Side-By-Side Utility and Recreational Vehicles—A Safety Analysis

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ABSTRACT

Recently there has been a dramatic increase in the popularity and sales of side-by-side utility and recreational vehicles (sometimes referred to as UTVs and ROVs). One potential reason for the increased popularity is the perceived additional safety of the side-by-side compared to a standard ATV. These side-by-sides more closely resemble passenger vehicles than ATVs because of such features as a steering wheel, bench or bucket seats, 3 point safety belts, and a roll-cage or protective structure. However, there are increasing numbers of low speed accidents on these vehicles resulting in catastrophic injuries and even deaths.

This paper will analyze the causation of these low speed accidents and will address the effectiveness of the safety features of these vehicles at protecting the occupants during such events. This paper will first address the vehicle dynamics involved and their role in the loss of control and tip-over of the vehicle. Secondly, the paper will examine various occupant restraint systems (i.e. belts and the occupant containment envelope) found on these vehicles.

Conclusions will be made addressing the short-comings of some of the current designs, and suggestions at how to improve these will be discussed.

INTRODUCTION

A mother from Texas, whose young son was killed when the Yamaha Rhino he was a passenger on had a ¼ roll tip-over, described her first impressions of the vehicle as follows:

I suppose we all rely on our past experiences to help us make decisions regarding safety. As a mother I can honestly say I was terrified of standard ATVs. Not only because of the negative publicity such vehicles receive due to accidents but because of the "open air design". It seemed to me at the time that someone using such an ATV wouldn't be adequately protected in an accident because so much of the rider is exposed. That being said, the first time I saw the Yamaha Rhino the design itself didn't lend itself to the ATV category. The Yamaha Rhino is designed, in my opinion, to look much more like a "little truck". The front of the machine, the roof, roll bar, the cargo bed, and the seatbelts all add to this illusion. With my first impression of the Rhino being that of a vehicle, I had the expectation that the machine would perform much like a truck.

Another owner described the vehicle as “a little pickup truck”, and another stated, “The thing that made me feel safe about taking them [grandchildren] was that it had seatbelts.”

The above illustrates the influence of perceived safety advances of these types of vehicles on the decision to purchase or to operate such, especially with regards to parents who are buying the vehicle and are allowing their children to operate or be passengers on them. As will be demonstrated in this paper, however, these safety features are not always preventing accidents and/or protecting occupants during accidents.

Extensive research and testing has been performed by The Engineering Institute and Gilbert Engineering with regard to certain of these vehicles, especially the Yamaha Rhino, and the majority of this paper will deal with this research and analysis.

OVERVIEW

Analysis of The Rhino side-by-side
Static Stability, Loss of Control and Rollover

The static and dynamic testing of the Rhino by The Engineering Institute is covered in detail in the paper *Dynamic Analysis of Side-by-Side Utility and Recreational Vehicles, Paper Number 09-0260* by Roberts published at the NHTSA sponsored ESV 2009 conference[1].

Therefore, a summary of the static and dynamic testing will be covered in this paper. For supplemental and complementary material please see the above referenced paper.
In 2001, Public Law 106-346 required the Department of Transportation to fund a study by the National Academy of Sciences
on whether the static stability factor is a scientifically valid measurement that presents practical, useful information to the public, including a comparison of the static stability factor test versus a test with rollover metrics based on dynamic driving conditions that may induce rollover events.

The findings of this study were published in "An Assessment of the National Highway Traffic Safety Administration's Rating System for Rollover Resistance—Special Report 265" in 2002[2]. The study was overwhelmingly positive with regard to using the Static Stability Factor (SSF) as an indicator of a vehicle's resistance to rollover, with lower SSFs indicating less rollover resistance or a greater chance of a rollover. The following excerpts demonstrate the above statement.

Through a rigid-body model, SSF relates a vehicle's track width, T, and center of gravity height, H, to a clearly defined level of the sustained lateral acceleration that will result in the vehicle's rolling over. The rigid-body model is based on the laws of physics and captures important vehicle characteristics related to rollover. (p. 3)

An increase in the SSF reduces the likelihood of rollover. (p. 3)

SSF captures important vehicle characteristics related to rollover propensity and is strongly correlated with the outcome of actual crashes… (p. 5)

SSF is an important indicator of vehicle rollover propensity. Based on a rigid-body model of a vehicle, it relates easily measured vehicle parameters to a level of sustained lateral acceleration that leads to vehicle rollover. Real vehicles roll over at lower sustained levels of lateral acceleration than the accelerations predicted by the SSF. (p. 31)

SSF is preferable to other static measures as an indicator of a vehicle's rollover propensity. (p. 36)

The study also summarized NHTSA findings with regard to the SSF and star ratings system. In the system at the time of the study's publication, NHTSA assigned vehicles 1 through 5 stars depending on the SSF with 5 stars indicating the highest rollover resistance. On a percentage basis, a vehicle with 5 stars has a risk of rollover of less than 10 percent, and a vehicle with a 1 star rating has a risk of rollover greater than 40 percent. A 1 star rating was given to vehicles with a SSF of 1.03 or less, a 5 star equaled 1.45 or greater.

Though a proponent of the SSF and its usage as a good first indicator, the Academy also stressed the need for dynamic testing, especially as a supplement to the SSF. The report indicates that dynamic testing is performed by every major automobile and truck manufacture as well as government agencies, consumer groups, and enthusiast magazines. The following are some of the group's findings regarding dynamic testing.

Metrics derived from dynamic testing are needed to complement static measures, such as SSF, by providing information about vehicle handling characteristics that are important in determining whether a driver can avoid conditions leading to rollover. (p. 3)

Dynamic testing is needed to understand the loss-of-control phase of a crash… (p. 36)

One of the committee's recommendations in the area of vehicle dynamics (see Chapter 2) is that NHTSA pursue the use of dynamic testing to supplement the information provided by SSF (see Chapter 5). (p. 78)

Thus static metrics—such as SSF—and dynamic tests are complementary, and both are needed to investigate a rollover crash in its entirety, from initiation to final outcome. (p. 88)

The dynamic testing proposed by the study would ideally not only test the rollover resistance and show deficiencies in that regard, but would also demonstrate how controllable the vehicle is (or, conversely, how difficult to control the vehicle is). As mentioned in the study, some rollover accidents can be broken down into three phases. Phase 1 is referred to as the Control Region. During this phase, the vehicle is responding as expected and basically following the commands of the driver in a predictable manner. Phase 2 is the Transition Region. During this phase, the vehicle no longer is responding in a predictable manner and the driver is losing control of the vehicle. Phase 3 is the Out-of-control Region where the driver has lost control of the vehicle, and the rollover is initiating. The following diagram is taken from the study's report.

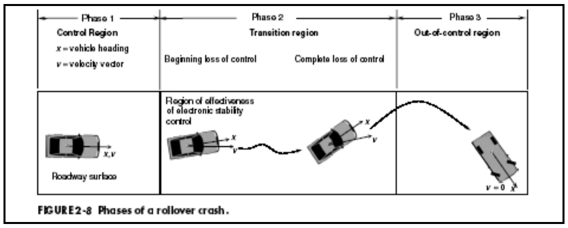

FIGURE 2-8 Phases of a rollover crash.

Figure 1. Diagram of the phases of a rollover crash

Testing by The Engineering Institute and Gilbert Engineering also showed how the static and dynamic testing are complementary to each other. The Engineering Institute measured the SSF of the Yamaha Rhino in unloaded and loaded conditions. The SSF was determined by first measuring the height of the center of gravity on a tilt-table. For this, the vehicle suspension was locked so that the only compliance in the system was due to tire sidewall deflections. After measuring the CG height for each loading configuration, the SSF was calculated using this number and the average track-width of the vehicle. The results of the static testing are summarized in the figure below.

Configuration	Average CG Height (in.)	Average SSF
Vehicle Only	24.5	0.88
Vehicle Plus 160 lb Driver	27.3	0.79
Vehicle Plus 160 lb Driver and Passenger	28.3	0.77
GVWR	31.1	0.71

Figure 2. Rhino SSF test results

The results of this testing indicated that the Rhino has a high rollover propensity. Even in the unloaded condition, it is seen that the vehicle is already well below the 1.03 SSF that NHTSA uses as the maximum value for a 1 star rating. Also, the static testing showed the high sensitivity of the vehicle to addition of occupants and cargo. The addition of a 160 lb occupant raised the center of gravity by 2.8" which reduced the SSF by 10%. Therefore, based on the static numbers, it was concluded that this vehicle would easily roll over due to tire friction forces alone. Dynamic testing was pursued to (1) determine the rollover threshold and (2) to examine the handling characteristics of this vehicle which would have the greatest effect on the Phase 2: Transition Region of the rollover accident scenario.

The dynamic testing clearly demonstrated the vehicle's high rollover propensity. The vehicle experienced imminent rollover (arrested by the outriggers) during several tests. Lateral accelerations to cause rollover were much less than those predicted by the SSF and were as low as 0.55 G's. Certain maneuvers such as J-turns and U-turns while accelerating could make the vehicle tip at speeds around 12 mph.

The low speed maneuvers such as the J-turn and U-turn were surprising in that there was relatively no feedback to the driver indicating the initiation of the rollover event. The tip to the outriggers occurred quickly and without warning. This is demonstrated in the figure below which shows the time between when the vehicle first responds to the input and the time to which it is committed to rolling over. Also shown is the time between when the lateral acceleration exceeds 0.3 g's and when the vehicle is committed to rollover. The times are seen to be 0.7 and 0.5 seconds, respectively.

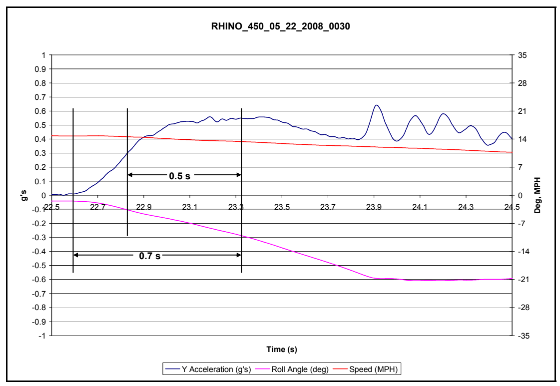

Figure 3. Plot of step steer data

Testing by Gilbert Engineering on a 2006 Rhino 660 showed similar results. The vehicle's rollover threshold was exceeded in a J-turn maneuver with a lateral acceleration as low as 0.57 g's. The stock Yamaha Rhino has such low capacity that drivers are likely to exceed its capacity in everyday use.

During steering reversals and at the limits of the SAE J266 testing, another result of the dynamic testing demonstrated how the design of the Rhino actually encourages the initiation of the loss of control phase. The vehicle exhibited severe oversteer which is unpredictable and can easily lead to a loss of control. The oversteer is promoted by the vehicle's suspension design, in particular the rear-only anti-sway bar. In a corner, this rear anti-sway bar is acting to lift the inside rear wheel as shown in Figure 3. This causes a loss of traction on the rear, causing the rear of the vehicle to want to spin-out and the driver to lose control. The rear only anti-sway bar is necessitated by the rear drive design. The rear of the vehicle does not have a differential. Rather, both half-shafts are driven by the same splines, meaning both rear wheels must rotate at the same speed. In a cornering maneuver on a normal-friction surface, this would cause tire scrub and severe understeer. Therefore, the anti-sway bar is installed to lift the inside rear wheel in a turn to avoid this.

The 2000 Edition of the SAE *Manual on Design and Manufacture of Torsion Bar Springs and Stabilizer Bars*[3] warns against a rear-only stabilizer bar. The manual states that, "Stabilizer bars are generally installed on both front and rear suspensions or in front suspension only. Use of a stabilizer bar on the rear suspension only can sometimes have an adverse effect on vehicle handling. Such installations should be tested under severe cornering conditions to ensure the desired handling characteristics." Also, the vehicle dynamics principles relating the relative stiffness of the front to the rear with understeer/oversteer is something that is very well understood. It is well known by vehicle engineers that a stiffening of the rear relative to the front, as would be done with a rear-only anti-sway bar, decreases the vehicle's understeer (or increases its oversteer).

Figure 4. Screen capture from dynamic testing inside rear tire lift.

The Engineering Institute tested an alternative design. The Rhino was modified by adding 4 inch spacers at each wheel, removing the spool rear drive and replacing it with a front differential from another Rhino, and removing the rear anti-sway bar completely. The vehicle performed significantly better with these design changes. The sustained lateral accelerations needed to cause rollover were well into the 0.8 g range. Also, certain tests that consistently caused the Rhino to tip in the stock configuration, e.g. a U-turn while accelerating, did not make the alternative design tip.
The open differential was necessary to demonstrate the increased understeer as a result of removing the rear anti-sway bar. Had the spool drive been retained without associated front to rear spring rate and roll rate balancing, it was opined that the vehicle would exhibit too much understeer, especially at low-speed, tight steer maneuvers.

Figure 5. Photograph of modified Rhino

Subsequent to testing of the Rhino, The Engineering Institute was retained by an UTV/ATV manufacturer to evaluate their side-by-side vehicles. The Engineering Institute redesigned the control arms and suspension system, calculated new spring and damping rates, and ordered and installed the necessary springs and shock absorbers. For test track evaluation, two iterations of rear anti-sway bars were tested and the front anti-sway bar was designed to be adjustable. By simply removing the rear anti-sway bar and setting the front to full soft, the understeer was detrimental to low speed turning, in particular on reduced friction surfaces. It was shown through proper front to rear roll stiffness tuning that steady-state understeer could be achieved even with the spool final drive. This testing is ongoing and the data is still being analyzed. Detailed analysis will be presented in a later paper.

A second modified Rhino was tested by Gilbert Engineering. The Rhino was modified with a suspension kit from Direct Concept Engineering (DCE). The modifications included longer control arms front and rear, remote reservoir shocks, coil-over springs, suspension droop-limiting straps, and longer drive axles. ITP Baja Cross X/D tires mounted on ITP wheels were also used.

Using the static numbers for the Rhino 450 measured by The Engineering Institute and the increased track width due to the suspension kit, the DCE Rhino has a theoretical SSF of 1.20. The DCE Rhino did not rollover in any pavement test runs at speeds as high as almost 37 mph and lateral forces as high as 0.96g. The only tip-up occurred on the dirt surface with a maximum lateral acceleration of 0.93 g's. The driver's notes indicated a "big dig" into the surface during this maneuver.

Figure 6. Photograph of DCE modified Rhino

As can be seen from the above results, simple static and dynamic testing has shown that the Yamaha Rhino not only has a high rollover propensity, but it also has a high propensity for loss of control. However, reviews of real-world accidents in the Rhino, particularly low-speed, ¼ roll events, indicate that the high rollover propensity is the major culprit; as the speeds and steering often don't push the vehicle into the loss-of-directional-control region.
Had Yamaha performed similar dynamic tests, as, according to the National Academy of Sciences, every major automobile and truck manufacturer does, these inherent problems would have been obvious.
In September of 2008, one of this paper's authors was asked to present his findings with regards to the Rhino to the United States Consumer Product Safety Commission.

In March of 2009, Yamaha announced a voluntary repair campaign[4]. The letter to owners states that, "The CPSC announced this repair program for Rhino 660 and 450 models. Yamaha is also voluntarily implementing the same free repairs for Rhino 700 models. "According to the CPSC, the following two repairs are needed 'to help reduce the chance of rollover and help improve vehicle handling':

1) Installation of a spacer on each of the rear wheels.
2) Removal of the rear anti-sway bar.

"**You should not operate your Rhino until it is modified with these repair parts**." (emphasis added in announcement)

Gilbert Engineering tested the CPSC modifications on a Rhino 660. The testing indicated that although the vehicle still tipped in each type of maneuver performed, the lateral force capacities were nearly 0.2g higher than those for the stock Rhino. This allows for some safety margin between real world driver demands and vehicle lateral force capacity.

Active and Passive Safety Features
The Yamaha Rhino has certain safety features that are perceived to make this vehicle a safer alternative to standard all-terrain vehicle designs. These safety features include bucket-type seating, three-point retractable safety belts, a safety-cage/roll-cage, a steering wheel, and various hand-holds.

The Rhino is equipped with a three-point safety belt with a cable mounted stalk and a single retractor. In a paper published at the ASME International Mechanical Engineering Congress and Exposition in 2002, Thomas et al. discuss the excursion of belted occupants during rollovers, specifically with regard to belt spool out[5]. In discussing the evolution of emergency-locking retractors (ELR's) the paper states that, "Over the past thirty years, ELR's have become a common feature in automobile restraint systems. During this time there have been two types of lockup mechanisms used in retractors installed in production vehicles: the vehicle sensitive ELR (one that locks up in response to the accelerations experienced by the vehicle in which it is installed) and the webbing-sensitive ELR (one that lucks up in response to the acceleration of the belt webbing as it is extracted from the spool). Historically, a vast majority of the restraint systems that incorporated an ELR used a vehicle-sensitive lockup mechanism as the primary locking feature. Many systems in use for more than the past decade have used a dual-sensitive locking mechanism that includes both the vehicle-sensitive and the webbing sensitive features."

The paper also further states that another positive feature of the vehicle sensitive ELR is that it often can be activated by accelerations seen during loss of control situations preceding an actual rollover. This locking is said to occur prior to the occupant motion resulting in a withdrawing of the belt webbing.

A third point that should be emphasized from this paper is that at the time it was written, the authors stated that, "Currently we are not aware of any mainstream productions in use in the United States that are webbing-sensitive-only ELR's."

The findings of this paper are highly relevant to the Rhino. The retractor employed in the Rhino's safety-belt system is, in fact, webbing-sensitive-only. Because of this, it is much less likely to restrain an occupant in a low-speed rollover/tip-over event. Oftentimes, it is seen that the accelerations during the tip-over or rollover are not sufficient to cause the occupant to move in such a manner as to activate the webbing sensitive locking mechanism.

In addition, the Rhino is equipped with bowl-shaped bucket seats and a fairly long stalk attaching the buckle to the vehicle's frame. This combination causes the lap-belt to not fit snuggly on children and small adults. This allows movement of the hips and pelvis. NHTSA addressed the need for the proper design of a lap belt in order to restrain the torso of a wide-variety of occupants, and discussed the need that seats other than the driver's seat have belts that fit a range from a 6-year-old child to a 95th-percentile adult male, and that driver's belt fit occupants from a 5th-percentile adult female to a 95th-percentile adult male[6].

Because of the retractor design and the inability of the belt to fit snugly on smaller persons, the occupant's first line of defense, the safety belt, can be ineffective in a low-speed tip-over event. The second line of defense perceived as being a protection during tip/rollovers is the roll-cage. Originally, the Rhino was sold without any type of doors or netting to prevent excursion of leg, arm, and torso, meaning the sole safety envelop protecting the occupants is the roll-cage. However, in some tip-over events, the roll-cage can actually increase the likelihood or severity of injury. Pizialli et al. warn of the increased injury risk from simply adding a roll-cage to an ATV in a 1993 SAE paper entitled *Investigation of the Net Safety Impact of an Occupant Protection System From All-Terrain Vehicles*[7]. Pizialli warns against the increased risk of injury from the "mousetrap" effect which is when the occupant is pinned or crushed between the roll-cage and ground. One way to minimize this is to reduce the contact points between the roll-cage and ground as the side of the vehicle strikes during a tip-over or rollover.

As seen from the view of the Rhino in Figure 5 and 7, the Rhino's roll-cage is positioned very close to the occupant's seating position, is one of the widest parts of the vehicle, and creates a flat-plane in the plane perpendicular to the direction the photograph is taken.

All of these design attributes can increase the likeliness of extremity injury during a tip-over as arms, legs, hands, feet, and even heads can be crushed by the roll-cage. The fact that the cage creates a flat plane and has no extrusions to reduce the contact points means that there are basically infinite crush points as the cage strikes the ground in a tip-over event. In other words, if an appendage is extruded anywhere along the periphery of the roll-cage, it is going to be crushed between the roll-cage and ground.

Figure 7. View of Yamaha Rhino.

As a result injuries to legs and feet of Rhino operators and passengers, Yamaha initiated a special offer to Rhino owners to have their Rhinos retrofitted with doors and additional handholds. The letter to owners included the following: "Unfortunately, some occupants have been seriously injured during such rollovers when they put their arms or legs outside the vehicle, resulting in crushing or other injuries. **Special Offer to Rhino Owners:** **"**Yamaha has developed new doors and additional passenger handholds for the Rhino. These new features…are designed to help keep occupants from sticking arms or legs out of the vehicle in response to a side rollover. They may also enhance passenger stability and comfort."[8]

Analysis of the Honda Big Red

Figure 8. Photograph of Big Red prepared for testing

A 2009 Honda Big Red MUV 2009 was tested. The average measured track width of the Big Red was slightly more than 8 inches greater than that of the 660 tested. Measurements of the Big Red confirm that it is statically more stable than the Yamaha Rhino. The increase in static stability also predicts an increase in dynamic stability.

Dynamic testing verified the Big Red to have increased rollover resistance. On pavement, the minimum lateral acceleration to cause tip onto the outriggers was 0.72 g's in a J-turn with an entrance speed of 24.6 mph. In dirt, the Big Red tipped during a J-turn with an entrance speed of 22 mph and an associated lateral acceleration of 0.75 g's.

The vehicle did not tip in any of the fixed-steer and U-turn maneuvers. The differential on the rear of the vehicle acted to limit the available traction in these types of maneuvers when operated in the unlocked position.

Active and Passive Safety Features of the Big Red

The Honda Big Red's website addresses the safety features of the vehicle. The Honda Big Red is equipped with, in addition to 3-point seat belts, doors and netting. The roll cage is also shaped as to allow for fewer crush points in the event of a tipover, and the occupants are placed further away from the roll cage than in some other side-by-sides.

The retractor for the belts is both vehicle and webbing sensitive. A video describing the ELR and its tuning for an off-road environment can be found via the following link: http://powersports.honda.com/2010/big-red/innovations/seatbelts.aspx

Active and Passive Safety Features of a Polaris RZR

A similar vehicle to the Rhino that incorporates improved occupant retention and protection is the Polaris RZR. A Polaris RZR was loaned to The Engineering Institute for static analysis. The below photograph shows some of the safety features of the RZR. The photograph shows a deep footwell, arm and hand restraint through use of netting, and shoulder/torso and hip restraints integrated into the roll-cage of the vehicle.

In addition to what is demonstrated in the photograph, the RZR also has a vehicle-sensitive retractor that locks at angles greater than 15 degrees off of the installation angle, and the roll-cage is not a flat plane resulting in fewer possible crush points.

Figure 9. Photograph of occupant restraints of Polaris RZR.

Consumer product Safety Commission (CPSC) commentary of side-by-side safety

The United States CPSC has reached many of the same conclusions expressed in this paper through their own study and testing of ROVs.[9]

Citing testing on ROVs from November 2008 to February 2009, the CPSC concluded that ROVs "may exhibit inadequate lateral stability, undesirable steering characteristics, and inadequate occupant protection during a rollover crash." In addition, they identified three aspects of the vehicles' design that have "the greatest impact on occupant safety." These aspects are the SSF, the handling of the vehicle, and occupant retention and protection.

With regard to handling, after subjecting the vehicles to SAE J266 testing, CPSC expressed concern that some models exhibited oversteer. CPSC stated that they believed ROVs should exhibit understeer characteristics similar to automobiles.

In addressing the static stability of ROVs, CPSC expressed a desire to see SSFs in the range of 1.03 to 1.45 for the vehicle with two occupants. CPSC states that because of the variance in severity of off-road environments, ROVs "should at least meet the minimum lateral stability requirements for cars on a level on-road environment."

Addressing occupant retention, CPSC believes that just relying on 3 point belts to protect occupants is not adequate. They state, "A number of factors such as occupant seating location within a vehicle, physical side guards such as doors and shoulder guards, four-point seat belts, and technologies for increasing seat belt use, can improve occupant retention."

CONCLUSIONS

Though side-by-sides/UTVs/ROVs appear to be much safer than a standard ATV, life-altering injuries and deaths attest otherwise.
The Rhino, for example, is a dynamically unstable vehicle with insufficient occupant protection during low-speed tip-overs, especially for extremities such as hands, arms, feet, and legs.

In the years since the special offer to retrofit the Rhino with doors and additional handholds, there have continued to be injuries, and the doors and handholds have been shown to not be an adequate fix for the safety flaws of the Rhino. The changes to the Rhino addressed through the free repair campaign in conjunction with the CPSC increase the dynamic stability of the vehicle, but do not adequately increase the vehicle's stability.

Simple vehicle analysis and testing has demonstrated the instability of the Rhino. Testing has shown that the vehicle can tip-over at low speeds and lateral accelerations. Additional testing of modified Rhinos has shown a simple means of increasing the directional and rollover stability of the vehicle.

The Honda Big Red, released after the Rhino, showed an improvement over the Rhino in dynamic testing; however, the vehicle still tipped during certain maneuvers. The rear differential installed on the vehicle helped prevent any tip-overs in the U-turn maneuvers tested. The Big Red also has improved occupant containment features, including doors, nets and a roll cage shaped with fewer possible crush points. The Big Red has bucket-type seating similar to the Rhino.

The RZR is another ROV that demonstrates improved occupant containment through its belt system, occupant placement, netting, and side bolsters.

The conclusions reached by The Engineering Institute and Gilbert Engineering based upon their testing and analysis are supported and echoed by The United States Consumer Product Safety Commission.

As these vehicles continue to rise in popularity, it is imperative that they are analyzed from a safety engineering standpoint to reduce the number of future injuries and deaths. It is felt that low speed tip-overs of these types of vehicles could and should be prevented, firstly; and secondly, there should be adequate occupant protection such that low speed accidents do not result in serious or life-threatening injuries.

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