATV
American Academy of Orthopedic Surgeons	AAOS
American Academy of Pediatrics	AAP
American College of Surgeons	ACS
American National Standards Institute	ANSI
ATV Safety Institute	ASI
British Standard Institution	BSI
Computer-Aided Design	CAD
Consumer Product Safety Commission	CPSC
Crush Protection device	CPD
Farm and Ranch eXtension in Safety and Health	FReSH
Farm Safety for Just Kids	FS4JK
Hazardous Occupations Orders for Agriculture	AgHOs
Intermountain Primary Children's Hospital	IPCH
Iowa's Center for Agricultural Safety and Health	ICASH
National Children's Center for Rural and Agricultural Health and Safety	NCCRAHS
National 4-H Council	N4-HC
National Institute for Occupational Safety and Health	NIOSH

National Safe Tractor and Machinery Operation Program	NSTMOP
North American Guidelines for Children's Agricultural Tasks	NAGCAT
Occupational Safety and Health Administration	OSHA
Personal Protective Equipment	PPE
Specialty Vehicle Institute of America	SVIA
Three-Dimensional	3D

1 CHAPTER 1 – FORCES REQUIRED TO OPERATE CONTROLS ON AGRICULTURAL ALL-TERRAIN VEHICLES: IMPLICATIONS FOR YOUTH

1.1 ABSTRACT

Farmers are the largest occupational users of All-Terrain Vehicles (ATVs) in the United States (U.S.). Agriculture has the highest percentage of ATV-related occupational injuries (59%) and fatalities (65%) among all U.S. industries. Several studies have shown that youth are largely involved in ATV-related crashes on U.S. farms. Moreover, a number of researchers reported a strong relationship between ATV-related injuries of youth and their physical and mental capabilities. Thus, it is hypothesized that youth are involved in ATV-related incidents because they cannot effectively activate the vehicle controls. There is a need to evaluate the potential mismatches between the youth's physical capabilities and utility ATVs' operational requirements (e.g., reach distances and activation forces of the vehicle's controls).

This study aimed to evaluate potential discrepancies between the required activation forces of eight controls of fifty-four utility ATVs and the strength of youth of varying ages (6-20 years old), genders (males and females), and strength percentiles (5^{th}, 50^{th}, and 95^{th}). A handheld force gauge, a button load cell, and a pressure glove were used to measure the activation forces of the main controls (handbrake, footbrake, handlebar, throttle lever, ignition switch, headlight switch, hand gearshift, and foot gearshift) of the utility ATVs. The data collected was compared with the corresponding youth's strength found in previous studies.

The results of this study demonstrated a physical mismatch between the forces required to operate ATV controls and youth's strength. Turning the handlebar, pressing the footbrakes, and pushing the ATV off are the most difficult tasks for ATV operation. For instance, youth aged 6-10 would be able to activate the footbrake of only 64% of the evaluated ATVs. The inability to depress the foot affects the youth's ability to reduce the speed or stop the ATV and can prevent the operator from diverting from obstacles or potential bystanders. The results were even more striking when considering the ability of a youth operator to push the ATV off if pinned underneath it. Less than 13% of all evaluated vehicles could be pushed off by male

operators aged 16-20 years old of the 95th strength percentile. These discrepancies compromise the youth's ability to ride ATVs, increasing their risk of crashes.

The information learned in this study could be used by policy makers and youth occupational health professionals to prevent ATV-related incidents in agricultural and other settings.

1.2 INTRODUCTION

Agriculture is the most dangerous industry for youth in the United States (U.S.) [1]. From 2003 to 2010, among workers younger than 16 years, the number of worker fatalities in agriculture was consistently higher than in all non-agricultural industries combined [1].

Youth perform various farm tasks, including herding livestock, harvesting produce, and operating farm machinery such as tractors and ATVs. Due to the physical limitations (e.g., strength, anthropometry, field of vision) of youth, some work tasks could be riskier for them than adults, thus increasing their likelihood of being injured or killed. Several studies have shown a strong relationship between the injuries of youth and their ages, anthropometry, and developmental abilities [2-4]. In addition, the results of several studies showed that youth younger than 16 are not capable of safely operating agricultural tractors [5-7].

Based on the literature, one of the most common causes of U.S. farm injuries among youth in agricultural settings is farm machinery [8], with ATVs being either the most frequently cited cause [9,10] or the second after tractors [1,11,12]. Hendricks, Goldcamp [11] reported ATVs as the primary source of vehicle injury for youth on farms, causing 63% of the vehicle-related injuries. According to Weichelt and Gorucu (2018), ATVs were the leading cause of injury in agriculture among youth (0-17) [9]. The number of reported fatalities and nonfatal injuries in the U.S. among youth caused by ATV on "AgInjuryNews.org" were 52 and 26, respectively [9]. Over the years, ATV injuries have increased among farm youth [1,13]. Youth younger than 18 accounted for 36.8% of all ATV-related injuries according to the data from the 2019 National Electronic Injury Surveillance System. Moreover, 15.3% of all those injuries occurred on farms or ranches [14].

ATVs have narrow wheelbase, and high center of gravity [15,16], which make them unstable when traversing rough and uneven terrains or negotiating hills, which are commonly observed scenarios on farms and ranches [17]. Utility ATVs and sport models (which include youth ATV models) have significant design differences. Utility models have higher ground clearance, stronger torque for hauling and towing, rear and front racks for carrying loads or mounting equipment, a hitch to pull implements, and higher weights [18]. In addition, utility models usually have a 12-V power plug, which is uncommon for sport models. For those reasons, utility ATVs are more suitable and more commonly used for farm tasks. As such, in this manuscript, we define the term agricultural (or "ag.") ATVs as utility ATVs that are used on farms. Although some sports models can also be used on farms, this study focuses on the common utility ATVs.

Despite the compelling evidence showing that utility ATVs are unfit for youth, the most commonly used guidelines for ATV-youth fit disregard the rider's physical capabilities. Instead, those recommendations are mainly based upon rider's age [19], vehicle maximum speed [20], vehicle engine size [21] , and farm machinery training certificate [22]. For instance, youth as young as 14 are allowed to operate utility ATVs, while employed on non-family-owned farms if they receive training through an accredited farm machinery safety program [22]. The National Safe Tractor and Machinery Operation Program (NSTMOP) is a project of Hazardous Occupations Safety Training in Agriculture for youth ages 14 and 15. The NSTMOP training includes tractor and ATV education. Students are certified after successfully passing a fifty-question written knowledge exam, as well as an operating skills test and a pre-op/driving test [23]. However, these programs lack adequate coverage of specific ATV-related topics such as active riding and physical matches of ATVs and youth.

It has been hypothesized that many ATV-related injuries occur because youth ride utility ATVs that are not fit for them [19,24-29]. However, there is a lack of systematic and quantitative data comparing utility ATVs' operational requirements and youth's physical capabilities.

Considering that 95% of all ATV-related fatalities involving youth between 1985 and 2009 included utility vehicles [30]; the purpose of this study is to evaluate the mismatches between the operational requirements of agricultural ATVs and the physical capabilities of youth.

To the best of our knowledge, the present study is the first comprehensive study that quantitatively evaluated the mismatches between the forces required to operate the controls of utility ATVs and youth's strength. This study will provide objective evidence to assist in developing evidence-based recommendations for youth regarding the safe operation of utility ATVs. In the absence of such evidence, prior recommendations for ATV operation have been made, largely, based on the rider's minimum age [19-22,31].

1.3 MATERIAL AND METHODS

1.3.1 Study Overview

Fifty-four utility ATVs were evaluated in the present study. Selected models consisted of vehicles of varying sizes and mileages (0 - 4,000 mi) from the most common ATVs on U.S. farms (Honda, Yamaha, Polaris, and CF Moto). Moreover, general descriptive variables such as manufacturer, model, series, engine capacity (cc), drive terrain (4W/2W), transmission, suspension type, and presence of a steering assist system (EPS) were also recorded for further analysis of results.

This study focused on the activation forces of eight main ATV controls of utility ATVs, namely: 1. Handbrake lever, 2. footbrake pedal, 3. steering handlebar, 4. throttle lever, 5. ignition switch, 6. headlight switch, 7. hand gearshift lever, and 8. foot gearshift lever. These controls were selected because they are the most important and frequently used controls in agricultural machines [5]. In addition, the inability of an operator to effectively activate these selected controls would place them and any bystanders at risk of serious injury or fatality. The force required to push the ATV off the operator's body (from an upside-down position) after rollover was also considered, since a significant number of rollover accidents result in the rider being pinned underneath the vehicle and dying by asphyxia [32].

Youth's corresponding strength was compared to the forces required to activate the eight ATV controls and also to the ATV's curb weight (rollover scenario). For each comparison, riders received a binary score (1 if rider's corresponding strength was greater than the force required to activate the control; or 0 otherwise). Riders with a total score of 8 (sufficient strength to activate all 8 controls) were classified as "capable of riding the ATV." On the other hand, riders with a total score below 8 (insufficient strength to activate at least one or more controls) were classified as "not capable of riding the ATV."

1.3.2 Data collection and experimental procedures

1.3.2.1 General descriptive variables

General descriptive variables for each vehicle were divided into five main groups: (1) vehicle identification, (2) drive terrain, (3) transmission system, (4) suspension, and (5) steering system. A summary of all variables is presented in Figure 1.1.

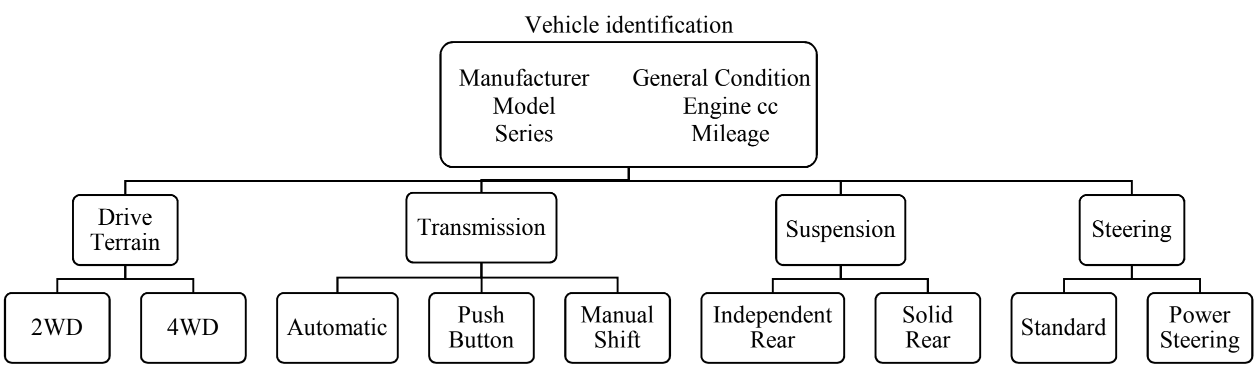


Figure 1.1. General descriptive variables

1.3.2.2 Activation forces of ATV controls

Data collection procedures of the activation forces of vehicle controls were divided into three sections: (a) Braking system, (b) Handlebar steering, and (c) Auxiliary controls. In addition, the forces required to push the upside-down ATV off the operator's body are described in section (d), which is titled "ATV Resistance Force".

(a) Braking System

According to ATV Safety Instructor Carina J. Ellis, “the footbrake pedal controls the rear wheels’ brake; it is generally activated individually (i.e., without the aid of the hand brakes) when riding downhill so that the rider can freely use their hands to control the vehicle” [33]. Also, by only using the rear brakes, the risk of the ATV tipping forward is reduced (by using the hand brakes, the rider can accidentally activate the front brakes as well). Therefore, the footbrake’s activation force was measured in a simulated downhill scenario, as shown in Figure 1.2. The ATVs were placed facing the ground, and the footbrake pedal was completely depressed and then slowly released and pressed again when the ATV started to roll down the ramp. The lowest data point before the ATV started to roll was identified as the minimum force required for stopping the vehicle. For each ATV, the procedure was repeated three times.

Activation forces on the footbrake were measured with a button load cell model 10MR02-500 (Mark 10, Copiague, NY, USA). The load cell was attached to a shoe and connected to a laptop through a USB serial connection during data collection.

Figure 1.2. Foot brake testing, with button (foot)-loadcell interface: (a) side view, and (b) front view

The handbrakes are used for every scenario other than the downhill. Its performance is evaluated based on the vehicle deceleration rate, i.e., the relationship between the time it takes to stop the vehicle entirely and the distance traveled within this time (stopping distance) [34]. Hence, the forces required to activate the handbrake levers were recorded along with their respective stopping distances for further investigation of a potential relationship. This relationship is important because it allows for estimating the minimum force required to brake the vehicle in the shortest distance.

The vehicles were accelerated at a speed of 6.7 m s^{-1} (the most common speed at which ATV accidents occur – [35,36]) on a flat gravel surface. A red tape was placed on the ground to indicate a set point in which the rider should activate the brake, as shown in Figure 1.3. The ATVs were initially placed at a distance of 20 ft from the red tape. The stopping distance was manually measured and recorded.

The tests to measure the forces required to activate the handbrake were divided into three main categories: 1) "test with no brake" (no load is applied to the brake lever), 2) "tests with variable forces" (the rider consciously applies partial depression of the lever), and 3) tests with full brake (brake lever fully depressed). Tests with extreme forces (no brake and full brake) were repeated three times, while the tests with "variable forces" were performed five times because they included a wider range of forces. The forces were plotted against their respective stopping distance, and linear regression (braking distance = a + b activation force^{-1} + c activation force^{-2} – where a, b, and c are constants) was performed to estimate the minimum force required to stop the ATV in the shortest distance. The braking distance would decrease as the force applied to the brake lever was increased. However, the braking distance would plateau once the brake lever was fully depressed, regardless of the force being applied to the brake lever. Therefore, we deemed that the selected relationship was the best model to fit the data (braking distance vs. force applied to the hand brake lever).

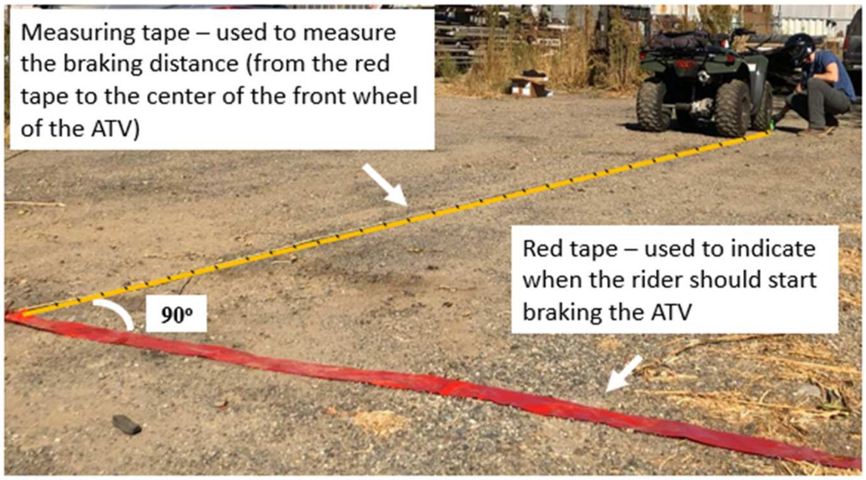


Figure 1.3. Hand brake testing, with red tape to indicate braking point and measuring tape to measure the travel distance

A grip pressure sensor glove (GPSG), BT5010 (SENSOR PRODUCTS Inc., Madison, NJ, USA), was used to measure the forces required to activate the vehicle's handbrakes. The pressure data was converted into force measurements by multiplying the pressure values by the total area of the sensors. Continuous measurements were obtained through a USB serial connection to a portable computer via custom-built software Tactilus 4.1.002rc6, provided with the GPSG system. The GPSG pressure range was 0–100 psi, in 0.1 psi increments. A preliminary test was performed to investigate if different riders would yield different mean force values for a given ATV, as suggested by Kung [37]. Data collected from three different subjects and analyzed through an ANCOVA showed no significant difference between mean values ($p = 0.08$), thus the use of the GPSG was deemed appropriate for data collection.

(b) Handlebar Steering

The handlebar steering test was performed with the vehicle in motion because most ATV incidents occur in motion, and friction forces between soil and tire differ if the vehicle is static versus in motion. Moreover, the resulting force required to turn the handlebar also depends on the soil moisture content, the type of soil (e.g., sand, clay.), and the tire pressure. Since most of the ATVs evaluated in this study were obtained from local farmers and data was collected on their property, we were unable to control the soil type and moisture content during the field tests. However, we ensured that all vehicles had their tires calibrated according to the manufacturer's catalog. Furthermore, whenever it was possible, the handlebar steering experiments were performed on flat gravel surfaces.

Activation forces to steer the handlebar were measured with the GPSG glove system (Figure 1.4). The vehicle was ridden at a constant speed of 5 m s^{-1} in a circular path with a radius of 7.6 m, as show in Figure 1.4. The radius of 7.6 m was selected based on the recommendations of the U.S. ANSI/ROHVA 1-2011 Standard for Recreational Off-Highway Vehicle testing [38]. On the other hand, the speed of 5 m s^{-1} was selected based on the ATVs' dynamic handling test results of Grzebieta et al. (2015). Briefly, this combination of speed and radius produces lateral accelerations (≈ 0.34 g) near the lowest vehicle rollover threshold reported by Grzebieta et al. (2015), which was about 0.36 g for an ATV model Kymco MXU300. In other words, this is a conservative combination that focuses on the rider's safety and would yield a low injury risk for the test rider in the case of an incident [39]. Since we only had one glove to collect the data, tests were conducted in both clockwise and counterclockwise directions, so we could measure the forces required to pull/push the handlebars. All tests were repeated three times in each direction [39], and the forces required to steer the handlebars were identified as the maximum force measured during the all the tests.

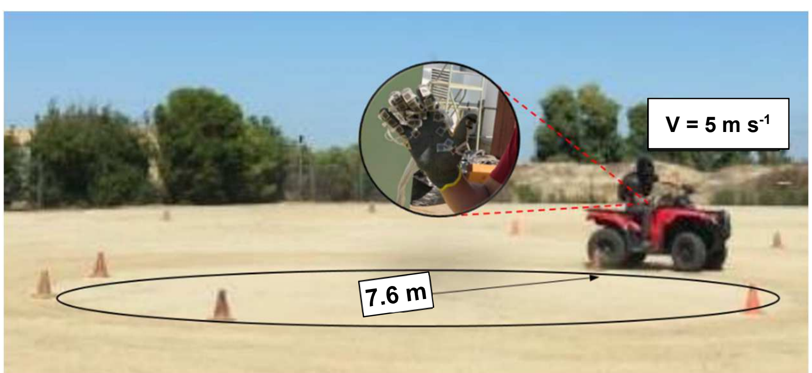


Figure 1.4. Handlebar steering test, with GPSP and cones to indicate the perimeter of the circular path

(c) Auxiliary Controls

The activation forces of the auxiliary controls (ignition switch, headlight switch, throttle lever, hand gearshift, and foot gearshift) were measured with a handheld force gauge model 475055 (EXTECH

Instruments, Waltham, MA, USA) as done for a previous study with agricultural tractors [5]. Continuous and peak force measurements (three replicates for each control) were obtained through an RS-232-to-USB serial connection to a portable computer via custom-built software Extech Data Acquisition 407001A. The force gauge was always placed perpendicular to all ATV controls.

Manufacturer-certified calibration was performed prior to data acquisition procedures for data collection devices used in this project (button-load cell, GPSG, and the hand-held force gauge).

(d) ATV Resistance Force

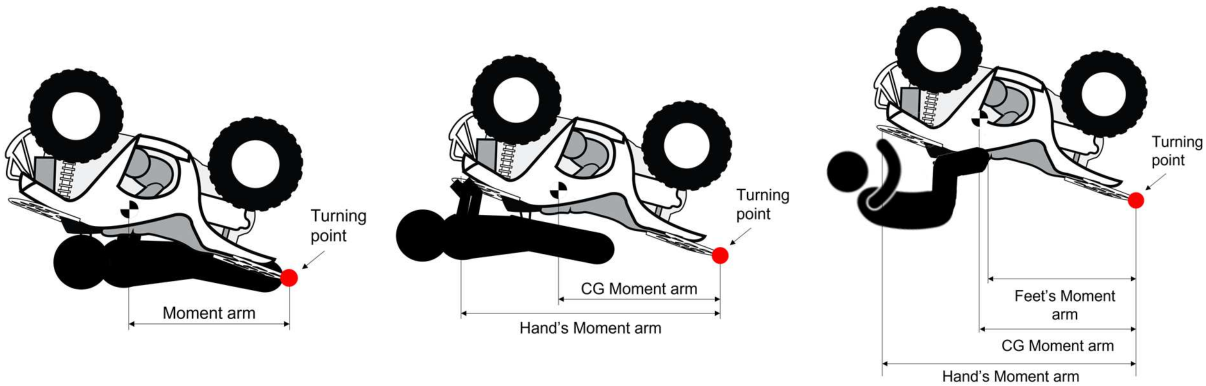
The force required to push the ATV off (from an upside-down position) was calculated as the vehicle's net weight.

It is important to clarify that a rollover can occur under diverse conditions; and therefore, yield different post-rollover configurations (i.e., the final location of the operator and the ATV). To simplify the matter and adopt a conservative approach, we consider three different post-rollover scenarios (Figure 1.5):

1. The ATV is upside-down, and its center of gravity (CG) is standing on top of the rider's chest (rider's moment arm equals the horizontal distance between the ATV's CG and its rear rack). In addition, we consider that the rider has both hands free to push the ATV off but cannot use their legs. We deem that this configuration is the worst-case scenario, and if riders are strong enough to push the ATV off in this case, they are likely able to push the ATV off on all other rollover configurations.

2. The ATV is upside-down, and its front rack/chassis is standing on top of the rider's chest (largest moment arm). In this scenario, we also consider that the rider has both hands free to push the ATV off but cannot use their legs.

3. The ATV is upside-down, and its front rack/chassis is standing on top of the rider's chest, like in scenario 2. The difference is that now we consider that the rider can use both his hands and legs to push the ATV off. This configuration represents the best-case scenario and was useful to assess if our consideration for the worst-case scenario was too restrictive.



(a) (b) (c)

Figure 1.5. Rollover scenarios. (a) Worst-case scenario; (b) Medium difficulty scenario; and (c) Best-case scenario

For the first scenario, the rider's minimum corresponding strength was assumed to be the same as the ATV's curb weight. On the other hand, for the second and third scenarios, the minimum rider's corresponding strength was calculated according to equations (1.1) and (1.2).

$$R_{MCS} = ATV_{CW}\ x\ \frac{Hand's\ moment\ arm}{CG_y} \quad (1.1)$$

$$R_{AS} * Hand's\ moment\ arm + R_{LS} * Feet's\ moment\ arm \leq ATV_{CW} * CG_y \quad (1.2)$$

Where:

R_{MCS}: Rider's minimum corresponding strength

ATV_{CW}: ATV's curb weight

Hand's moment arm: Distance between the point where the rider's hands touch the ATV and the ATV's rear rack

CG_y: Horizontal distance between the CG location and the end of the ATV's rear rack

R_{AS}: Rider's arm strength

R_{LS}: Rider's leg strength (maximum voluntary contraction force – MVC)

Feet's moment arm: Distance between the point where the rider's feet touch the ATV and the ATV's rear rack

For simplification purposes, the hand's moment arm was assumed to be the same as the ATV length, and the feet's moment arm was assumed to be the same as the CG_y. The location of the ATV's CG was estimated from various sources [39-42] due to the lack of exact data.

1.3.2.3 Youths' strength

Youth's physical strength for different body parts (e.g., legs, hands, feet, and fingers) were used from multiple sources [43-45]. Corresponding youth strength and ATV controls are presented in Table 1.1.

Table 1.1. Corresponding youth strength

	Fit criterion	**Corresponding youth strength**
1	Foot brake	Press strength with the foot on a pedal [44]
2	Hand brake	Pull strength on a cylindrical bar - one-hand [43]
3	Handlebar	Push strength on a cylindrical bar - one-hand [43]
4	Throttle lever	Push with thumb [44]
5	Ignition switch	Push with Index finger [44]
6	Headlight switch	
7	Hand gearshift	Pushing force on a convex knob [44]
8	Foot gearshift	Press strength with the foot [44]
9	ATV resistance (worst-case rollover scenario 1)	Push strength on a cylindrical bar - two-hands [43]
10	ATV resistance (scenario 2)	Push strength on a cylindrical bar - two-hands [43]

11	ATV resistance (best-case rollover scenario 3)	Push strength on a cylindrical bar - two-hands [43] + Maximum voluntary contraction force (MVC) of the quadriceps [45]

The mean MVC of each age group (6-10; 11-15, and 16-20) was calculated as the average MVC reported for all youth within that particular age group. For example, the mean MVC of the age group 16-20 was calculated as the average MVC reported for youth aged 16.5 and 17.5.

The corresponding strength for youth of different percentiles (5th and 95th) was estimated based on the standard deviation and mean reported values

1.3.3 Data Analysis

The use of ATVs for work requires the ability to repeatedly engage the vehicle controls [46], which may cause muscle fatigue and injure the operator [47]. To mitigate such outcomes, it is recommended that operators do not apply more than 30% of their maximum strength (recommended exertion) [47]. Thus, the “recommended exertion” is reported in addition to the youth’s strength. For those cases, the forces needed to activate controls that are repeatedly engaged (i.e., brakes, handlebar, and throttle lever) were compared to 30% of the youth’s maximum corresponding strength.

General descriptive variables are presented throughout the text using descriptive statistics. The percentage of observations for which mismatches were observed is presented in tabular form. Bar graphs based on age groups and force scenarios (normal vs. recommended exertion) were used to display the percent of vehicles without any limitations to youth. For comparison, the percentage of observations for which mismatches were observed for an average (50th percentile) adult were also displayed on the bar graphs.

The primary results consist of measures of the activation forces required to activate the main ATV controls and push the ATV off if the rider is pinned underneath it, and the corresponding strength of youth. This study evaluated youth in the age range of 6 to 20 years old, from three strength percentiles (5th, 50th, and

95th). Force measurements of ATV controls were replicated three times for each vehicle. Average force for each ATV model was used in comparing the activation forces to youth's corresponding strength.

Furthermore, some utility ATVs are equipped with electric power steering (EPS), which supplements the torque that the driver applies to steer the handlebar. For this reason, the mean force required to steer the handlebar of ATVs equipped with and without EPS units are displayed jointly and individually in tabular form.

1.4 RESULTS

Fifty-four ATVs were evaluated from eight distinct manufacturers. Around 39 % of the vehicles were brand new, while 73 % (n = 24) of the remaining ATVs were classified as in either good or excellent condition. Engine capacity ranged from 199-686 cc, with most vehicles in the range of 400-686 cc. Moreover, 50% of the ATVs evaluated presented electric power steering (EPS), 4 wheel-drive (77%), solid suspension (61%), and manual transmission (72%).

A summary of descriptive statistics for the controls' findings is presented in Table 1.2. A wide range and high coefficient of variation (CV) were observed for the activation forces of almost all controls. The mean activation force of the handlebar was substantially lower (34%) for ATVs equipped with an EPS unit.

Table 1.2. Descriptive statistics for control activation forces (N)

ATV Controls	Mean (N)	Std (N)	CV (%)	Min (N)	Max (N)
Foot brake	151.3	60.0	39.6	67.2	340.0
Hand brake	21.3	24.3	113.7	1.4	82.2
Handlebar (all)	36.5	25.6	70.0	3.7	75.0
Handlebar (EPS)	29.5	25.1	84.9	3.7	61.6
Handlebar (standard)	45.2	24.4	53.9	3.9	75.0
Throttle lever	13.1	6.8	51.7	4.0	29.8
Ignition switch	12.4	6.4	51.8	3.2	27.2
Headlight switch	10.4	8.8	84.2	1.3	35.2
Hand gearshift	41.8	29.0	69.5	3.0	104.6
Foot gearshift	57.9	8.8	15.2	47.0	75.0

ATV curb weight	2700.0	512.6	19.0	1677.0	4070.1

Findings for corresponding youth strength vs. activation forces of individual controls are presented in Table 1.3 (males) and Table 1.4 (females). The auxiliary controls presented low difficulty for youth of all age groups and genders. For instance, all simulated youth were able to activate the headlight switch of 89.4% of all ATVs evaluated, the throttle lever and the foot gearshift of all ATVs, and the hand gearshift of 69.4% of the ATVs. A common characteristic among all controls with a high success rate is that they consist of either switches or levers and are mainly operated with the fingers (e.g., index finger or thumb). Moreover, the handlebars also have very low difficulty for youth (males can operate 100% of the handlebars while females can operate at least 96.6% of the handlebars – Tables 1.3 and 1.4).

On the other hand, the simulations revealed that vehicles' footbrake presented severe difficulty to the youth. For instance, 6-10 years-old males of the 5th strength percentile were able to activate only 22.7% of all evaluated footbrakes. The inability to depress either the foot or the handbrakes affect the youth's ability to reduce the speed or stop the ATV. In addition, failing to reduce the vehicle speed can prevent the operator from diverting from obstacles or potential bystanders. These are critical findings since several studies have shown that most ATV crashes include hitting a stationary object [48-52].

Table 1.3. Percent of observations (n = 54) for which controls did not limit ATV usage by male children of various age and strength percentiles.

Age group	6-10			11-15			16-20		
Percentile	5th	50th	95th	5th	50th	95th	5th	50th	95th
Footbrake	22.7	63.6	79.5	63.6	97.7	100	68.2	100	100
Footbrake*	**0**	**0**	**0**	**0**	**9.1**	**31.8**	**0**	**34.1**	**81.8**
Handbrake	100	100	100	100	100	100	100	100	100
Handbrake*	**70**	**95**	**100**	**90**	**100**	**100**	**100**	**100**	**100**
Handlebar	100	100	100	100	100	100	100	100	100
Handlebar *	**48.3**	**96.6**	**100**	**48.3**	**100**	**100**	**48.3**	**100**	**100**
Throttle lever	100	100	100	100	100	100	100	100	100
Throttle lever*	**75.7**	**94.6**	**100**	**75.7**	**100**	**100**	**100**	**100**	**100**
Ignition switch	100	100	100	100	100	100	100	100	100

Headlight switch	93.6	100	100	100	100	100	100	100	100
Hand gearshift	97.2	100	100	77.8	100	100	100	100	100
Foot gearshift	100	100	100	100	100	100	100	100	100
Rollover (scenario 1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rollover (scenario 2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0
Rollover (scenario 3)	0.0	0.0	0.0	0.0	0.0	11.1	0.0	11.1	40.7
Total (controls only)	33.3	70.4	83.3	61.1	98.1	100	74.1	100	100
Total (rollover scenario 1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (rollover scenario 2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0
Total (rollover scenario 3)	0.0	0.0	0.0	0.0	0.0	11.1	0.0	11.1	40.7
Total* (controls only)	**13**	**18.5**	**18.5**	**14.8**	**25.9**	**44.4**	**18.5**	**46.3**	**85.2**

*Reasonable to exertion force

The simulations involving most youth of all age and gender groups indicated that they cannot push the ATV off for all considered rollover scenarios (i.e., corresponding strength is less than the vehicle's weight). For example, a male youth aged 16-20 from the 95th percentile (strongest group of subjects) could only push off 40.7% of the ATVs for our best-case scenario. That number is significantly smaller (13% and 0%) for the second and first scenarios, respectively. The results are even more striking for female subjects since females could only push off 11.1% of the evaluated ATVs for our best-case scenario and 0% of the ATVs evaluated for the worst-case scenario. A similar trend is observed for the activation forces of the footbrakes as well.

Table 1.4. Percentage of observations (n = 54) for which controls did not limit ATV usage by female children of various age and body-size percentiles.

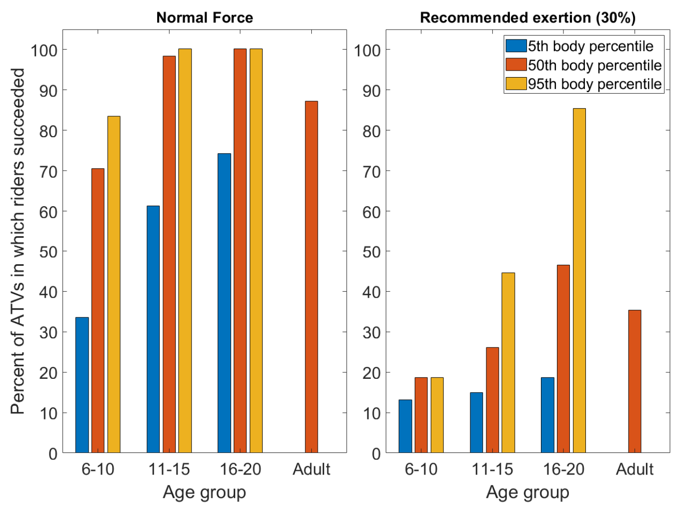
Age group	6-10			11-15			16-20		
Percentile	5th	50th	95th	5th	50th	95th	5th	50th	95th
Footbrake	2.3	63.6	95.5	29.5	77.3	100	9.1	88.6	100
Footbrake*	**0**	**0**	**6.8**	**0**	**0**	**29.5**	**0**	**0**	**40.9**
Handbrake	100	100	100	100	100	100	100	100	100
Handbrake*	**70**	**87.5**	**100**	**92.5**	**100**	**100**	**100**	**100**	**100**
Handlebar	96.6	100	100	100	100	100	100	100	100
Handlebar *	**34.5**	**72.4**	**100**	**48.3**	**96.6**	**100**	**96.6**	**100**	**100**
Throttle lever	100	100	100	100	100	100	100	100	100
Throttle lever*	**51.4**	**83.8**	**100**	**70.3**	**97.3**	**100**	**100**	**100**	**100**
Ignition switch	92.3	100	100	100	100	100	100	100	100
Headlight switch	89.4	100	100	95.7	100	100	100	100	100

Hand gearshift	69.4	100	100	91.7	100	100	100	100	100
Foot gearshift	100	100	100	100	100	100	100	100	100
Rollover (scenario 1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rollover (scenario 2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7
Rollover (scenario 3)	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	11.1
Total (controls only)	18.5	70.4	96.3	37	81.5	100	25.9	90.7	100
Total (rollover scenario 1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (rollover scenario 2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7
Total (rollover scenario 3)	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	11.1
Total* (controls only)	**13**	**16.7**	**24.1**	**14.8**	**18.5**	**42.6**	**18.5**	**18.5**	**51.9**

*Reasonable to exertion force

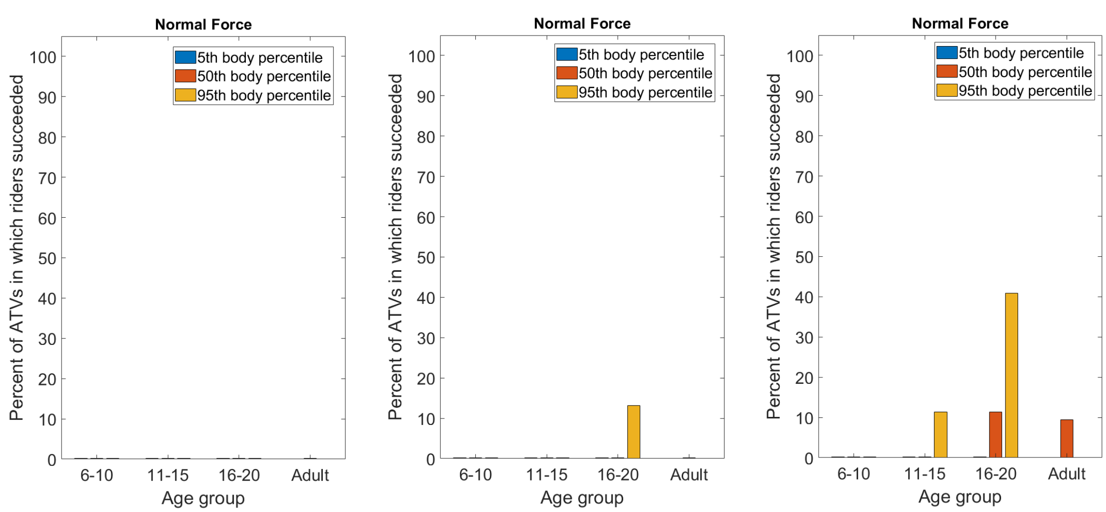
The results indicated that a 6-10-year-old male youth from the 5th strength percentile can activate the hand gearshifts (97.2%) of a larger percentage of the evaluated ATVs compared to an 11-15-year-old male youth of the same strength percentile (77.8%). A similar trend is observed when comparing the percentage of footbrakes that 11-15 and 16-20-year-old female subjects of the 5th strength percentile can activate. Although unexpected, the results are in accord with the original youth strength data [43-45] used in the present study.

The percent of ATVs in which riders passed all criteria is presented in Figure 1.6, Figure 1.7 (males), Figure 1.8 and Figure 1.9 (females). The results indicate that most youth from the 50th and 95th percentiles are strong enough to operate the controls of a large number of the evaluated ATVs. For instance, the average (50th percentile) female operator aged 6-10 is capable of operating the controls of 70.4% of all evaluated ATVs. That number increases sharply for older youth or youth of the same age but higher strength percentile. A similar trend was also observed for male operators. On the other hand, the plots of totals highlight that most operators cannot push the ATV off if pinned underneath it (Figure 1.6 and Figure 1.9).



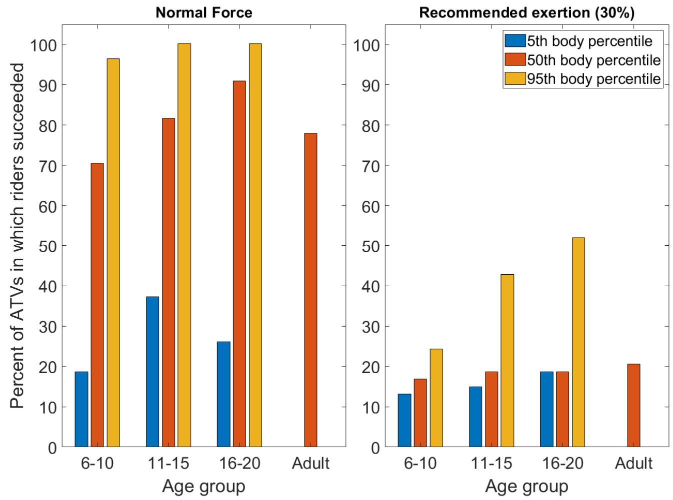
(a) (b)

Figure 1.6. Percent of observations (n = 54) for which male youth passed all criteria (controls only). (a) Normal force and (b) Recommended exertion.



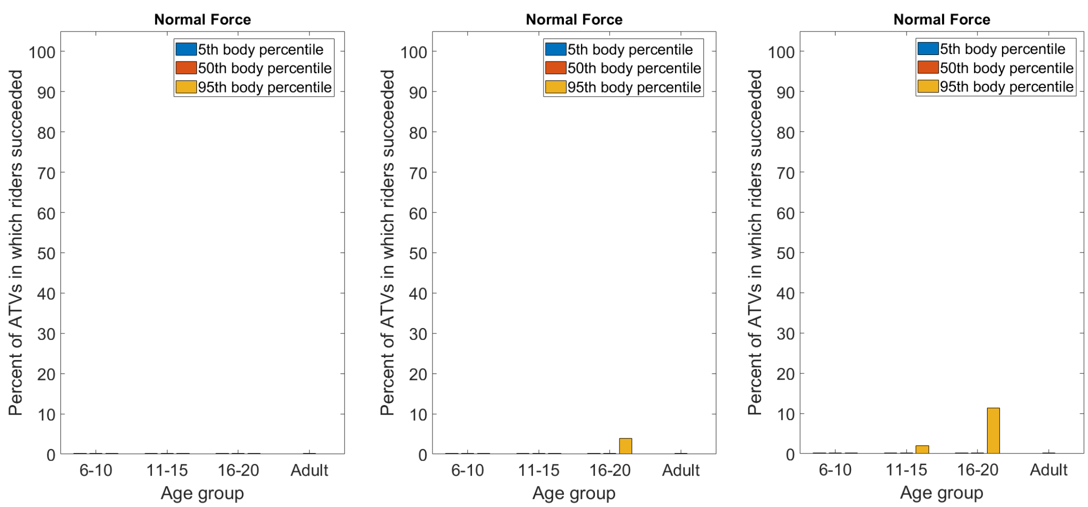
(a) (b) (c)

Figure 1.7. Percent of observations (n = 54) for which male youth passed all criteria (a) controls and rollover scenario 1, (b) controls and rollover scenario 2, and (c) controls and rollover scenario 3.



(a) (b)

Figure 1.8. Percent of observations (n = 54) for which female youth passed all criteria (controls only). (a) Normal force and (b) Recommended exertion.



(a) (b) (c)

Figure 1.9. Percent of observations (n = 54) for which female youth passed all criteria (a) controls and rollover scenario 1, (b) controls and rollover scenario 2, and (c) controls and rollover scenario 3.

A clear trend in the results indicates that older youth were capable of riding a larger percentage of ATVs. This trend indicates that they are less likely to get involved in ATV accidents compared to their younger counterparts. Similar findings were also observed by other studies that evaluated the fit of youth for agricultural vehicles [5,6,53]. Data from the U.S. Consumer Product Safety Commission (CPSC) [54] support the present findings, as youth younger than 12 years old have a higher death rate than youth aged 12-15.

An interesting observation is related to the "recommended exertion" scenario (Figures 6b and 8b); all operators, including adults, are at risk when comparing "recommended exertion" with normal forces. The number of ATVs without limitations in footbrake, handbrake, handlebar, or throttle-lever decreases sharply for youth of all ages and strength percentiles. For instance, the handlebar, which did not present any significant difficulties for youth under normal conditions, becomes a factor of concern as males aged 16-20 of the 5th percentile can only activate the handlebars of 48% of all evaluated ATVs. Furthermore, the percentage of ATVs without limitations on the footbrake for females aged 16-20-years of the 95th percentile decreased from 100% (under normal conditions) to 40.9% under "recommended exertion."

The "recommended exertion" scenario also affects the percentage of ATVs without limitations in any controls for youth ("Totals"). The average male operator aged 16-20 presented a drop of 53.7% in the total percentage of ATVs without limitations. The results were even more striking for the females, as the average female operator aged 16–20-year presented a drop of 72.2% of the evaluated ATVs. These results provide quantitative evidence that youth cannot continuously activate some ATV controls, i.e., youth (and adults) should not be riding utility ATVs for extended periods, such as work.

1.5 DISCUSSION

The present results indicated mismatches between youth's strength and utility ATVs' operational requirements, especially for the footbrake, and the forces required to push off an ATV if pinned underneath it. Common causes of fatal and traumatic injury involving ATVs include rollovers and collisions [48,50,55,56]. These causes imply a functional loss of control of the vehicle or a failure to avoid unexpected hazards [5]. The inability of youth to properly activate the vehicles' controls with 100% certainty likely increases their exposure to incidents and consequently injuries or fatalities.

The simulations related to rollover incidents indicated that most youth cannot push the ATV off if pinned underneath it. This raises serious concern about riders' safety. Previous studies reported that 68% of farmworkers get pinned under the ATV after a rollover accident, and 42% of those operators die due to mechanical asphyxia [32]. Injuries and fatalities due to mechanical asphyxia can be reduced by the proper design and installation of a Crush Protection Device (CPD) [57]. CPDs provide a crush protection clearance for the rider in an overturned ATV [58]. Making CPDs mandatory for ATVs ridden by youth would likely improve riders' safety.

Our data indicates that most youth aged 16-20 of the 50th and 95th strength percentiles would be able to activate the controls of a larger percentage of the evaluated ATVs compared to a 50th strength percentile adult. That unexpected result is likely due to the high variability in the strength of adults, and the common decrease in muscle mass and strength with age, especially for adults after the age of 60 when compared to those under the age of 30 [59,60].

Current ATV-youth fit guidelines are mainly based on the rider's age and vehicle engine size. However, these recommendations are not supported by the present findings, which clearly showed that there were youth who could effectively activate all, some, or none of the ATVs' controls evaluated, regardless of vehicle's engine size. As such, engine size and rider's age alone are poor indicators of youth-ATV fit.

Despite the data showing a clear trend in which older youth can safely ride a higher percentage of ATVs, this can create a false sense of preparedness. Other factors may also affect the rider's safety, such as their psychological and cognitive development, personal traits (e.g., thrill-seeking), and their riding experience [31,61,62]. In this regard, parents' assessment is critical to determine whether and to what extent youth should be involved in ATV operations.

1.5.1 Study limitations

There are several limitations of this study that need to be considered when interpreting the results. Youth strength tests were not designed to evaluate their capability of activating ATV controls. Instead, the data is a subset of a larger dataset to provide designers with ergonomics data for use in the design of safer products

[44]. Unfortunately, no analogous data were available to describe the specific forces required for youth to operate ATVs. The present study is the first to provide such information.

In addition, the corresponding strength for youth of different percentiles was estimated based on reported mean and standard deviation values, using the standard normal table (Z table). To make these estimates possible, we had to assume that the original data was normally distributed, which may not be the case. This issue could be addressed if the dataset containing individual observations was available.

Another limitation concerns the ATV models evaluated in this study. Although we used a systematic approach to identify common ATVs used in the U.S., the sample is subject to sampling error and is not necessarily representative of the models ridden specifically by youth. Moreover, safe and effective riding of utility ATVs involves consideration of issues other than the forces required to operate its controls. ATVs are rider-active; that is, the rider must be able to shift their body weight to safely perform maneuvers such as turning, negotiating hills, and crossing obstacles [63].

Several limitations are related to the general condition of the evaluated ATVs. Even though an ATV may appear to be in a good general condition, that does not necessarily imply that all specific systems (e.g., brake and steering systems) are working properly, which could modify the activation forces of their respective controls. This issue may limit the generalizability of the results. It could be addressed by inquiring from ATV owners about their last inspection/maintenance.

Lastly, the measurements of activation forces for the handbrake, footbrake, and handlebar were not obtained using standard methods (e.g., as described by the Society of Automotive Engineers – SAE or ISO standards). Since the forces of those controls are affected by many factors such as ground conditions and tire abrasion, which are difficult to control, the study's approach adopted conservative (minimal force) alternative methods.

1.6 CONCLUSIONS

This study evaluated the potential mismatches between youth's strength and the forces required to safely operate eight different controls of fifty-four utility ATVs. The main findings were that: (1) the activation forces required to operate utility ATVs typically exceed the strength of most youth aged 6-20 years old, especially females; (2) youth should not operate ATVs continuously for extended periods (e.g., work) – for instance, the typical 16-20 year-old male of the 50th strength percentile is not strong enough to operate at least 50% of all evaluated ATVs; (3) the ability to activate ATVs' footbrake along with the ability to push off the ATV if pinned underneath are the most critical factors to determine whether youth are capable of riding based on their strength; (4) only engine size and rider's age are poor indicators of youth-ATV fit.

These findings raise serious concern about the ability of youth to safely operate utility ATVs in common use on U.S. farms. As such, the readiness of youth to ride ATVs, especially for occupational purposes, should be carefully evaluated by their parents/guardians.

Furthermore, the present data brings to question the validity of current youth-ATV fit guidelines as ATV engine size and rider's age seem to be inadequate for determining whether or not a youth is strong enough to operate the controls of a utility ATV. Therefore, there is a need to review and update current youth-ATV fit guidelines. Those guidelines should include recommendations based on quantitative and systematic data comparing the physical ability of youth and the operational requirements of ATVs.

Overall, a mixed approach combining engineering redesign, policymaking, parent involvement, and safety education is needed to prevent ATV injuries in youth of all ages [62].

2 CHAPTER 2 – ABILITY OF YOUTH OPERATORS TO REACH AGRICULTURAL ALL-TERRAIN VEHICLES' CONTROLS

2.1 ABSTRACT

The use of All-Terrain Vehicles (ATV) as a working machine represents a heavy burden to the American public health system. ATV death rates in the U.S. occupational sector dramatically increased by 275% from 1992 to 2007, primarily led by youths younger than 16 years old. The agricultural industry is the most dangerous for youths, with ATVs being the most frequently cited cause of incidents. Moreover, several researchers identified a correlation between ATV-related injuries of children and their physical capabilities, which mainly comprise anthropometric dimensions and physical strength. Therefore, it is hypothesized that youths are frequently involved in ATV-related incidents because they ride vehicles that are unfit for them. There is a need to assess the fit of Agricultural ATVs for children based on youths' anthropometric dimensions.

This study focused on evaluating potential inconsistencies between the operational requirements of utility ATVs and the anthropometric dimensions of youth through virtual simulations. Virtual simulations were performed to assess eleven youth-ATV reach criteria proposed by several ATV safety advocacy organizations (National 4-H council, CPSC, IPCH, and FReSH). In total, 17 utility ATVs along with male-and-female-youth of nine different ages (8 – 16 years old) and three height percentiles (5^{th}, 50^{th}, and 95^{th}) were evaluated.

The results demonstrated a physical mismatch between ATVs' operational requirements and youth's anthropometry. As such, youth should not ride utility ATVs. This study provides quantitative and systematic evidence to modify/update current ATV safety guidelines. Furthermore, youth occupational health professionals could use the present findings to prevent ATV-related incidents in agricultural and other settings.

2.2 INTRODUCTION

The use of utility All-Terrain Vehicles (ATVs) as working machines adds a heavy burden to the American public health system [50]. According to data from the 2019 National Electronic Injury Surveillance System, over 95,000 emergency department (ED) visits were due to an ATV-related incident. Around 36.8% of those ED visits involved youth younger than 18 years old, and 15.3% of the incidents happened on farms or ranches [14]. Indeed, using utility ATVs in the farm setting is extremely dangerous for youth; ATVs are the most frequently cited cause of incidents [9,10] or the second after tractors [1,11,12].

ATVs have low-pressure tires, narrow wheelbase, and high center of gravity [15,16,64]. Utility ATVs and sport models (which include youth ATV models) have several design differences. Utility models have higher ground clearance, stronger torque for hauling and towing, rear and front racks for carrying loads or mounting equipment, a hitch to pull implements, and higher weights [18]. Accordingly, utility ATVs are more suitable and more commonly used for tasks in the agricultural setting. Therefore, in this manuscript, we define agricultural (or "ag.") ATVs as utility ATVs used on farms and ranches.

Agricultural ATVs have heavy weights and fast speeds that require complex maneuvering. Youth's physical capabilities may not be sufficient to perform those complex maneuvers correctly. In fact, many studies have shown that youth are more vulnerable to injuries than adults because of their less developed physical capabilities and psychological and behavioral characteristics [2,3,65-70], which likely affect their ability to safely operate agricultural vehicles [5-7,53]. Furthermore, previous studies have shown that ATV-rider misfit is another important risk factor [53,71].

Despite compelling evidence showing that utility ATVs are unsuitable for youth, the most popular guidelines for ATV-youth fit disregard the rider's physical capabilities. Instead, those recommendations are mainly based on the rider's age [19], vehicle's maximum speed [20], vehicle's engine size [21], or farm machinery training certificate [22]. For instance, youth as young as 14 can operate utility ATVs while employed on non-family-owned farms if they receive training through an accredited farm machinery safety program, such as the National Safe Tractor and Machinery Operation Program (NSTMOP) [22]. The

NSTMOP training includes tractor and ATV education, where students must pass a written knowledge exam and a functional skills test to receive a certificate [23]. Nevertheless, programs such as the NSTMOP lack appropriate coverage of specific ATV-related subjects such as active riding and physical matches of ATVs and youth.

The riders' physical inability to operate ATV's controls properly increases their chance of incidents and consequently leads to injuries and fatalities. In addition, the traditional guidelines adopted to fit ATVs for youth are inconsistent in evaluating their preparedness to ride. The suggested fitting criteria are subject to variances in state law and lack scientific-based evidence. While some recommendations based upon the riders' physical capabilities exist [21,61,63,72], the adoption of these recommendations has not gained attention because they are not comprehensive and lack quantitative and systematic data.

Recommendations based on riders' physical capabilities appear to provide a better foundation to determine if the machine is suitable for the rider [53]. Therefore, there is a need to evaluate youth-ATV fit based on the riders' physical capabilities (anthropometry, strength, and field of vision).

Since 95% of all ATV-related fatalities involving youth between 1985 and 2009 included ag. ATVs [30], the purpose of this study is to evaluate the mismatches between the operational requirements of utility ATVs and the physical capabilities of youth.

It has been hypothesized that youth are mainly involved in ATV incidents because they ride vehicles unfit for them. This study evaluated ergonomic inconsistencies between youth's anthropometric measures and utility ATVs' operational requirements. The ability of youth to safely operate ATVs was evaluated through computer simulations that comprised 11 fit criteria and male-and-female youth of varying ages (8-16 years old) and height percentiles (5^{th}, 50^{th}, and 95^{th}) operating 17 utility ATV models.

2.3 MATERIAL AND METHODS

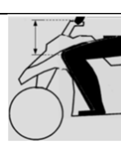
This study evaluated the conformity of youth to fit guidelines (dependent variable) because the ability of youth to properly reach the ATV controls dictate their ability to ride safely [6,53,61]. Youth-ATV fit was analyzed through virtual simulations and was carried out in five steps. First, we identified 11 guidelines for the fit of youth and ATVs. The second step consisted in identifying a database containing anthropometric measures of youth of various ages (8-16 years old), genders (males and females), and height percentiles (5^{th}, 50^{th}, and 95^{th}). The third step consisted of collecting the dimensions of 17 ATV models to create a three-dimensional (3-D) representation of them. The fourth step consisted of using SAMMIECAD (SAMMIE CAD Inc., Leics., UK) and Matlab (Matlab, v2021a; Mathworks, Natick, MA) to evaluate if the youth's anthropometric measures conform to the guidelines identified in step one. Lastly, we validated the results of the virtual simulations in field tests with actual riders and ATVs.

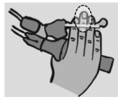
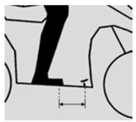
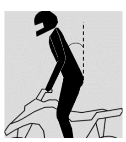
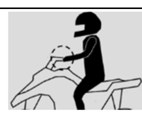
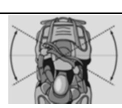
2.3.1 Fit Criteria

The fit criteria provide movement-restraint thresholds that check if the rider can safely reach all controls and perform active riding, which requires the operator to shift their center of gravity to maintain the vehicle's stability, especially when turning or traveling on slopes [73]. Maintaining a correct posture is essential because otherwise, the rider's ability to control the vehicle is compromised, which puts them and potential bystanders at risk.

The reach criteria considered in this study were selected based on the recommendations of the following institutions: (a) National 4-H Council [63], (b) U.S. Consumer Product Safety Commission (CPSC) [21], (c) Intermountain Primary Children's Hospital (IPCH) [72], and (d) Farm and Ranch eXtension in Safety and Health (FReSH) Community of Practice [61]. Disregarding overlaps, these guidelines consisted of 11 anthropometric measures of fit, which are presented in Table 2.1 below.

Table 2.1. ATV-rider reach fit criteria

ID	Criterion		Institution(s)	"Fit success"
1	Handlebar-knee distance		National 4-H Council, CPSC	Handlebar–knee distance > 200mm. This is necessary to ensure the rider can reach the handlebar and steer around obstacles.

2	Hand size compared to ATV handlebar reach		National 4-H Council, IPCH	With hand placed in the normal operating position and fingers straight out, the first joint from the tip of the middle finger extends beyond the brake lever. This is important to guarantee that the rider can activate the brake lever.
3	Brake-foot position		National 4-H Council	Distance from the "ball" of the foot (at its most rearward position in the ATV's foot well) to the brake pedal divided by the length of the foot < 105%. A disproportional rate indicates a risk for ineffective foot–brake operation.
4	Standing-seat clearance		National 4-H Council, CPSC, FReSH	Clearance zone between rider's crotch and ATV seat > 150 mm. This is important to guarantee that the rider can rise the torso up from the ATV seat to maintain balance and avoid distracting longitudinal torso impacts that occur while traversing rough terrains.
5	Elbow angle		National 4-H Council, IPCH	A narrow elbow angle ($< 90^{o}$) indicates excessive arm flexion, while an angle too wide ($> 135^{o}$) indicates the arms are excessively straight due to the grips being too far apart, which forces the rider to lean the torso to the outside of the turn to achieve an adequate range of handlebar turning
6	Upper leg		National 4-H Council	Upper leg within 10^{o} of parallel to the ground. An upper leg too far off from parallel to the ground can compromise the rider's ability to activate the foot brake and keep balance.
7	Angle of lean from vertical		CPSC	Angle of lean from vertical $< 30^{o}$. This is important to guarantee a correct posture while riding the ATV. If the rider is too tall, they may have to lean forward significantly over the handlebars to steer when raised off the seat, which might shift the system's center of gravity and increase the likelihood of the ATV tipping forward.
8	Control reach		CPSC	Riders must be able to reach all ATV controls while seated upright.
9	Footrest reach		CPSC	Riders must keep their feet firmly on the footrests when not activating the foot-brakes. This is important to ensure the rider can maintain balance and not lose control of the ATV.
10	Knee angle		CPSC	Knee angle at least 45^{o} while sitting and with the feet flat on the footrest. An angle wider than 45^{o} indicates a risk for ineffective foot-brake operation.
11	Control grip		CPSC, FReSH	Riders must keep a grip on the handlebar and maintain throttle and brake control when turning the handlebar

	from lock to lock position. This is especially important while performing a sharp turn or a swerve.

2.3.2 Human Mockups

Human mockups were developed in SAMMIE CAD. This computer program allows users to create customized virtual humans based on eight anthropometric dimensions, as shown in Figure 2.1. In total, 54 youth mockups were created, a combination of two genders, nine ages (8-16), and three body size percentiles in height (5^{th}, 50^{th}, and 95^{th}). This age range was selected because most youth start operating farm machinery at 8 years old [65], and most ATV-related crashes occur with riders younger than 16 years old [30]. Two adult mockups (male and female of the 50^{th} body-size percentile) were also created to establish a baseline for comparisons. The anthropometric measures used as input to SAMMIE CAD were retrieved from the database of Snyder et al. (1977), which includes measurements from 3,900 subjects from 2 to 18 years of age for both genders [74]. The adopted anthropometric measures were based on the mean values of groups of subjects with the same age, gender, and height.

Some of the required inputs were not available in the database used for this study, such as shoulder breadth, seated shoulder height, and arm length. For those cases, the missing inputs were computed using the available data. For example, the shoulder breadth was assumed to be the same as the biacromial breadth; the seated shoulder height was calculated by subtracting the head and neck length from the seated height. In another example, the arm length was assumed to be the same as the acromion-fingertip length (Figure 2.2).

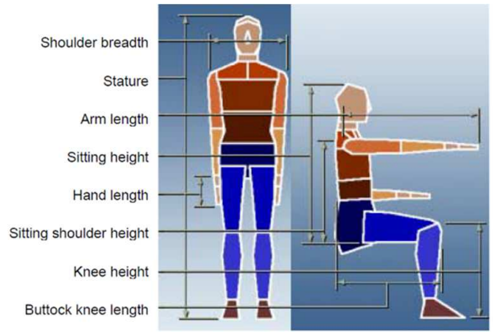
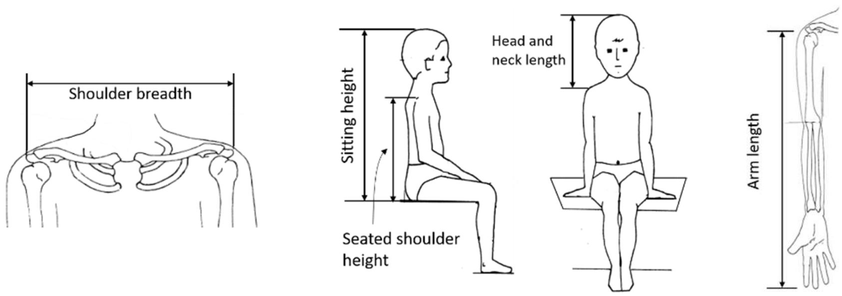


Figure 2.1. SAMMIE CAD human creation. Selected input variables. Source: SAMMIE CAD Inc.



(a) (b) (c)

Figure 2.2. Interpolation of missing variables. (a) Shoulder breadth; (b) Seated shoulder height; (c) Arm length

2.3.3 ATV Mockups

In total, we evaluated 17 utility ATV models. Selected models consisted of vehicles of varying engine sizes (200-700 cc) from the most common ATV manufacturers on U.S. farms (Apollo, Arctic Cat, CF Moto, Honda, Polaris, and Yamaha). Moreover, general descriptive variables such as manufacturer, model, series, engine capacity (cc), drive terrain (4W/2W), transmission, and suspension type were recorded for data maintenance purposes.

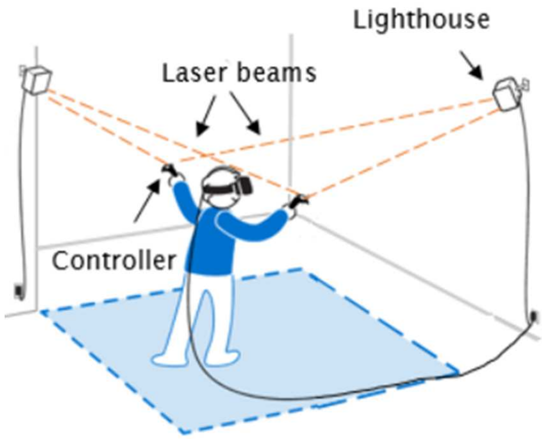
ATV mockups were developed based on the spatial coordinates (X, Y, Z) of selected ATV features (e.g., ATV seat, chassis, handlebars, footrests, and controls). An original attempt to record spatial coordinates of ATV features consisted of using Photogrammetry, a technique in which several pictures of an object are taken from various angles and then processed to create a 3-D model. Nevertheless, this technique proved inefficient, as initial trials were time-consuming, and the results had unsatisfactory accuracy. A second attempt consisted of using a virtual reality (VR) tracking system. This alternative proved fast and reliable (accuracy of ±1 mm); hence this technique was selected.

2.3.3.1 Data acquisition

The VR tracking system (Vive – HTC Corporation, China) utilized in this experiment consisted of two controllers and two infrared laser emitter units ("lighthouses"), as shown in Figure 2.3. The system allows the user to move in 3-D space and use motion-tracked handheld controllers to interact with the environment. The system uses the lighthouses to shoot horizontal and vertical infrared laser sweeps that are detected by photodiodes positioned in the surrounding of the controller's surface [75]. The position and orientation of the controllers are calculated by the difference in time at which each photodiode is hit by the laser [76]. By placing the controller over selected vertices of ATV features, it was possible to record their spatial coordinates, which allowed the development of the 3-D ATV mockups.

A custom program was developed to calibrate the system, log, and manipulate data. This program was initially retrieved from Kreylos (2016) [76] and then modified to meet the specific needs of the present study. The software runs in Linux operating systems and has several functionalities that are useful to the user. Examples of these functionalities are a 3-D grid, which allows for real-time visualization of labeled points, and a measuring tool (which can be used to verify if the measurement scale makes sense).

A probe was custom-manufactured and attached to the controllers to ease the calibration process and data collection. The probe was made of metal and had a rounded tip, which made it wear-resistant and prevented it from damaging the ATVs. The measurements were collected inside a tent covered by a white rooftop that reduces the interference of solar rays in the communication between the lighthouses and the photodiodes in the controllers (Figure 2.3). In total, 38 points were collected per ATV. The points were selected aiming to get an efficient representation of all selected ATV controls (hand brake lever, foot brake pedal, steering handlebar, throttle lever, hand gearshift lever, foot gearshift pedal, ignition switch, headlight button, and other auxiliary controls) and additional features that were used to assist the virtual simulations, such as the seat and the footrests. After data filtering, the measurements were processed in SAMMIE CAD for a 3-D representation of the vehicle evaluated.



(a)

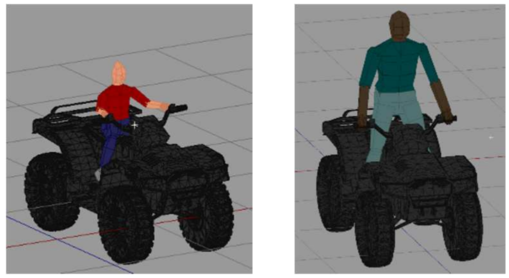
(b)

Figure 2.3. Data acquisition. (a) Visual schematics of the VR tracking system, (b) Field procedure.

2.3.4 Data Analysis

ATV-rider fit was evaluated through computer simulations in two programs: an ergometric analysis software (SAMMIE CAD) and a numerical computing software (Matlab).

Fit criteria 4, 5, 6, 7, 8, 9, and 10 were evaluated in SAMMIE CAD because their assessment involved complex interactions between riders and ATVs, such as measuring the angle of the rider's knee while riding. SAMMIE CAD provides a 3-D environment and full control of human mockups, which makes it possible to evaluate those complex interactions. The simulations performed in SAMMIECAD consisted of (1) creating 3-D human mockups; (2) creating 3-D ATV mockups; and (3) integrating (1) and (2) in the virtual environment to simulate their interaction. For each simulation, the correct reach posture was achieved by positioning the human limbs according to the specific task's requirement. For example, a seated position was adopted when evaluating reach fit criterion 10 (knee angle), as shown in Figure 2.4a. On the other hand, a standing straddling posture was selected when evaluating reach fit criterion 4 (clearance zone between the rider's crotch and ATV seat), as shown in Figure 2.4b.



(a) (b)

Figure 2.4. Different reach postures. (a) Seated posture (9 years old - 5th percentile boy); (b) Standing straddling posture (18 years old – 95th percentile boy).

Some criteria involve the youth reaching a specific control (e.g., criteria 5, 7, 8, and 9). We used the feature “Reach” under the “Human” menu on SAMMIE CAD to evaluate the ability of the youth mockups to reach the selected controls. The “Reach” was set as “Absolute,” and “Object Point” was set as “Control.” When the selected control could be successfully reached, the software would display an animation of the human limb reaching the desired object (the rider was assigned a score of 1 – meaning that they fulfilled the requirements of that criterion). On the contrary, when the object was out of reach, SAMMIE CAD would show an error window and display the required distance for the human limb to reach the desired control (the rider was assigned a score of 0 – meaning that they failed to pass that specific criterion).

Simulations involving buttons and levers were performed with the fingertip of the index finger or the thumb, accordingly. Simulations involving levers or the handlebars were performed with palm-grip-hand postures. All controls on the right side of the ATV were simulated with the right hand/foot, and all controls on the left side of the ATV were simulated with the left hand/foot. Specific controls that required using both hands, such as the handlebars, were simulated with both hands.

Criteria 1, 2, 3, and 11 were evaluated through Matlab because their assessment required the computation of simpler calculations, such as the distance between the rider’s knee and the ATV’s handlebars. We wrote a code based on conditional statements to assess whether riders’ anthropometric measures conformed to the constraints imposed by the ATV design. For instance, when evaluating criterion 1, the distance between the ATV footrests and the handlebars minus the rider's knee height must be greater than 200 mm (Table 1).

It is important to highlight that all simulations could have been performed in SAMMIE CAD. However, Matlab has the fundamental advantage of automation, which allows much faster computation of the data. In addition, some simulations performed in Matlab were validated in SAMMIE CAD to ensure the reliability of the results.

For each reach criterion, riders received a binary score (1 if the rider fulfilled the requirements of that criterion; and 0 otherwise). Riders with a total score of 11 (adequate reach for all evaluated criteria) were classified as "capable of riding the ATV." On the other hand, riders with a total score below 11 (inadequate reach of at least one or more criteria) were classified as "not capable of riding the ATV."

2.3.5 Validation

In order to validate the results of the virtual simulations, an experiment including three adults (two males and one female) and one study ATV (model Yamaha Grizzly EPS - 700) was carried out. Each subject had completed an ATV safety riding course prior to the experiment and was awarded a certificate from the *ATV Safety Institute* [46]. The capability of the subjects to fulfill each fit criterion was evaluated and recorded. For the field tests, we used a measuring tape graduated in mm to measure distances and a digital angle finder (General Tools & Instruments LLC., New York, NY, USA) to measure angles. To assist in some of the angle measurements, we used a straight edge, 48" ruler (model J48EM, Johnson level & Tool, Mequon, WI, USA) and a magnetic level (model 7500M, Johnson level & Tool, Mequon, WI, USA).

The anthropometric measures of the subjects were taken with a body-measuring tape and then used as input in SAMMIE CAD to create 3-D mockups. The results observed in the experimental setting were then compared to those observed in the virtual simulations through the Cohen's Kappa coefficient (K) [77], which is a statistic widely used to measure inter-rater reliability for qualitative (categorical) items [78]. A Z-test (α

= 0.05) was performed to evaluate whether the value of K was statistically different than zero, which would imply that the virtual simulations are reasonable.

2.4 RESULTS

Seventeen ATV models were evaluated from eight different manufacturers (Apollo, Arctic Cat, CF Moto, Honda, Polaris, and Yamaha). Engine capacity ranged from 174-686 cc, with most vehicles in 100-400 cc (35 %). Moreover, more than half (58%) of the ATVs evaluated had electric power steering (EPS), 4 wheel-drive (58%), solid suspension (88%), and manual transmission (48%).

Findings of individual reach criteria for the ATV models are presented in Table 2.2 and Table 2.3. The last column of those tables (Total) represents the percent of observations for which riders scored 11 points (i.e., they passed all the fit guidelines). Criterion 1 (Handlebar-knee distance) seemed difficult for 16-year-old-males of the 95th body-size percentile. This result may be attributed to the height of these subjects, which decreases the gap between their knee and the handlebars [53].

Table 2.2. Percent of observations (n = 17) for which reach criteria did not limit adult-sized ATV usage by males of various ages and percentiles.

Age	Percentile	Criteria											
													
		1	2	3	4	5	6	7	8	9	10	11	Total
8	5th	94	100	65	25	0	0	42	42	0	0	6	0
	50th	94	100	77	33	0	8	50	58	8	8	12	0
	95th	94	100	94	67	0	8	83	83	8	8	35	0
9	5th	94	100	77	50	0	0	42	42	0	0	12	0
	50th	94	100	94	83	0	8	58	67	8	8	29	0
	95th	94	100	94	92	8	50	83	92	50	50	41	8
10	5th	94	100	77	42	0	8	58	67	8	8	12	0
	50th	94	100	94	92	8	25	92	100	25	25	35	8
	95th	94	100	94	100	8	58	92	100	58	58	65	8
11	5th	94	100	94	92	0	8	92	100	8	8	29	0
	50th	94	100	94	100	8	50	92	100	50	50	41	8
	95th	94	100	94	100	8	58	92	100	58	58	71	8
12	5th	94	100	94	92	8	42	92	100	42	42	41	8

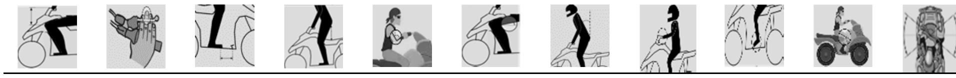
	50th	94	100	94	100	33	58	92	100	58	58	65	29
	95th	88	100	94	100	58	92	92	100	92	92	88	47
13	5th	94	100	94	100	8	50	92	100	50	50	35	8
	50th	94	100	94	100	42	92	92	100	92	92	71	42
	95th	82	100	94	100	67	92	92	100	92	92	88	47
14	5th	94	100	94	100	33	58	92	100	58	58	71	33
	50th	94	100	94	100	58	92	92	100	92	92	88	53
	95th	82	100	94	100	92	92	92	100	92	92	88	53
15	5th	94	100	94	100	42	58	92	100	58	58	71	41
	50th	88	100	94	100	83	92	92	100	92	92	88	59
	95th	82	100	94	100	100	100	92	100	100	100	88	65
16	5th	88	100	94	100	67	92	100	100	92	92	88	59
	50th	82	100	94	100	92	92	100	100	92	92	88	59
	95th	71	100	94	100	92	100	100	100	100	100	88	65
Adult	50th	82	100	94	100	100	92	100	100	92	92	88	65

Unlike criterion 1, criterion 2 (hand size compared to ATV handlebar reach) did not present any difficulty for the virtual youth (Table 2.2 and Table 2.3). Indeed, virtual subjects of all ages, body-size percentiles, and genders succeeded in this criterion for all (100%) evaluated vehicles.

Criteria 3, 4, 6, 7, 8, 9, 10, and 11 all presented a similar trend where young riders do not conform well to these criteria, but older riders do (Table 2.2 and Table 2.3). The contrast in success rate among subjects of different ages and height percentiles are likely also attributed to the variations in height among the subjects. For example, virtual 8-year-old-female riders of the 95th percentile did not pass criterion 5 for any of the evaluated ATVs. In contrast, their 16-year-old-counterpart passed the same criterion for 75% of the evaluated ATVs (Table 2.3), a surprising difference of 75%.

The results from Table 2.2 and Table 2.3 indicate that 8-year-old youth would probably not be able to control utility vehicles when traversing rough or uneven terrains (Criterion 4 – Standing seat clearance). This finding likely explains the fact that youth are more subject to loss of control events (LCEs) than adults [79].

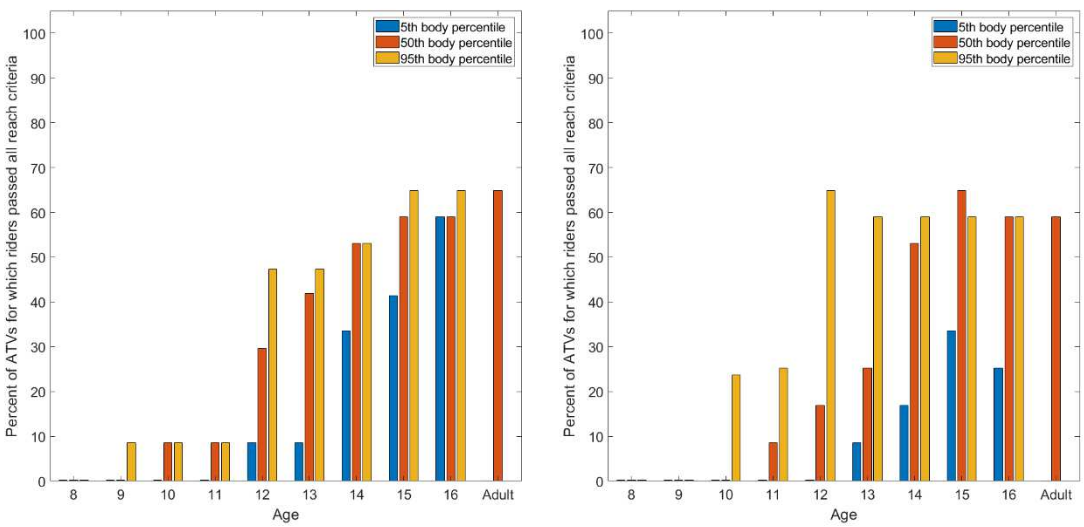
Table 2.3. Percent of observations (n = 17) for which reach criteria did not limit adult-sized ATV usage by females of various ages and percentiles.

Age	Percentile	Criteria 											
		1	2	3	4	5	6	7	8	9	10	11	Total
8	5th	94	100	53	17	0	0	8	8	0	0	6	0
	50th	94	100	77	25	0	0	25	25	0	0	12	0
	95th	94	100	94	75	0	8	83	83	8	8	12	0
9	5th	94	100	77	42	0	0	58	58	0	0	12	0
	50th	94	100	88	75	0	8	83	83	8	8	12	0
	95th	94	100	94	83	0	33	92	92	33	33	41	0
10	5th	94	100	82	58	0	0	67	67	0	0	12	0
	50th	94	100	94	75	0	25	92	92	25	25	35	0
	95th	94	100	94	100	25	67	100	100	67	67	65	24
11	5th	94	100	88	75	0	8	100	100	8	8	18	0
	50th	94	100	94	92	8	42	100	100	42	42	41	8
	95th	94	100	94	100	25	75	100	100	75	75	77	25
12	5th	94	100	94	83	0	33	100	100	33	33	29	0
	50th	94	100	94	100	17	58	100	100	58	58	65	17
	95th	94	100	94	100	67	92	100	100	92	92	88	65
13	5th	94	100	94	92	8	33	100	100	33	33	41	8
	50th	94	100	94	100	25	67	100	100	67	67	77	25
	95th	88	100	94	100	67	92	100	100	92	92	88	59
14	5th	94	100	94	92	17	33	100	100	33	33	65	17
	50th	94	100	94	100	58	83	100	100	83	83	77	53
	95th	88	100	94	100	67	92	100	100	92	92	88	59
15	5th	94	100	94	100	33	58	100	100	58	58	71	33
	50th	94	100	94	100	67	92	100	100	92	92	88	65
	95th	82	100	94	100	75	92	100	100	92	92	88	59
16	5th	94	100	94	100	25	67	100	100	67	67	77	25
	50th	94	100	94	100	67	83	100	100	83	83	88	59
	95th	82	100	94	100	75	92	100	100	92	92	88	59
Adult	50th	94	100	94	100	67	75	100	100	75	75	77	59

The results of the simulations related to Criterion 7 (Angle of lean from vertical) indicated that youth 9 years old and younger are more likely to lean forward over 30^{o} (safety threshold) when raised off the seat to reach the handlebars of ag. ATVs. As a result, the center of gravity of the ATV can shift forward, thus increasing the chances of a forward rollover.

Lastly, some results of the simulations related to Criterion 5 (elbow angle) were concerning. Males up to 11 years old and females up to 13 of the 50^{th} percentile passed this criterion for less than 50% of the evaluated ATVs.

The percent of ATVs in which riders passed all criteria is presented in Figure 2.5. The main finding is that youth should not ride utility. For instance, the average (50^{th} percentile) male operator aged 16 passed all eleven safety criteria for less than 60% of the evaluated agricultural ATVs. That number decreases sharply for younger youth or youth of the same age but smaller height percentile. A similar trend was also observed for female operators.



(a) (b)

Figure 2.5. Percent of observations for which riders passed all 11 fit criteria. (a) Males and (b) Females.

2.4.1 Validation

The results of the validation tests are presented in Table 2.4 and summarized in a confusion matrix (Table 2.5). In the confusion matrix, the test outcome (pass/no pass) is labeled in both horizontal and vertical axes. The horizontal axis represents the number of outcomes predicted by the virtual simulations, and the vertical axis represents the ground truth data (field experiments). The results of the virtual simulations were very close to those of the field tests, with a total accuracy of 88%.

Table 2.4. Validation tests separated by subject and specific fit criterion.

Subject	**Subject 1**		**Subject 2**		**Subject 3**	
Criterion	Real	Virtual	Real	Virtual	Real	Virtual
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	0	0	1	1	1	1
5	1	1	0	1	0	1
6	0	1	0	1	0	0
7	1	1	1	1	1	1
8	1	1	1	1	1	1
9	1	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1

The Z-test determined that the Cohen's Kappa coefficient (K = 0.45) was significantly greater than zero (p = 0.036), indicating that the virtual simulations are reasonable. This novel approach to evaluate ergonomic inconsistencies between youth's anthropometry and the operational requirements of ATVs proved to be an effective and accurate technique. As such, this methodology is an excellent resource for occupational health professionals to evaluate the fit of work machines to their respective operators, not just in agriculture but also in other occupational settings, and not just for youth, but also operators of different ages, races, ethnicities, and body types.

Table 2.5. Confusion matrix based on the validation tests.

Actual outcome (field tests)		Pass	No Pass
	Pass	27	0
	No pass	2	4
		Predicted outcome (virtual simulations)	

Not all results of the virtual simulations matched those of the field tests. One unexpected result is related to criterion 6 (upper leg angle). It was observed that the mean angle between the rider's upper leg and the horizontal plane (parallel to the ground) was 16.7^o, slightly above the recommended threshold (10^o).

Similarly, two subjects failed to pass criterion 5 (elbow angle) in the actual field tests but passed it in the virtual simulation. During the field tests, we asked riders to sit comfortably as if they were just about to start riding the ATV. We argue that it would be possible to ask riders to adjust their way of sitting so that they would pass both fit criteria; however, it would not result in the most ergonomic posture from the rider's standpoint. On the hand, in the virtual simulations, our ultimate goal was to manipulate the 3-D subjects' bodily mockups to physically conform to the fit criteria without infringing any constraints. Thus, it was impossible to predict whether the final adopted postures would match those selected by riders. Therefore, we argue that despite some outcomes of the virtual simulations did not match those of the field tests, the results of the virtual simulations are still reasonable. One just has to be cognizant that the outcomes of the virtual simulations represent a hypothetical scenario where the rider is able to attain a posture based on their anthropometric measures, not on their preferences.

Furthermore, the rationale behind criteria 5 and 6 merits separate discussion. It was clear from our results that some riders would fail these criteria even though they seemed perfectly able to operate the study ATV comfortably and safely. In fact, all subjects who participated in this experiment received a certificate from the *ATV Safety Institute* [46].

2.5 DISCUSSION

This study evaluated limitations in youth's anthropometric dimensions when riding commonly used ATVs. Using a combination of actual field measurements and a novel digital simulation approach, the present study evaluated 11 ATV-fit criteria for youth. The major finding was that youth should not ride adult-sized models, which is a common practice in the U.S. [53,71,80]. This finding raises serious concern regarding youth's ability to ride ATVs, especially when unsupervised.

2.5.1 Limitations of Youth

The present findings outlined that some youth are too small, which makes them incapable of properly reaching the vehicle's hand/foot brakes, resting their feet on the footrests, or having to lean forward beyond 30^{o} to reach the handlebars when rising off the seat. Failing to activate the ATV brakes limits the youth's ability to reduce the speed or to stop the vehicle, which likely prevents them from avoiding unexpected hazards, such as obstacles or bystanders [5]. In fact, previous research has shown that a significant number of ATV incidents include hitting a stationary object [48-52].

In addition, the inability to place the feet on the footrests when not breaking the ATV entails a functional loss of control of the vehicle. ATV LCEs occur frequently and are a significant cause of injury and death in agriculture [81-83]. This finding indicates an opportunity for manufacturers to consider changing the design of their machines, allowing riders to adjust the ATV's seat height, which would likely reduce longitudinal torso impact while traversing rough and uneven terrains. Furthermore, leaning beyond 30^{o} can cause the ATV to tip forward, resulting in a rollover. Most ATV-related crashes on farms and ranches, especially those resulting in deaths, consist of rollovers [32,52,55,57,64,84].

On the other hand, some youth are too tall, which decreases the clearance zone between their legs and the handlebars. A clearance zone smaller than 200 mm makes it difficult for the rider to properly reach and steer the handlebars [21,63]. In consequence, riders may lose control of the vehicle [32,85] or have difficulty keeping it at a safe speed. As mentioned before, this series of events can lead to injuries and deaths.

2.5.2 Lack of inclusive designs

Further, the results indicated that most utility ATV models are unfit for youth. As such, there is an increased chance of incidents when youth ride these vehicles. There is a need to design ATVs that better accommodate riders of various sizes.

2.5.3 Changes in guidelines and policies for youth operating ATVs

Current guidelines for ATV-youth fit are mainly based on the rider's age [19] and vehicle's engine size [21] and maximum speed [20]. However, these recommendations are not supported by the present findings, which clearly showed that some fit criteria favor smaller youth while some benefit taller youth, regardless of the rider's age and vehicle's design parameters (i.e., engine size and maximum speed). Furthermore, previous studies have also demonstrated that rider's age and ATV design parameters alone are insufficient to evaluate youth-ATV fit [53,86,87].

Despite some results showing that youth are capable of riding many ATVs, other risk factors such as experience, psychological, and cognitive development cannot be overlooked [31,61]. Youth who are high in thrill-seeking are more likely to engage in risky ATV riding behaviors, regardless of their safety awareness [62]. Those cases require external interventions, such as changes in g policymaking, improved ATV design, and use of crush protection devices [62]. As such, the present study provides quantitative and systematic data evaluating youth's physical capability to ride ATVs. This data supports manufacturers in considering design changes or manufacturing new machines and provides critical evidence contributing to the scientific basis for modifying regulatory/advisory guidelines for youth operating utility ATVs.

2.5.4 Study limitations

There are noteworthy limitations of this study that need to be considered when interpreting the results. First, one may argue that the database selected for this study (Snyder et al., 1977) is outdated. Nevertheless, to the best of our knowledge, this is the only available source that includes enough parameters to create youth mockups on SAMMIE CAD. In addition, there is no clear evidence of the secular trend in anthropometry over U.S. youth over the past 40 years [6]. For instance, when investigating other sources (CHILDATA – DTI [88]), we did not observe any significant differences (p-value < 0.05) in the mean values of shoulder breadth and hand length for youth aging five or ten years old. However, it is reasonable to assume that there might be differences in the sizes of the youth population of 2022 and their counterparts of 1977. This potential difference should be considered in the interpretation and generalizability of the present findings.

Second, although we used a systematic approach to identify common ATVs used in the U.S., the sample is subject to sampling error and may not be fully representative of the models ridden specifically by youth. Moreover, safe and effective riding of utility ATVs involves consideration of factors other than the ability of youth to reach its controls. ATVs are rider-active vehicles, which means that riders must be able to shift their body weight to safely perform maneuvers such as turning, negotiating hills, and crossing obstacles [63,71].

Third, the 3-D representation of the ATV models evaluated in this study is simple and does not include several features, such as the fuel tank, rear basket, and many others. However, all the elements necessary for the specific purposes of our simulations were included. Also, the virtual simulations were validated with experimental tests, ensuring the reliability of our results. Another limitation relates to the absolute location of each control, which had to be determined due to feasibility issues. The further-most position was used as the standard position for all controls with gradual adjustment such as the hand gearshift, while pedals were set to resting position.

Fourth, all the human mockups were placed at the ATVs' seat reference point (SRP). This may not be the "best-case" scenario from a reach standpoint since many riders, especially small youth, tend to sit closer to the handlebars (ahead of the SRP) to allow control reaching. The effect of seating adaption to reach controls while riding requires further assessment.

Finally, the reach simulations were performed with static mockups, i.e., we did not evaluate any trunk or hip movement. In real riding situations, riders may shift their hips forward and/or bend their trunks to reach an otherwise unreachable control. However, these compensatory mechanisms may increase risk exposure since they may entail limitations in active riding and/or limit the operator's field of vision.

2.6 CONCLUSIONS

This study evaluated the potential mismatches between youth's anthropometric measures and operational requirements of seventeen ATV models. The main findings were that: (1) Most riders failed to pass at least one out of the eleven fit criteria for the evaluated vehicles; (2) Youth should not ride utility ATVs; (3) only engine size, maximum speed, and rider's age are insufficient indicators of youth-ATV fit.

The present findings, along with the results of a recent study regarding the forces required for effective ATV operation [86], raise serious questions about the ability of youth to safely operate utility ATVs in common use on U.S. farms and about the validity of current youth-ATV fit guidelines. Therefore, we recommend that the readiness of youth to ride ATVs, especially for occupational purposes, should be carefully evaluated by their parents/guardians. Moreover, we argue that current youth-ATV fit guidelines should be reviewed and updated based on quantitative and systematic data comparing the physical ability of youth and the operational requirements of ATVs.

ATV-related injuries and deaths among youth are a consequence of causes from various sources that are not necessarily related to each other. As such, to prevent those injuries and fatalities, there is a need for a mixed approach combining engineering redesign, policymaking, parent involvement, and safety education.

3 CHAPTER 3 – AGROGUARDIAN: A NOVEL ALL-TERRAIN VEHICLE CRASH DETECTION AND NOTIFICATION SYSTEM

3.1 ABSTRACT

All-Terrain Vehicle (ATV) incidents are a predominant cause of injury and death in the United States. The agricultural industry is the most dangerous for ATV riders, with 50% of all ATV-related occupational injuries and 65% fatalities. Most ATV off-road crashes (farms and ranches) result in traumatic injuries where the rider needs immediate care but is unable to seek help because they are severely injured. Moreover, most of these crashes occur in isolated areas of hard access and without cellular service. Thus, making it challenging to contact first-responders promptly. Therefore, this study aimed at developing and testing a low-cost, ATV crash-prediction-and-detection device (AgroGuardian) that immediately alerts first responders, even when the rider is unable to do so, and there is no cellular service available. AgroGuardian includes three individual systems: (1) Embedded data logging system, (2) Smartphone application, and (3) Remote database. AgroGuardian's performance was assessed through experimental tests simulating a rollover incident and normal riding conditions. The results indicate that: (1) AgroGuardian has a rollover prediction system with an accuracy superior to 99%; (2) AgroGuardian has a rollover detection system with an accuracy superior to 99%; (3) AgroGuardian has a fast EMS notification time (40.70 s); (4) Crash localization presented an accuracy of 2 m.

3.2 INTRODUCTION

All-Terrain Vehicle (ATV) incidents are a predominant cause of injury, death, and financial loss in the United States [89]. The Consumer Product Safety Commission estimates that over 700 ATV-related fatalities and 90,000 injuries occur annually [54]. In addition, the annual cost of lives and health care from ATV-related incidents has increased almost five times in the past decade, reaching more than 22 billion dollars spent in the year of 2016 [90-92]. The agricultural industry is the most dangerous for ATV riders, with 50% of all ATV-related occupational injuries and 65% fatalities [93,94].

To prevent these incidents, several studies have focused on identifying risk factors for ATV-related crashes [82,95-98]. For instance, the crash location is associated with the likelihood and severity of ATV-related injuries and fatalities [94,96,99-101]. Although on-roadway crashes have significantly increased over the past years [56,102], ATV-related deaths are still predominant in off-road crashes [94,99,103-105], mainly farms or ranches [32]. Moreover, seven out of the top ten states with the highest number of deaths reported from 2007 to 2011 are among the ten states with the highest percentages of the population living in rural areas in 2010 [106,107].

The majority of ATV off-road crashes consist of either rollovers or collisions [48,50,55,100,103]. Rollover incidents on farms (or ranches) often result in the rider being pinned underneath the vehicle, which leads to death by mechanical asphyxia in almost 29% of the cases [32,108]. On the other hand, collision events usually culminate in the rider being ejected from the ATV and hitting either the torso (49% of the time) or the head (13% of the time), resulting in a traumatic injury (blunt trauma) [32,41,100]. Mechanical asphyxia and traumatic injuries are particularly critical because they require immediate medical attention; otherwise, the chances of survival to the injured are dramatically reduced [109,110]. Indeed, mechanical asphyxia and traumatic injuries were widely reported as the principal causes of death in ATV-related crashes on farms and ranches [32,100,102,103,108].

A plausible explanation for the predominance of fatalities in off-road accidents lies in the time needed for first aid to be administered. A previous study reported that 68.8 % of ATV-related deaths occur within 3 hours from the incident time [110]. According to several studies [90,98,99], several crashes occur in areas beyond which an ambulance could drive from a hospital to the crash location and back again within 60 minutes. Further compounding the issue, off-road crashes present some unique challenges that significantly delay first responders intervention, such as (1) poor cellular service, making it challenging to reach out for help; (2) difficulty for first responders to locate and obtain access to the crash site, which may be a trail located in dense woods; and (3) remove the injured from the crash site and transport them to the nearest hospital [90,98,104].

Two possible solutions for addressing the outlined issues involves developing a device to: (a) predict crashes and alert the riders ahead of time so they can take action to prevent the incident; or (b) detect when a crash happens and promptly notify first responders. For such, the factors that lead to the crash must be continuously monitored. Previous studies have shown that speeding is the leading cause of ATV collisions [56,102,103,107]. Furthermore, steep slopes and high vibration levels have been described as leading sources of ATV rollovers in agricultural settings [55,81,82]. Therefore, parameters such as the vehicle's speed, acceleration, vibration level, and attitude (roll, pitch, and yaw) are of particular interest for predicting or detecting ATV crashes. Nevertheless, there is no standardized data recording system specific for ATVs [53], which is a significant barrier to developing an ATV crash-prediction-and-detection device.

Many off-road crashes involving ATVs result in injuries that require immediate care. However, the riders are often unable to seek help because they are severely injured. Further aggravating the issue, a number of crashes occur in isolated areas with poor or no cellular service. Thus, making it challenging to contact first responders promptly. While there is no ATV crash prediction device, ATV crash-detection devices are commercially available in other countries. However, this technology is unavailable for most ATV users due to its high cost of acquisition and maintenance; also, the system is unavailable in the U.S. Therefore, there is a need to create a low-cost ATV crash-prediction-and-detection device that promptly alerts first responders, even when riders cannot do so, and there is no cellular service available.

Our long-term goal is to decrease the severity of injuries and the number of fatalities in ATV-related off-road crashes. The objective we have for this study, which is a step towards attaining our long-term goal, is to develop an automatic ATV crash prediction, detection, and notification device (AgroGuardian) that promptly directs first responders to the crash location. This device aims to prevent crashes by alerting users of dangerous riding conditions and to reduce first responders' response time, thus increasing the likelihood of injured riders surviving and sustaining less severe injuries [90,98,99]. The objective of this research was achieved based on the following specific aims:

(a) Develop a system (AgroGuardian) to monitor the ride parameters, predict the likelihood of a crash, and alert riders;

(b) Develop a system that automatically detects when a crash occurs and directs first responders to the accident location, even when riders are unable to do so themselves, and there is no cellular service available;

(c) Add several safety modules to AgroGuardian, including an autonomous shut-off system, anti-robbery, geo-fencing, and ATV tracking (speed, acceleration, and vibration).

(d) Test and validate the performance of AgroGuardian, including tests for crash detection and alert and tests for other proposed functions such as data recording and detection of dangerous riding conditions.

3.3 MATERIAL AND METHODS

AgroGuardian consists of an embedded data logging system and control unit, a smartphone application (iOS), and a cloud database (Figure 3.1).

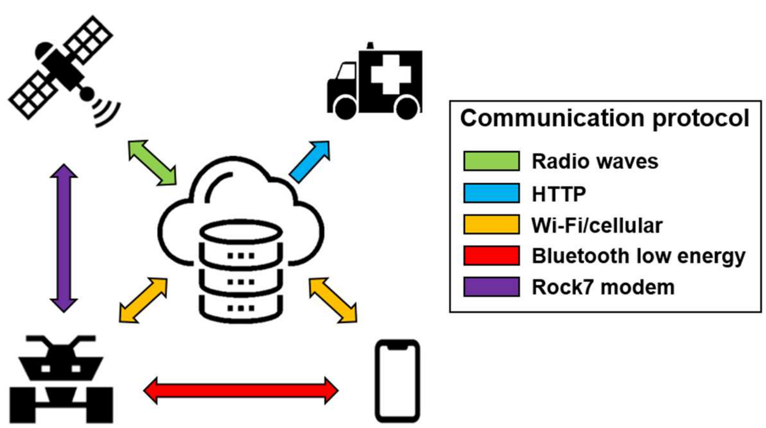


Figure 3.1. AgroGuardian System and communications

The embedded system was used for two main tasks: (1) monitor and record ATV riding parameters (e.g., vehicle's location, trip history, velocity, acceleration, vibration, and attitude); and (2) automatically trigger an emergency alert when a crash or dangerous riding conditions were detected.

Two distinct smartphone applications (apps) were developed, one for general public use (G.P.), and one for research purposes (R.P.). The G.P. app was developed to provide users an interface to interpret and interact with their ATV data and provide custom services such as rider's credentials, customized geo-fencing, and danger alerts. In addition to the features present in the G.P. app, the R.P. app allows users to set system parameters such as data recording frequency and have fast data access, for in-site data analysis and interpretation. Lastly, the cloud database was built to remotely store, manage, and transfer users' data to the smartphone applications. In the next sections, we present a detailed description of the developed systems.

3.3.1 Embedded data logging system and control unit

A Raspberry Pi 4 Model B (RPi, 4GB) single-board computer (Adafruit, New York, NY, USA) was used as the controller of the embedded system. The RPi uses a 1.5GHz 64-bit quad-core Arm Cortex-A72 CPU and has 802.11 ac/n wireless LAN, and Bluetooth 5.0. In addition, the RPi has several ports for communicating with peripherals, including HDMI, USB, SD Card reader, and general-purpose input/output (GPIO) pins. The embedded data logging system and control unit consists of five systems, namely: Rollover detection, Rollover report, Vehicle tracking, geo-fencing, and Real-time dangerous riding behavior notification (rollover prediction). A portable battery (Anker PowerCore II 20000) was used to supply power to the system. When the ATV engine was turned on, the ATV's battery was used to recharge the portable battery.

3.3.2 Rollover detection

Rollover occurrences were determined by comparing the ATV's static stability angles to the ATV's roll and pitch angles in real time. When either roll or pitch angles were higher than the ATV's lateral or longitudinal stability angles, respectively, an internal counter would be updated. When the counter was above a certain threshold (25 consecutive readings / 5 s) the system would trigger the emergency system alerting first responders. The importance of implementing a counter is explained by the fact that false positive rollover detection may occur. The counter circumvents erroneous detections by evaluating a sequence of events instead of a single occurrence. A scheme of the rollover detection system is illustrated in Figure 3.2.

The ATV static stability angles are the critical angles at which an ATV begins to roll (either sideways or forward/rearward). Lateral (side) and longitudinal (rear) stability angles are important measures of the relative stability of an ATV and have been used to describe the rollover propensity of specific vehicles [40-42]. These angles are generally determined through tilt table tests or calculated based on center of gravity (C.G.) location that is usually determined by lifting axle method. The static stability angles used in the present study were determined based on the results of previous studies [40,42].

The ATV's attitude (including roll and pitch) was measured with an Inertial Measurement Unit (IMU – model LSM9DS1, manufacturer Adafruit). To improve the accuracy and robustness of vehicle's attitude estimate, a Madgwick filter [111] was implemented. This filter fuses gyroscope, accelerometer, and magnetometer measurements to calculate the vehicle's attitude. The vehicle's attitude is initially estimated by the integration of gyroscope measures, which in the long term inherently yields drift. The long-term drift from the gyroscope integration is compensated by the accelerometer estimates of attitude. The magnetometer measures are used to compensate for magnetic distortions from potential sources of interference around the sensor, such as electrical appliances (for instance, a GPS sensor), and metal structures (e.g., the ATV's frame).

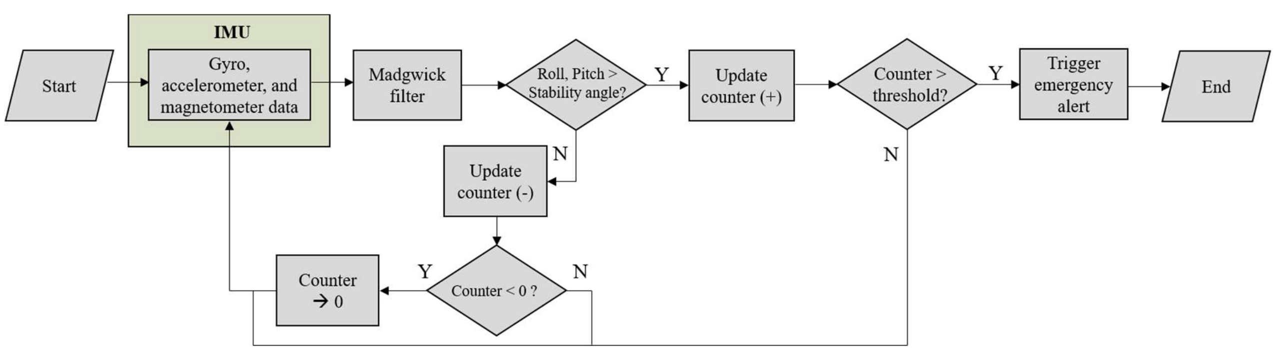


Figure 3.2. Rollover detection process

In case the system fails to detect a rollover, and the operator is conscious and capable of pressing a key or button, redundancy was implemented through a backup system consisting of a radio frequency (R.F.) receiver (315 MHz, model T4 with chipset model PT2272, manufacturer Adafruit), and a 4-button R.F.

remote control keyfob (315 MHz, chipset model PT2262, manufacturer Adafruit). The riders could use the keyfob to manually trigger the emergency alert in case the rollover detection system based on the IMU failed. The R.F. receiver was connected to the RPi through GPIO pins.

3.3.2.1 Rollover detection performance assessment

Fifteen angle values larger and 15 angle values smaller than the static stability threshold for side rollover (roll) of an ATV model Honda TRX 500 (2018) were randomly selected to assess the performance of the rollover detection system. The stability threshold values were retrieved from Grzebieta et al. (2015) [40]. The threshold for longitudinal rollover was calculated as the average between the threshold for left and right rollover. AgroGuardian's embedded system was manually tilted and kept at the selected angles. A binary score was assigned to each test (angle value) according to the following logic:

$$\text{Score} = \begin{cases} 0, \text{ if rollover is detected when } \theta < T \text{ (F.P.)} \\ 0, \text{ if rollover is not detected when } \theta > T \text{ (F.N.)} \\ 1, \text{ if rollover is not detected when } \theta < T \text{ (T.N.)} \\ 1, \text{ if rollover is detected when } \theta > T \text{ (T.P.)} \end{cases}$$

Where, θ is the random angle at which the system was tilted, T is the lateral (side) stability angle (retrieved from Grzebieta et al., 2015), F.P. are the false positive case, F.N. are the false negative case, T.N. are the true negative cases, and T.P. are the true positive cases.

A similar procedure was replicated to evaluate the system's performance in detecting rear/front rollovers (pitch).

3.3.3 Rollover report – emergency alert

Rollovers were reported through *Noonlight*, which is a third-party platform that can trigger requests to emergency services. In summary, when a rollover is detected by the embedded system (1), the Raspberry Pi sends a message off-board via the Iridium Satellite Network (2) that triggers an emergency alert, pre-set on the cloud database (3). Then, the database sends a *HyperText Transfer Protocol* (HTTP) request to *Noonlight* (4), informing the crash occurrence and location. Noonlight's certified operators immediately text or call the user. If the user cannot cancel the alert or does not respond, Noonlight's operators notify first responders (5). A scheme of the accident report procedure is illustrated in Figure 3.3.

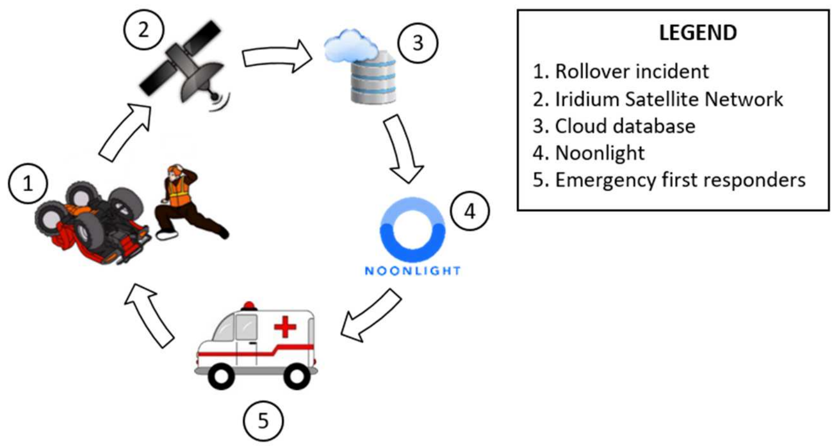


Figure 3.3. Emergency alert procedure.

The system's capability and promptness in reporting a crash were evaluated based on the response time. The response time was defined as the time it took from the rollover incident occurrence moment until *Noonlight*'s confirmation of AgroGuardian's emergency alert.

3.3.4 Vehicle tracking system

A Global Positioning System (GPS – model Ultimate GPS Breakout v3, manufacturer Adafruit) and the IMU recorded the vehicle's location, speed, acceleration, and trip history. Communication between the IMU and the RPi was implemented via a *Serial Peripheral Interface* (SPI) connection, and the communication between the GPS and the RPi was implemented through a *Universal Asynchronous Receiver Transmitter* (UART) GPIO pin.

Due to the environment of some ATV off-road crashes (e.g., dense woods), GPS signals might be unavailable or yield inaccurate measures. To address this issue, IMU data (which allows continuous position tracking) was fused with GPS data through an Unscented Kalman Filter (UKF) [112]. The UKF is a non-linear version of a Kalman Filter [113,114], which is an algorithm that combines multiple sensor information to estimate the state of a system, such as the vehicle's position [115]. The fundamental advantage of the UKF over the Kalman Filter is that it works for non-linear systems, which is the case for most robots and sensors [116].

3.3.4.1 *Vehicle tracking performance assessment*

Vehicle tracking metrics were evaluated in a study of an ATV model Honda Rancher 4x4 (2018), equipped with AgroGuardian and a Real-Time Kinematic GNSS receiver (RTK – model Piksi Multi GNSS, manufacturer Swift Navigation).

(a) Position

Data from both devices were collected during a ride in a straight line of 30.5 m (100 ft), at selected speeds of 2.23, 3.57, and 5.36 m s^{-1} (5, 8, and 12 mph, respectively). Those speeds were chosen because they are the most common ATV speeds, according to a survey among 79 interviewees [117]. In total, there were three replicates for each selected speed.

The RTK receiver positions were adopted as a reference to calculate the relative deviation in the GNSS module positions. AgroGuardian's position estimate accuracy was evaluated based on the Euclidian distance between AgroGuardian's position estimate and the RTK's data. The coordinates of both receivers were converted to UTM coordinates using the WGS 84 datum. The deviation in meters obtained by the GNSS module from the RTK was calculated using equation 3.1.

$$\overline{D} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\left(X_{RTK} - X_{agro}\right)^2 + \left(Y_{RTK} - Y_{agro}\right)^2} \tag{3.1}$$

Where,

$\overline{D}$: Average position deviation in AgroGuardian's GPS module to the reference device (m);

n: Number of observations;

X_{RTK} and Y_{RTK} are point coordinates obtained by the RTK module;

X_{agro} and Y_{agro} are point coordinates obtained by the GNSS module.

(b) Velocity

In order to maintain a constant speed during the experimental trials, the ATV was equipped with a QuadCruise control unit (MC S2580E, MCCruise). The control unit of the cruise control system consists of a computer unit, electric throttle servo, Cable Interface Unit (CIU), and a Bluetooth module for remote controls [118]. More information about the installation and operation of this device is available in a previous study [64].

Although the QuadCruise controlled the ATV speed remotely, an operator was always riding the vehicle for safety purposes. In summary, the vehicle was accelerated to the desired speed (which was adjusted by the operator) and then ridden for at least 10 s, to allow the GPS module to track a stable velocity (Figure 3.4). Three pre-set speeds were evaluated: 2.23, 3.57, and 5.36 m s^{-1} (5, 8, and 12 mph, respectively), with three replicates for each speed. The average velocity error was calculated according to equation 3.2.

$$\bar{V}_{error} = \frac{1}{n}\sum_{i=1}^{n}\left|V_{RTK\ i} - V_{agro\ i}\right| \quad (3.2)$$

Where,

$\bar{V}_{error}$: Average velocity error (m s^{-1});

n: Number of observations

$V_{RTK\ i}$: RTK receiver velocity (m s^{-1});

$V_{Agro\ i}$: AgroGuardian velocity (m s^{-1});

The majority of the observations occurred out of the constant speed zone (e.g., start/end of data collection with ATV stationary, speeding zone), which could add bias to the estimation of $\bar{V}_{error}$, since the number of observations outside of the constant speed zone is higher than the number of observations in the constant speed zone. For this reason, only observations in the constant speed zone were used in the calculation of $\bar{V}_{error}$.

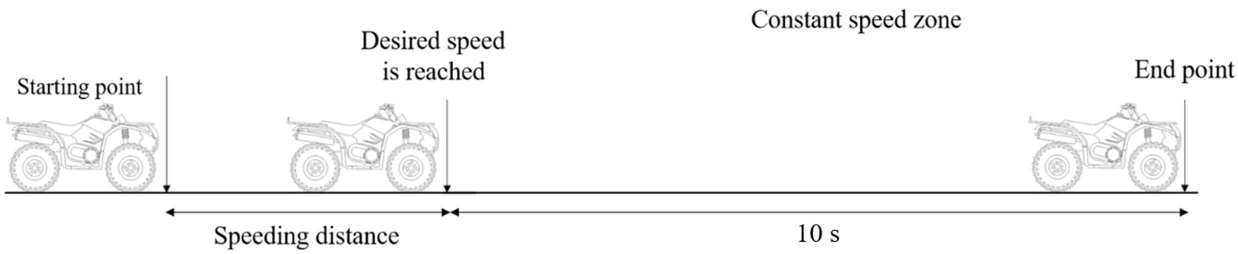


Figure 3.4. Schematic of the procedure to evaluate the "Velocity Measurement performance" in AgroGuardian.

3.3.5 Geo-fencing

Geo-fencing was implemented in AgroGuardian as a polygon shape. The vehicle is only allowed within the polygon, and when it exits the boundary, the user receives a warning message through the smartphone application (both G.P. and R.P. applications include this feature). Users can create customized geo-fencing for each specific ATV via smartphone apps. A map pops up, and the user needs to indicate on the screen the vertices of the desired polygon.

Geo-fencing is important because it creates an extra layer of verification, informing the user when a vehicle is entering a zone that it was not supposed to. For instance, a rider can enter an unauthorized area without being aware. This situation places riders at risk, as they might be subject to encountering wild animals or unintentionally trespassing private properties. For these cases, the geo-fencing alert can be lifesaving.

In addition to improving riders' safety, geo-fencing can be used for theft detection/prevention. For instance, if users detect that the vehicle is exiting a pre-set boundary without their consent, they can remotely shut the vehicle's engine off by sending a signal to RPi that will activate the engine shut-off system.

A relay (model FeatherWing, manufacturer Adafruit) was implemented in the system to control the flow of current from the ATV's battery to its engine (engine kill switch). When the user activates the "engine shut off button," implemented in both the G.P. and R.P. apps, the relay would interrupt the passage of current, thus shutting the ATV's engine off.

3.3.5.1 Geo-fencing performance assessment

Geo-fencing was tested using three different polygons: a regular polygon (rectangle), a rounded shape polygon (circle), and an irregular polygon. A binary score was assigned to each test according to the following logic:

$$\text{Score} = \begin{cases} 0, \text{ if vehicle is detected inbounds when the vehicle is out of bounds (F.P.)} \\ 0, \text{ if vehicle is detected out of bounds when the vehicle is inbounds (F.N.)} \\ 1, \text{ if vehicle is detected out of bounds when the vehicle is out of bounds (TN)} \\ 1, \text{ if vehicle is detected inbounds when the vehicle is inbounds (T.P.)} \end{cases}$$

The coordinates of the virtual areas were collected from Google Maps (Alphabet Inc., Mountain View, CA, USA). The first polygon (regular shape) was delimited by the coordinates of its four vertices; whereas the second polygon was defined by 23 points collected around the perimeter of a roundabout; and the last polygon (irregular) was defined by 22 points.

3.3.6 Real-time dangerous riding behavior notification system

Another feature of AgroGuardian consists of notifying the rider or supervisor when the system predicts a dangerous riding condition. A classification model based on machine learning (ML) algorithms was developed and implemented in AgroGuardian's core system. This algorithm calculates the likelihood of a rollover event based on the ride's parameters (vehicle's speed, roll, pitch, and turning radius) and ATV model (weight, height, width, wheelbase, and seat height). To the best of our knowledge, this is the first algorithm developed to predict the likelihood of a rollover for ATVs specifically. If the probability of a rollover event is greater than a certain (adjustable) threshold (for the present manuscript, we chose this threshold to be 50%), the system issues an audiovisual alert, consisting of a high-intensity red LED and a piezo buzzer.

3.3.6.1 Classification Algorithm

A dataset containing 51,700 samples was used to create the classification model. The samples were either retrieved directly from available sources [119-121] or created based on previous studies [39,40,122]. The dataset consisted of observations from mathematical simulations, finite element analysis (FEA), and realistic simulations, including static and dynamic tests. For the samples consisting of mathematical simulations and FEA, the occurrence of a rollover was calculated instantly based on the data. For the samples consisting of realistic simulations (static and dynamic tests), the occurrence of a rollover was determined by an observer. Further, the dataset consisted of fourteen ATV models under diverse riding scenarios, including terrain slope (0, 5, 10, 15, 20, and 25°), vehicle speed (5 to 50 km h^{-1} in installments of 2.5 km h^{-1}), and turning radii (5 to 50 m in installments of 2.5 m). The presence (or not) of a rider was also considered in the model. Each sample was classified in either non-rollover (0) or rollover (1). Detailed information about the input variables and their units is presented on Table 3.1.

During the process of data curation, it was observed that the dataset was imbalanced (about 85% of the samples consisted of non-rollover examples). The disparity in the number of samples of each class could potentially affect the model's accuracy. However, we deemed that it would be best not to alter the dataset before training a prediction model because even though there is great disproportion, the number of classes is minimal and the absolute number of samples in each class is high. Furthermore, instead of assessing the prediction model's performance through its overall accuracy, we evaluated its balanced accuracy and F-score, which are frequently used measures to evaluate prediction models trained on imbalanced data [123]. The dataset was first normalized (z-transformation) and then split into three subsets for training (60%), cross-validation (20%), and testing (20 %).

Table 3.1. Prediction model's input variables and description

Input Variable	Unit	Description
ATV weight	Kg	ATV net weight (no rider and fuel tank empty)
Width	mm	Measured from left to right across the widest part of the ATV, including tires but not including any side mirrors
Length	mm	Measured from left to right across the longest part of the ATV.
Wheelbase	mm	Measured between the center of the front and rear wheel hubs from the same side
Seat height	mm	Measured from the ground up to the ATV seat center

Speed	km/h	ATV last recorded speed before incident
ATV pitch angle	degrees	ATV last recorded pitch before incident
ATV roll angle	degrees	ATV last recorded roll before incident
Turning radius	mm	Calculated as the tangential speed (in m/s) divided by the yaw rate (in radians/s)
Presence of a rider	(binary score - 0 if none, or 1 otherwise)	Part of the data used to train the classification algorithm consisted of autonomous ATVs without any riders

Four classification algorithms were tested: K-nearest neighbors (KNN), Random Forest, Support Vector Machine (SVM), and Deep Neural Network (DNN). The algorithms were developed from the packages sklearn [124] and keras [125], which are Machine Learning packages for Python. In addition, several tuning parameters were tested based on the recommendations of a previous study [126]. The output of each model consisted of a binary variable (0 – if no rollover was predicted, or 1 otherwise). A summary of tuning parameters for the algorithms is presented in Table 3.2.

Table 3.2. Classification algorithms tuning parameters

Algorithm	Parameter	Values
KNN	n	5, 7, 9, 10
RF	Number of trees	100, 200, 250, 300
	Maximal depth	10
SVM	Kernel function	linear, polynomial, radial basis function, sigmoid
	C	$2^{-3}, 2^{-1}, 2$
	γ	$2^{-13}, 2^{-11}, 2^{-9}, 2^{-1}$
DNN	Activation	ReLU
	Hidden Layers (neurons)	2 (32/32)
	Model Optimizer	Adam
	Epochs	100

The performance of each algorithm was evaluated by the area under the curve (AUC) of the receiver operating characteristic (ROC) [127]. The algorithm with the highest AUC score was implemented in AgroGuardian's code. In case of a tie, the algorithm with highest accuracy was selected.

3.3.7 System specifications

All the electronic components of the embedded system (Figure 3.5) were placed inside a custom-manufactured enclosure, resistant to vibration and dust, which was installed on the rear rack of the ATV. The antenna of the GNSS was attached to the ATV front chassis. The acquisition prices, specifications, and manufacturers of the system's components are shown in Table 3.3.

Table 3.3. Summary of the components used in AgroGuardian's embedded system

Quantity	Component	Specifications	Manufacturer	Units cost (US$)*
1	Raspberry Pi 4	1.5GHz 64-bit quad-core Arm Cortex-A72 CPU, 4GB RAM, 802.11 ac/n wireless LAN, and Bluetooth 5.0, and 40 general-purpose input/output pins	Adafruit, New York, NY, USA	65.00
1	GNSS module	Frequency sampling rate 10 Hz, and input voltage of 3.3 or 5 V	Adafruit, New York, NY, USA	39.95
1	GNSS antenna	Provides an additional 28 dB of gain	Adafruit, New York, NY, USA	14.95
1	IMU	3-axis accelerometer (±2/±4/±8/±16 g); 3-axis magnetometer (±4/±8/±12/±16 gauss); and 3-axis gyroscope (±245/±500/±2000 dps)	Adafruit, New York, NY, USA	14.90
1	Rock7 modem	Input voltage of 5V, data arrives via email, or directly to private web service via HTTP POST	Sparkfun, Boulder, CO, USA	249.95
1	RockBLOCK External Patch Antenna	Frequency range of 1616 - 1626.5 MHz, and bandwidth of 15 MHz	Sparkfun, Boulder, CO, USA	64.95
1	Relay	Non-latching relay, input power of 3.3 V, 250V AC/DC, 1200 W, 10 A	Adafruit, New York, NY, USA	9.95
1	Connection cables	-	-	8.00
1	Portable battery	20100mAh battery		49.99
1	DC-DC converter	Input voltage of 3.2 to 35 VDC, and Output voltage of 1.25 to 30 VDC, maximum output current of 3 A		1.69
	Total			$ 519.33

* Prices retrieved from manufacturers' websites on 9-28-2020

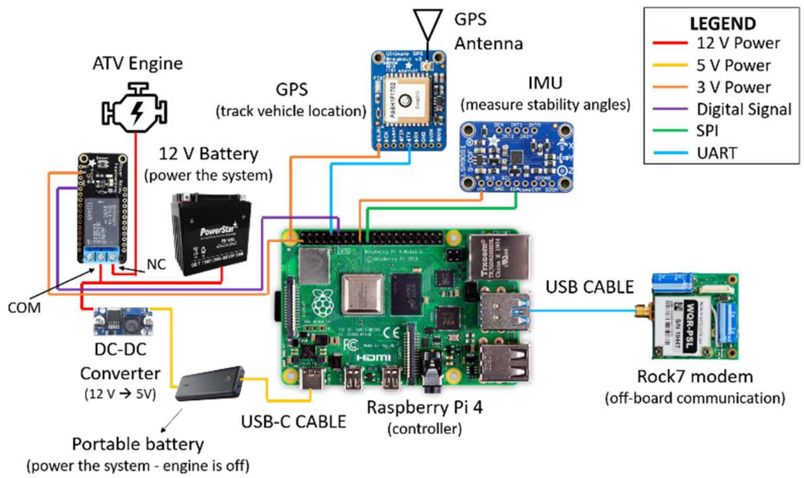
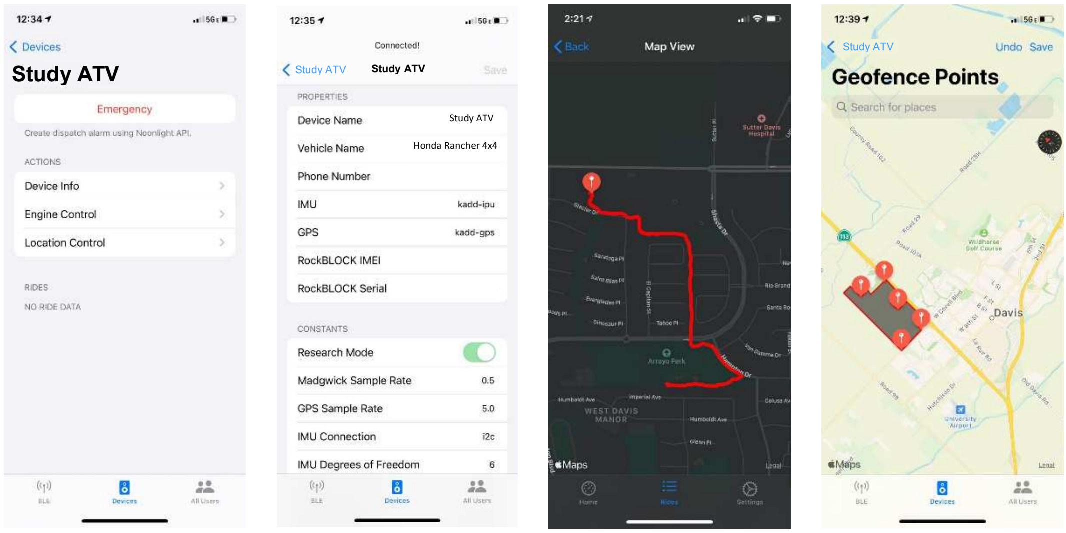


Figure 3.5. Embedded system mounted on a Honda Rancher ATV.

3.3.8 Smartphone application

The smartphone applications (G.P. and R.P.) (Figure 3.6) were developed using the Swift language, which is the primary programming language for iOS app development. To enhance the users' experience, customized features and functionality were implemented in the app through Cocoapods, which is a dependency manager for Swift. Cocoapods was built with the Ruby language, which allows packages to be installed and used in the original Swift application.

The applications maintain a simple layout that allows users to visualize their past rides. Users can switch between their ATVs via the "Devices" menu. When viewing a specific vehicle, all rides are organized by date. As a result, users can view overall ride histories per ride, month, or year. This organizational hierarchy is fully implemented in the application's backend rather than in the remote database. The purpose of implementing this hierarchy in the application's backend is to provide a comfortable and usable experience for users wishing to analyze all collected data. In addition, ATV supervisors can check the performance and riding behavior of their employees. Likewise, parents of young riders can track their children's performance as well. With the information supplied by the database, other statistics are calculated and displayed within the application, such as ride times, mileages, and maximum speeds.



(a) (b) (c) (d)

Figure 3.6. iOS application interface. (a) Vehicle’s menu, (b) Vehicle information (c) Trip history, and (d) Geo-fencing.

3.3.9 Application-Raspberry Pi communication

One of the main differences between the G.P. and the R.P. smartphone applications is their communication with the embedded system. The R.P. app is meant to neither be used in areas with no cellular service nor monitor the system while the ATV is not in use. For this reason, the communication between the R.P. app and the RPi only occurs through a proprietary Bluetooth Low Energy (BLE) communication protocol, which provides fast data access. Data is logged into the remote database when the embedded data logging system is connected to Wi-Fi.

On the other hand, data transmission between the RPi and the G.P. app only occurs through BLE when the user registers a new ATV into the system. For the other cases, the remote database is used as an intermediate between the embedded system and the user (via G.P. app). In summary, data is transferred from the RPi to the cloud database when a Wi-Fi connection is available, then, the data is shared from the remote database to the user's app.

As mentioned earlier, all the data logged into the embedded system is transferred to the cloud database through Wi-Fi, which inherently requires a Wi-Fi network connection to be established. However, Wi-Fi network is not necessarily available, especially in remote areas. In order to counteract this drawback, emergency messages are transmitted off-board through the Iridium Satellite Network via the Rock7 modem (available only in the G.P. app). This modem requires users to pay both an activation fee and a pay-as-you-go rate that is based on the number of bytes sent to the satellite network. Therefore, to minimize ongoing costs, the RockBLOCK was only used for emergency communication and remote engine shut off.

3.3.10 Cloud database

AgroGuardian's cloud database was developed based on Firebase Firestore, which is a flexible, scalable database for mobile, web, and server development from Firebase and Google Cloud Platform. It keeps data in-sync across client apps through real-time listeners and offers offline support for mobile and web, i.e., AgroGuardian's iOS application works regardless of network latency or internet connectivity. The riding parameters recorded with the embedded system are sent to the database once the system connects to a Wi-Fi network. These data are then stored in the database and further transferred to the user's smartphone, which allows users to interpret and interact with their ATV data.

3.3.11 Data Analysis

3.3.11.1 Rollover detection system & Geo-fencing

The performances of the rollover detection and geo-fencing systems were evaluated through a confusion matrix, and by the F Score [128], as presented in equation 3.3.

$$F_{Score} = \frac{TP}{TP + \frac{1}{2}(FP + FN)} \quad (3.3)$$

3.3.11.2 Rollover report

The system's response time highly depends on the efficiency of RockBlock's antenna to establish a connection with the Iridium Satellite Network and transfer the emergency signal off-board. In the case of an upside-down ATV (the result of a rollover incident), the antenna's efficiency could be compromised since it would not be facing the sky. To optimize the antenna's performance, we tested three design configurations (sensor orientation): antenna facing towards the sky, antenna placed orthogonally (90º), and antenna inverted (upside down). The average response time of each configuration were compared to each other through an analysis of variance (ANOVA) with a significance coefficient of 5 % ($\alpha = 0.05$). Thirty replicates of each design configuration were evaluated.

A benchmark of 60 s for the first responder's notification, as suggested by Funke et al.[129] and Champion et al.[130], was adopted as the desired outcome of the system. The design configuration with the shortest response time was compared to the benchmark by a t-test with a significance coefficient of 5% ($\alpha = 0.05$).

3.3.11.3 Vehicle tracking

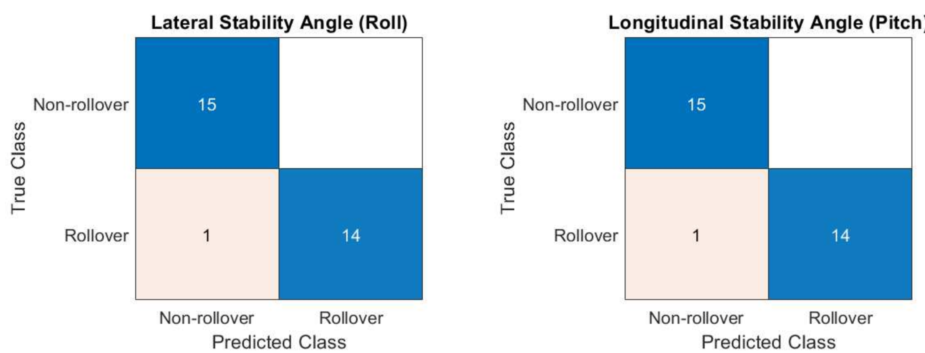
The performance of the vehicle tracking system was evaluated separately for both position and velocity estimates. The response variables were the average position deviation and the average velocity error. Critical values were set as 10 m (position), and 1.0 m s^{-1} (velocity). Although the desired outcomes may seem well below the accuracy delivered by the state-of-art GPS devices/tracking algorithms, very high accuracy is not critical for the success of this system. For instance, personal locator beacons (PLBs), which have an accuracy of about 100 m when interfaced with GPS, have been used successfully to aid EMS responders in locating ATV crash patients and stranded mountain hikers [131-135]. In addition, a benchmark of 100 m, 67% of the time, as proposed by Champion et al.[130] , was implemented when evaluating the accuracy of automated collision notification systems (ACNs) for automobiles.

The null hypotheses ($\overline{D} \leq 10$ m; $\overline{V}_{error} \leq 1.0$ m s^{-1}) were tested through a t-test with a significance coefficient of 5% ($\alpha = 0.05$).

3.4 RESULTS

3.4.1 Rollover Detection

A confusion matrix was computed and plotted for both lateral and longitudinal stability angles (Figure 3.7). In each matrix, the detection of a rollover event is labeled in both horizontal and vertical axes. The horizontal axis represents the number of incidents predicted in each class (rollover / non-rollover) by the system, and the vertical axis represents the ground truth data. True negative (T.N.) cases occur when the true class "non-rollover" and the predicted class is also "non-rollover" (upper left corner of the matrix). Similarly, F.P. cases occur when the true class is "non-rollover" but the predicted class is "rollover" (upper right corner of the matrix); F.N. cases occur when the true class is "rollover" but the predicted class is "non-rollover" (lower left corner of the matrix). Lastly, T.P. cases occur when the true class is "rollover" and the predicted class is also "rollover" (lower right corner of the matrix).



(a) (b)

Figure 3.7. Rollover detection system performance

The accuracy of the incident detection system is crucial because the outcomes of a misclassification come at an expensive cost. For instance, a false positive outcome would trigger first responders and lead them to a crash scene when there is no crash. On the other hand, a false negative outcome is equally critical because it implicates that first aid will not be rendered when it is needed the most.

AgroGuardian presented equal results for both lateral-rollover and longitudinal-rollover detection, highlighting its robustness. In addition, the overall accuracies of 0.96 and F-scores of 0.96, which are higher than the rollover accuracy reported by Funke et al. (2000) [130] (93 %), indicate that the system was very effective in distinguishing rollover incidents from non-rollover incidents.

A deep analysis of the data revealed that the system presented an angle estimate error of 0.8 ± 0.15º (95% Confidence Interval – CI). Since rollover detection is a binary variable, it is reasonable to conclude that the system will only fail when the ATV is ridden at slopes within 0.95º of their rollover thresholds. For example, assuming that the lateral rollover threshold of our study ATV (Honda Rancher, 2018) is 44.6º [40], the system will only fail if the ATV is operated in slopes between 43.65º and 45.55º. Indeed, in our trials, the system only failed when the sensor was tilted at 45º (lateral rollover tests). Similarly, for tests of longitudinal rollover, the system only failed when the sensor was tilted at an angle of 28.1º (the study ATV's longitudinal rollover threshold is 27.6º).

Due to the technical difficulties of conducting a rollover simulation (e.g., damage of the vehicle's frame or sensing equipment, sufficient number of replicates, etc.), we set up a bench test that included very specific tilting angles, such as those that are close to the ATV rollover thresholds. However, in a real scenario, riders are extremely unlikely to operate the ATV at angles close to the ATV thresholds. That is either because riders are afraid of riding at steep slopes [55] or because the ATV will simply roll over when it is tilted beyond its stability angle. Thus, we conclude that AgroGuardian will reach an accuracy superior to 99.99% in real riding conditions.

3.4.2 Crash Report System

The total response time of three key emergency signals was evaluated, including (I) rollover detection, (II) emergency notification receiving in AgroGuardian's web server, and (III) Noonlight confirmation of emergency alert. The time elapsed between (I) and (II) indicates RockBlock's antenna's capability of connecting to the Iridium Satellite Network. The time elapsed between (II) and (III) only depends on internet speed. For this reason, we evaluated the response time of the system in three separate ways: (a) Time elapsed between (I) and (II) (defined as off-board communication time); (b) Time elapsed between (II) and (III) (defined as internet time); and (c) Total time which is difference between (III) and (I).

An initial attempt at collecting the data consisted of placing the RockBlock antenna directly on top of the ATV handlebar (tallest point of the ATV). However, it was observed that RockBlock would always fail to send off-board messages when its antenna was placed upside-down (inverted), directly touching the ground without any gap. In order to fix this issue, we placed the sensor on the ATV chassis, which was located at the height of approximately 0.25 m (10 in.) below the handlebar. This new configuration created a clearance zone between the antenna and the ground when the ATV was upside-down. The remaining treatments were run as originally planned. The average response times of each treatment are presented in Table 3.4 below.

Table 3.4. Comparison of AgroGuardian's response time intervals in seconds for different sensor orientations

Sensor orientation	Range	Average (SD)[1]	CV (%)	p-value[2]
Off-board communication time				
Upright	14-190	35.60 (42.46)	119.26%	
Orthogonal	9-354	40.60 (66.86)	164.7%	0.357
Inverted	8-82	23.57 (18.60)	78.9%	
Server-Noonlight time				
Upright	3-12	5.10 (1.84)	36.2%	
Orthogonal	2-46	7.77 (9.12)	117.5%	0.366
Inverted	3-48	6.93 (8.84)	127.6%	
Total time				
Upright	18-196	40.70 (42.61)	104.7%	
Orthogonal	12-360	48.37 (68.14)	140.9%	0.364
Inverted	11-108	30.60 (23.15)	75.7%	

Definitions: SD = standard deviation; CV = coefficient of variation.

[1] Sample size (n) = 30

[2] F-test for comparison of means through ANOVA.

As expected, the internet time is independent of the sensor orientation (p-value = 0.366). Furthermore, no specific sensor orientation yielded a significantly smaller response time for off-board communication (p-value = 0.357) nor for the total time (p-value = 0.364). This is an important finding as it leads to the conclusion that the system works even when the ATV is upside-down. Results demonstrated that

RockBlock is capable of connecting to the Iridium Satellite Network as long as there is a clearance zone of at least 0.25 m above its antenna, which is about the height difference between the study's ATV handlebars and chassis.

It is important to mention that smaller ATV models such as youth models might have a different clearance zone between the chassis and the handlebars. For those cases, the validity of our results might be questionable, and more research would be needed. Nevertheless, the ATV evaluated (Honda Rancher TRX 500 2018) is representative of an average adult-sized ATV commonly used among riders on farms and ranches in the U.S.

Since no specific antenna placement yielded a significantly shorter response time, the sensor was placed upright on the chassis because of the greater ease of installation.

Emergency medical service (EMS) response time intervals for ATV crashes likely have a critical impact on patient health (e.g., chances of survival, injury severity, and hospital length of stay) [131]. For instance, a previous study about car incidents reported that riders are three times more likely to survive a crash if EMS is notified within 60 s [129]. Therefore, it is essential to minimize the EMS response time to an incident. The national U.S. average elapsed time between crash to EMS Notification is 228 s for the urban crashes and 408 s for the crashes in rural areas [129]. The results of the t-test confirmed that AgroGuardian's response time (95% CI = 40.70 ± 13.17 s) is significantly shorter than the benchmark of 60 s [130] (p-value < 0.001) and about ten times shorter than the national average for rural areas.

3.4.3 Vehicle Tracking System

The performance of AgroGuardian's tracking system is presented in a graph (Fig. 8) that compares the vehicle's location measured by AgroGuardian and by the RTK GPS. Since the collected data was converted into UTM coordinates, the x and y values of those coordinates become inherently large (e.g., x = -548,749.30; y = 4,176,423.74), which hinders the visualization of the data. In order to enhance the quality of Fig. 8, the coordinate points (x_i, y_i) from the experimental trials were converted from "world frame" (i.e., original UTM coordinates) to "local frame", by subtracting the origin (x_0, y_0) from the rest of the samples. It is important to highlight that the same origin was used for both datasets (AgroGuardian and RTK receiver). In other words, the data was processed according to equations 3.4 to 3.7:

$$x_{agro} = x_{agro} - x_{RTK\,0}; \tag{3.4}$$

$$y_{agro} = y_{agro} - y_{RTK\,0}; \tag{3.5}$$

$$x_{RTK} = x_{RTK} - x_{RTK\,0}; \tag{3.6}$$

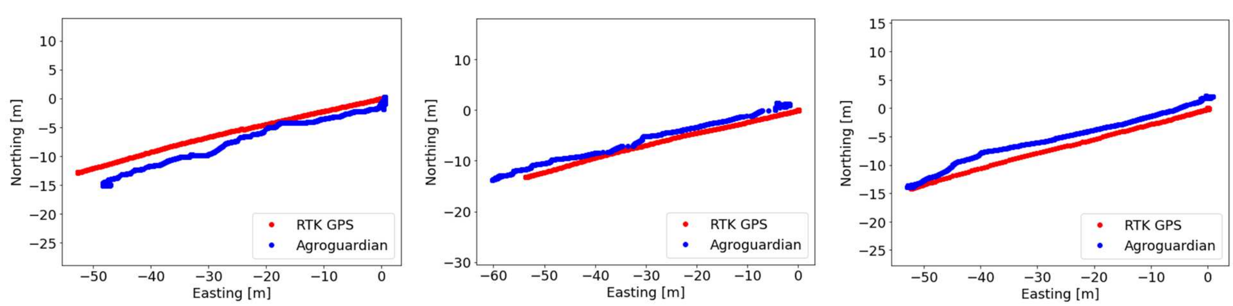
$$y_{RTK} = y_{RTK} - y_{RTK\,0}. \tag{3.7}$$

A summary of the performance of AgroGuardian's tracking system is presented in Table 3.5 and Figure 3.8. The sample size, mean, standard deviation, and confidence interval for position deviation for the GPS module were 29,013, 2.34, 2.01, and 2.32-2.36 m, respectively (Figure 3.8). Using a similar low-cost GNSS module, Silva et al. (2019) [136] obtained average deviations of 2.37 and 3.32 m in dynamic tests with the velocities of 2.22 and 4.17 m s^{-1}, respectively.

Table 3.5. Descriptive statistics for AgroGuardian's position estimate error (m)

Test velocity (m s^{-1})	Range	Average (SD)	CV (%)
2.23	0 - 8.53	3.22 (2.14)	67%
3.57	0 - 10.24	2.17 (1.88)	86%
5.36	0 - 12.13	1.67 (1.67)	100%
Total	0 - 12.13	2.34 (2.01)	86%

Definitions: SD = standard deviation; CV = coefficient of variation.



(a) (b) (c)

Figure 3.8. AgroGuardian's localization performance tests for several speeds. (a) Test at 2.23 m s^{-1} (5 mph), (b) test at 3.57 m s^{-1} (8 mph), and (c) test at 5.36 m s^{-1} (12 mph).

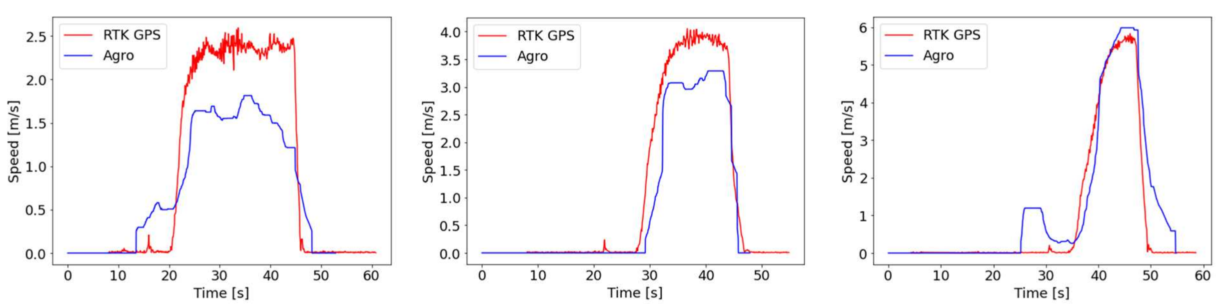
It is noteworthy that AgroGuardian's accuracy is much higher than PLBs, which served as a baseline for comparison. Moreover, the result from the t-test showed that the average position deviation of AgroGuardian's vehicle tracking system (95% CI = 2.34 ± 0.02 m) was significantly smaller than 10 m (p-value < 0.001), concluding our null hypothesis.

The average velocity error for the speeds of 2.23, 3.57, and 5.36 m s^{-1} were 0.77, 0.63, and 0.88 m s^{-1}, respectively (Table 3.6). Moreover, the average error across all replicates was 0.75 ± 0.02 m s^{-1} (95% CI). These values are significantly smaller than our selected benchmark of 1.00 m s^{-1} (p-value < 0.001). Despite the lower precision compared to the state-of-the-art tracking devices, it is possible to use AgroGuardian's low-cost system to track the riding parameters within reasonable accuracy.

Table 3.6. Descriptive statistics for AgroGuardian's velocity estimate error (m s^{-1})

Test velocity (m s^{-1})	Range	Average (SD)	CV (%)
2.23	0 - 2.72	0.77 (0.88)	114%
3.57	0 - 3.97	0.63 (0.97)	152%
5.36	0 - 4.89	0.88 (0.99)	112%
Total	0 - 4.89	0.75 (0.95)	126%

Definitions: SD = standard deviation; CV = coefficient of variation.

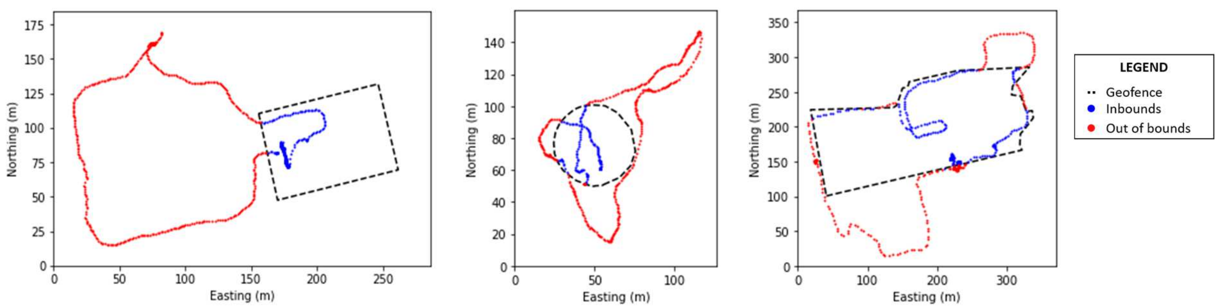


(a) (b) (c)

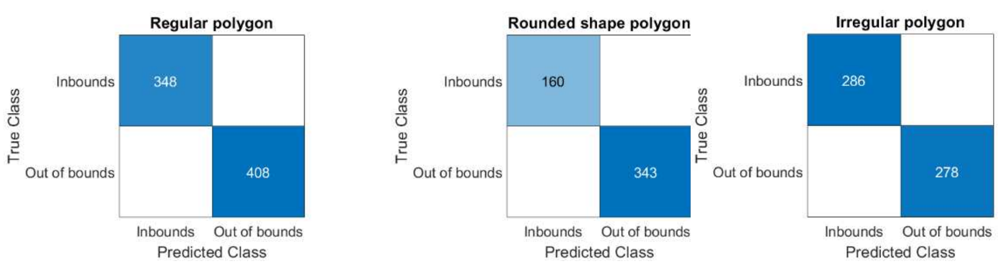
Figure 3.9. AgroGuardian's velocity performance tests for several speeds. (a) Test at 2.23 m s^{-1} (5 mph), (b) test at 3.57 m s^{-1} (8 mph), and (c) test at 5.36 m s^{-1} (12 mph).

3.4.4 Geo-fencing

A summary of the performance of AgroGuardian's geo-fencing is presented in Figure 3.10. AgroGuardian presented a perfect accuracy (100%) for detecting points inbounds and out of bounds, as can be seen in the maps and the confusion matrices, with F-Score = 1.0 for all tests. Furthermore, the results indicated that the system's accuracy is independent of the geo-fence shape, since all tests yielded the same results.



(a) (b) (c)



(d) (e) (f)

Figure 3.10. Geo-fencing performance assessment. (a) Test for regular polygon; (b) Test for rounded shape polygon; (c) Test for irregular polygon; (d), (e), (f) Confusion matrices of (a), (b), and (c), respectively.

As previously discussed, geo-fencing is a practical application that increases the rider's safety and also asset's safety. The accuracy achieved in the field trials reinforces AgroGuardian's potential capability of improving ATV riders' safety.

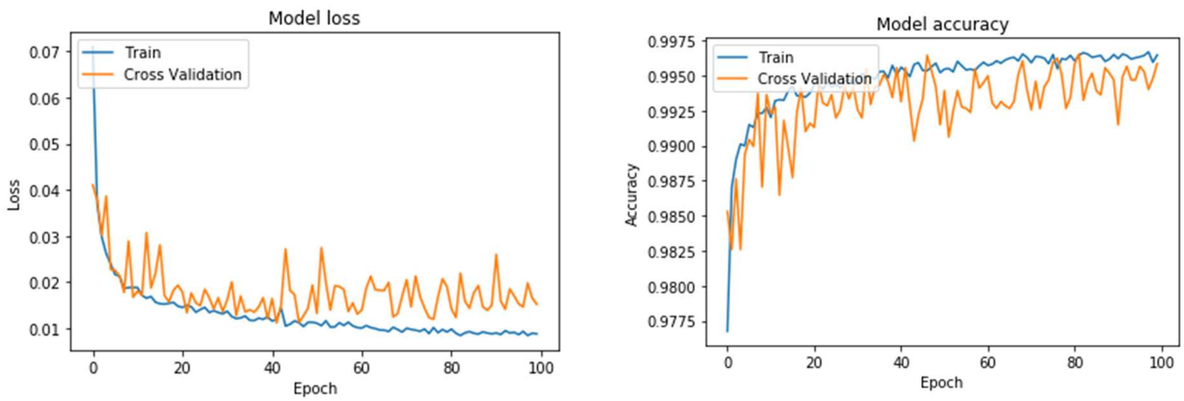
3.4.5 Real-time notifications

A summary of the performance of the top ten classification models is presented in Table 3.7. The results indicate that the models tested can predict rollover with reasonably high accuracy (> 99%). The model with the highest AUC, accuracy, and F-Score was the Deep Neural Network, with two fully connected hidden layers (32 neurons in each), and ReLU activation function.

Table 3.7. Performance summary of the classification algorithms

Rank	Algorithm type	Combination of Parameters	AUC	FScore	Accuracy
1	DNN	Activation = ReLU; Layers (neurons): 2(32/32); Optimizer = Adam; Epochs = 100	1.000	0.976	0.996
2	SVM	C = 2, gamma = 0.2, kernel = rbf	1.000	0.974	0.994
3	Random Forest	Number of trees = 300	0.999	0.955	0.990
4	Random Forest	Number of trees = 200	0.999	0.955	0.990
5	Random Forest	Number of trees = 100	0.999	0.958	0.990
6	Random Forest	Number of trees = 250	0.999	0.954	0.989
7	SVM	C = 0.2, gamma = 0.2, kernel = rbf	0.999	0.946	0.988
8	SVM	C = 2, gamma = 0.2, kernel = poly	0.999	0.974	0.994
9	KNN	Number of neighbors = 10	0.998	0.941	0.987
10	KNN	Number of neighbors = 9	0.998	0.951	0.989

The learning curves for the selected model (Rank #1) are presented in Figure 3.11. The learning curves indicate that neither underfitting nor overfitting has occurred. In total, 1,474 parameters were trained over a dataset containing 31,020 samples. The selected model achieved an overall accuracy superior to 99.5% over a testing dataset with 10,340 unseen data points. Furthermore, the model's balanced accuracy (0.993) and F-score (0.976) indicated that the imbalanced dataset did not represent a problem.



(a) (b)

Figure 3.11. Rollover prediction algorithm learning curves. (a) Model loss; (b) Model accuracy.

The fundamental advantage of the developed model over mathematical simulations or finite element analysis lies in its simplicity in terms of inputs and easiness of implementation for real-time applications (computing time smaller than 1 ms). For instance, mathematical simulations and finite element analyses require information either about the vehicle's center of gravity or stability angles, which are variables that require laborious field tests to be obtained. The proposed model takes as input ATV dimensions that are easy to determine or that are readily available on the internet, such as the vehicle's length, width, wheelbase, and seat height. Furthermore, finite element analysis implies a high computational cost, making its application almost prohibitive for real-time applications involving complex systems, such as an ATV.

The limitation of our model includes riding over bumps or hitting obstacles, which are also reported as causes of rollover [41,49,50,52,120,121]. Nevertheless, the model proved to be effective in predicting crashes under diverse riding scenarios. This feature will assist riders to ride cautiously under hazardous conditions, thus helping to prevent crashes.

Despite several guidelines and safety awareness programs, overall public knowledge of ATV safety appears to be limited [137-139]. For instance, one study among a rural population in Pennsylvania reported that about 66% of riders overestimate slope angles that are safe for riding [55]. Indeed, many ATV-related crashes involve riders who engaged in risky riding behaviors at the time of the crash [30,56,82,102,103]. Research studies on strategies for ATV education indicated that interventions are more effective if they offer action-oriented safety messages that are realistic and visually pleasing [16,140]. In this sense, AgroGuardian's notification system can warn inattentive riders by issuing real-time audiovisual alerts, guiding riders to take safety actions, such as reducing their speed.

3.5 DISCUSSION

A staggering number of riders die or sustain severe injuries every year due to ATV-related incidents. The full extent of geographic patterns of those injuries and deaths is yet unknown. However, compelling evidence suggests that riders injured in isolated or small rural areas suffer a disproportionately large mortality rate relative to their counterparts in urban and accessible areas [90,99]. That is despite the fact that riders injured in off-road crashes (e.g., farms and ranches) are more likely to be helmeted and less likely to be intoxicated or carry additional passengers [56,100,103]. Furthermore, the larger fatality rate on off-road crashes is likely associated with longer times of EMS patient access. On average, first aid rendering times are 38% longer for crashes in remote locations versus accessible locations, disregarding the time interval from crash-to-EMS notification [131].

Former attempts to prevent ATV-related injuries included both policy and educational safety [16] but the outcomes were not satisfactory. In addition, previous studies demonstrated that riders often disregard safety precautions despite this knowledge [62,99,139,141-143]. Given the lack of success in previous attempts, automatic systems for fast EMS contact rose as a potential solution for injury prevention. In the present manuscript, we developed a system (AgroGuardian) that predicts the likelihood of a crash and alerts the riders, thus allowing them to prevent the crash. For the cases when the rider cannot avoid the incident, AgroGuardian notifies EMS in less than a minute.

Performance tests indicated that: (1) AgroGuardian has a rollover prediction system with an accuracy superior to 99%; (2) AgroGuardian has a rollover detection system with an accuracy superior to 99%; (3)

AgroGuardian has a fast EMS notification time (40.70 s); (4) Crash localization presented an accuracy of 2.34 m.

3.6 CONCLUSIONS

In this study, we developed and evaluated the performance of an automatic ATV crash prediction, detection and notification device. The developed device can accurately predict or detect a rollover and its location and promptly contact EMS. In addition, the remotely controlled shut-off system, anti-robbery, geo-fencing, and danger alerts (or dangerous riding conditions) systems are functional and work based on adjusted values.

4 CHAPTER 4 – OVERALL CONCLUSIONS AND FUTURE WORK

4.1 Overall Conclusions

All-Terrain Vehicles cause a staggering number of injuries and fatalities every year across the world. In attempting to improve ATV safety we identified significant knowledge gaps in the literature pertaining to some risk factors associated with ATV-related incidents, namely: youth ATV operators and crash location (challenges for EMS to administer first aid to riders injured in remote and isolated areas). In this dissertation, progress towards these gaps in literature was made through two projects – Project 1: Capabilities and Limitations of Youth All-Terrain Vehicle Operators; and Project 2: AgroGuardian – A Novel ATV Crash Prediction, Detection, and Notification System.

4.1.1 Project1: Capabilities and Limitations of Youth All-Terrain Vehicle Operators

In the first project, we evaluated potential inconsistencies between the requirements for riding utility ATVs and the youth's physical capabilities in two separate studies (one study concerning youth's physical strength and another study concerning youth's ability to reach the ATV's controls). In the first study, we measured the forces required to activate the main controls of 54 utility ATVs and compared it to the physical strength of youth from different age groups (6-11, 12-15, and 16-20), strength percentiles (5^{th}, 50^{th}, and 95^{th}), and genders (males and females). The main findings were that: (1) the activation forces required to operate utility ATVs typically exceed the strength of most youth aged 6-20 years old, especially females; (2) youth should not operate ATVs for extended periods (e.g., work) – for instance, the typical 16-20 year-old male of the 50^{th} strength percentile is not strong enough to operate at least 50% of all evaluated ATVs; (3) the ability to activate ATVs' footbrake along with the ability to push off the ATV if pinned underneath it are the most critical factors to determine whether youth are capable of riding based on their strength; (4) only engine size and rider's age are not reliable indicators of youth-ATV fit.

In the second study, we assessed the suitability of utility ATVs for youth based on their anthropometry and eleven ATV-fit guidelines proposed by four ATV safety advocacy organizations (National 4-H council, CPSC, IPCH, and FReSH). The main findings were that: (1) Youth should not ride utility ATVs since most youth failed to pass at least one out of the eleven ATV-fit criteria for the 14 evaluated vehicles; (2) only engine size, maximum speed, and rider's age are insufficient indicators of youth-ATV fit since our results showed that some fit criteria favor smaller youth while some benefit taller youth, regardless of the rider's age and vehicle's engine size or maximum speed.

The results from these two studies (youth's strength and anthropometry) raise serious questions about the ability of youth to safely operate utility ATVs on U.S. farms and about the validity of current youth-ATV fit guidelines. We recommend that the readiness of youth to ride ATVs should be carefully evaluated by their parents/guardians. Moreover, we argue that current youth-ATV fit guidelines should be reviewed and updated based on quantitative and systematic data comparing the physical ability of youth and the operational requirements of ATVs.

Further, we stress that ATV-related injuries and deaths among youth are a consequence of causes from various sources that are not necessarily related to each other. Some of these sources include but are not limited to lack of mental and cognitive skills, limitations in the physical ability to reach and activate the controls of utility ATVs, lack of safety education/awareness, lack of helmet, and transporting passengers. As such, to prevent those injuries and fatalities, there is a need for a mixed approach combining engineering redesign, legislation, parent involvement, and safety education.

4.1.2 Project 2: AgroGuardian – A Novel ATV Crash Prediction, Detection, and Notification System

In the second project, we developed, manufactured, and tested a device (AgroGuardian) to make online predictions of the likelihood of an ATV rollover. If the calculated rollover likelihood is above a pre-set threshold, the device will alert the rider in real-time, thus assisting in the prevention a potential crash. Also, AgroGuardian automatically notifies EMS and emergency contact(s) when a rollover is detected even though no cellular service is available and the rider cannot take action. AgroGuardian's performance was assessed through experimental tests simulating rollovers and normal riding conditions. The results showed that: (1) the device's rollover prediction and detection systems have an accuracy superior to 99%; (2) the device has a fast EMS notification time (40.7 s); (3) ATV localization presented an error less than 2 m. The results obtained in the performance tests are encouraging and we hope to deploy this technology in the market as soon as possible.

4.2 Future Research

While working on this dissertation, several knowledge gaps were identified and are worth mentioning. The suggestions of future research are presented in the next two sessions, the first being related to mismatches between the rider's capabilities and the operational requirements of ATVs; and the second being related to crashes on remote and isolated areas.

4.2.1 Rider's capabilities and operational requirements of ATVs

One suggestion for future work is related to the fit of youth-ATV models to youth. A previous study [53] evaluated the fit of one youth-ATV model to 19 subjects and concluded that even youth-models are not suitable for youth riders. Since the sample size of this previous study was fairly small there is a need for a new study to expand this analysis.

Moreover, evidence suggests that female ATV operators are at an increased risk of incidents compared to their male counterparts. Women have an average height of 1.60 m (5'3") [144,145]; they are grouped into the large category of small adults (under 1.78 m) (5'10") and are recommended to use ATVs with a 400 cc engine [146,147]. In contrast, this ATV size is not recommended for operators carrying large loads or riding in rough and uneven terrains [148], all of which are commonly observed scenarios on farms and ranches. Therefore, there is a need to evaluate if the physical capabilities of female operators (strength, anthropometry, and field of vision) are enough to fulfil the operational requirements of utility ATVs.

Furthermore, upon completion of the present study, we found it difficult to evaluate the suitability of ATVs for youth based on the fit guidelines. It is not an easy task to accurately and consistently measure body angles and dimensions without appropriate tools and prior knowledge/experience. As such, parents, guardians, and dealerships may not be willing to evaluate the youth's readiness to ride the ATV based on the fit guidelines presented in chapter 2 of this dissertation. Hence, there is a need for the development of a tool or technique that allow stakeholders to quickly and easily assess the youth's readiness to ride a specific machine based on the fit guidelines. Particularly, computer vision techniques such as human pose estimation [149] emerge as potential solution for the outlined issue.

Lastly, other risk factors such as experience, psychological, and cognitive development cannot be overlooked [31,61]. Youth who are high in thrill-seeking are more likely to engage in risky ATV riding behaviors, regardless of their safety awareness [62]. In this regard, there is a need for a thorough assessment of youth's cognitive abilities, including their reaction time, attention/focus, quality of decision making, and error recovery.

4.2.2 ATV crashes on remote and isolated areas

Despite rollover being the most frequent cause of ATV incidents, other types of crash should also be considered when developing an automatic ATV-crash detection device. For instance, a significant number of ATV crashes consist of collisions, which can cause severe injuries to riders. Therefore, another suggestion of future work is related to an automatic collision detection device. Such device could be integrated to AgroGuardian and help prevent fatalities among riders injured on remote and isolated areas where first aid administration is challenging.

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