Journal of the National Academy of Forensic Engineers®

http://www.nafe.org
ISSN: 2379-3252
DOI: 10.51501/jotnafe.v42i2

Vol. 42 No. 2 December 2025

Analysis of a UTV Axle Fracture Associated with Rollover

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Abstract

An analysis of the fracture mechanism of a rear axle shaft of an off-road side-by-side utility vehicle (UTV) is presented in this paper. Two minors were recreating; they were riding a UTV within the fenced confines of the family farm. While driving on a dirt trail at a substantial velocity, the UTV yawed hard to the left, just before the turn in the trail. The leading side passenger's side tires dug into the soft soil, and the UTV overturned for three-quarters of a revolution. The belted driver was partially ejected during the overturn and fatally pinned underneath the vehicle's tubular rollover protective structure. After the event, the vehicle could not be driven as the left rear axle was fractured nearest the inner race of the outboard constant velocity (CV) joint, and the wheel hub and disc brake system were damaged. The investigation answered the question: "Did the overturn cause the axle fracture, or did the axle fracture cause a braking action and initiate the overturn?"

Keywords

Utility vehicle, UTV, rollover, fatigue, axle, CV joint, forensic engineering

Accident Details and the Tentative Overturn Mechanism

The incident vehicle, a single-row utility vehicle (UTV) in lightly used condition, was four years old at the time of the incident with a recorded engine time of approximately 350 hours and an odometer reading of approximately 2,000 miles (3,500 km). The vehicle was being driven by two minors, which was against the recommendations of the manufacturer as printed in the owner's manual and displayed with on-vehicle stickers, but in accordance with state law, given the fact that the vehicle was on private property.

The cattle ranch trail on which the UTV was being driven was familiar to the occupants — flat, dry, and well-traveled. The investigating officers measured and documented the final vehicle position and photographed the tire marks that ended at 4-wheel lift and vehicle overturn. A short debris field further indicated the overturning path. The reconstruction of the overturn provided an overturn velocity estimate of approximately 20 mph (~30 kph) at initiation, with the UTV rolling right-side leading for something more than ¾ of a revolution due to final rocking motion. The vehicle travelled between 25 to 30 ft (~8 to 10 m) after 4-wheel lift. The driver was asphyxiated following the overturn due to partial ejection and entrapment underneath the rollover protection system (ROPS). The UTV was not equipped with an electronic event recorder to measure and save data, such as engine rpm, throttle %, steering angle input, or brake application.

The UTV's owner attempted to move the vehicle into storage after the overturn but was unable to do so due to what he believed was drivetrain damage. A joint site and vehicle inspection was then conducted by engineering experts representing the driver's family and the manufacturer. This examination occurred less than two months after the fatal overturn. It was determined that the left rear axle at the constant velocity (CV) joint was broken, which caused a braking action at the left rear wheel position. **Figure 1** shows the right axle with a normal CV boot at the outboard position; a green arrow highlights the axle main shaft. In the **Figure 1** detail at left, a white arrow highlights the undamaged outer CV joint boot, while a blue arrow highlights the bearing carrier, which mounts the axle bearing and disk brake assembly.

Figure 2 shows the damaged left axle with a distorted CV boot at the outboard position. The twisted outboard CV boot, indicative of an axle fracture and the axle shaft rotating independently of the CV joint, is highlighted with a white arrow.

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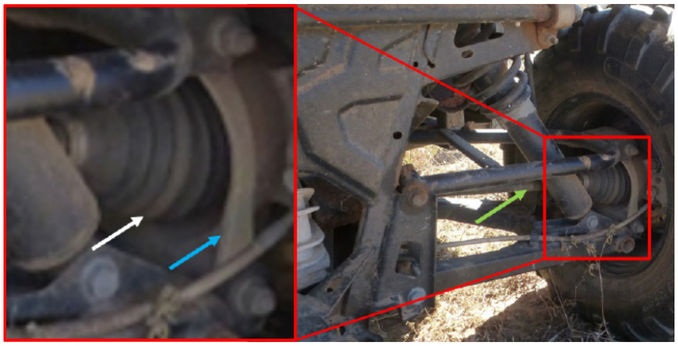

Figure 1
Right rear wheel assembly showing drive axle with normal CV boot indicative of axle shaft and joint rotating in tandem. Green arrow = axle main shaft; white arrow = right axle; and blue arrow = bearing carrier.

Figure 2
Left rear wheel assembly showing twisted CV boot indicative of axle shaft and joint turning independently. White arrow = twisted CV joint boot.

Figure 3 shows an overhead view of the left rear drive assembly, with the wheel and tire removed. From outboard to inboard is the grease cap (white arrow), which covers the cotter pin, castellated nut, washer, and threaded outboard end of the driving axle assembly. Next is the aluminum hub (black arrow), which has been painted black and contains four threaded studs to mount the wheel and the brake disc at the inboard side, which is secured by four low-profile hex head screws. The wheel hub is mounted against the bearing carrier (yellow arrow), a cast aluminum part that mounts the wheel bearing internally and the brake pad and shoe assembly externally (blue arrow). The

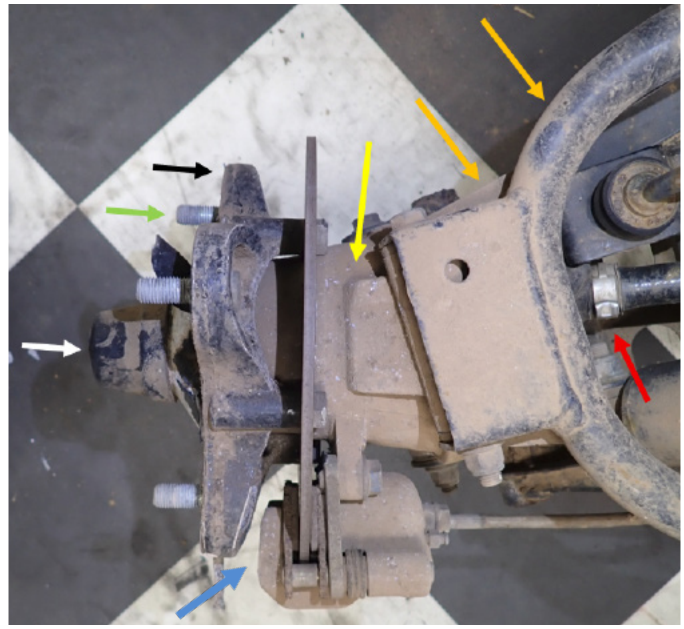

Figure 3
Left rear drive assembly, overhead view, tire and wheel dismounted. White arrow = grease cap; green arrow = lug stud; black arrow = hub; yellow arrow = bearing carrier; blue arrow = brake shoe assembly; orange arrows = A-arms; and red arrow = half shaft showing black axle, CV joint polymer boot, and mounting clip.

bearing carrier, along with all associated parts, moves up and down relative to the vehicle by the pivoting A-arms, which are mounted to the top and bottom (orange arrows). At the right of **Figure 3** is the drive axle, which mounts the outer CV joint rubber boot with a steel circumferential clip (red arrow).

The two rear independent drive axles were of conventional construction. Each axle assembly, also known as a half shaft, consisted of (from outboard at the wheel to inboard at the transaxle) a driving spline for torque transmission that mated to the wheel hub, a CV joint that allowed angular compliance of the axle shaft to the wheel, the main axle shaft, the dual offset joint (DOJ) that allowed both angular and axial position compliance of the axle shaft to the transaxle, and, finally, a driven spline mating to the transaxle (**Figure 4**). Both the DOJ and CV were protected

Figure 4
Exemplar half-shaft assembly for the incident UTV oriented with the outboard driving splined end at left and inboard driven splined end at right.

by flexible rubber boots, which rotated along with the axle, retained lubricating grease, and kept the bearings clean.

In addition to the CV boot, other relevant external damage at the left rear wheel position of the incident vehicle included a circumferentially fractured cast aluminum wheel hub, as shown in **Figures 5** and **6**. In **Figure 6**, note the chipped edges of the central fragment as indicated by red arrows. This chipping was consistent with damage after the circumferential crack separated the central and outer hub segments, during relative movement between the fractured segments.

Figure 5
Left rear wheel and tire showing paint spalling at the cast aluminum center hub.

Figure 6
Close-up of left rear wheel assembly showing the black painted steel wheel (blue arrow) that is secured by four threaded lugs and nuts (orange arrow), aluminum wheel hub (green arrow), spalling black factory paint to include a detached large flake at left (yellow arrows), and the circumferential hub crack with edge chipping (red arrows).

During forward travel of a UTV, a left rear axle failure would apply some level of differential braking to the vehicle, inducing counter-clockwise vehicle yaw. If this yaw commenced without warning and with sufficient severity, the vehicle would be misoriented compared to the travel direction and could overturn at normal travel speed due to side loading of the tires. As the UTV was rapidly approaching a left turn at the time of initiation of yaw marks by the tires (~25 mph = 40 kph), an overly aggressive steering input could also have presumably caused the overturn. It was the manufacturer's position throughout the investigation that driver input caused the overturn — and that a severe wheel strike during the overturn caused the left rear wheel and axle fractures.

Forensic Analysis

The UTV was transported to a local laboratory for disassembly and initial inspection as the basis of a formal forensic investigation[1]. The first action was removal of the outer plastic wheel cap to expose the castle nut and the cotter pin. The removal was done for both the right and left rear wheels to facilitate comparison. As shown in **Figure 7**, there is a patina of corrosion on the unpainted left threaded axle stub that is not present on the right stub. This is consistent with more moisture intrusion through the left grease cap when compared with the right but is otherwise inconsequential. The right rear cotter pin was unremarkable, but the left rear cotter pin was damaged inside the cap. The damage was evident after the ends were folded back from the position they were in after insertion and folding over the axle terminus. After photo documentation, the left rear cotter pin had to be further bent and hammered to remove it.

Notice how the right rear cotter pin through-hole in the threaded axle stub aligns with the castellated nut slot, while the left rear transverse axle stub cotter pin hole does not align properly with the cotter pin recess. The left rear

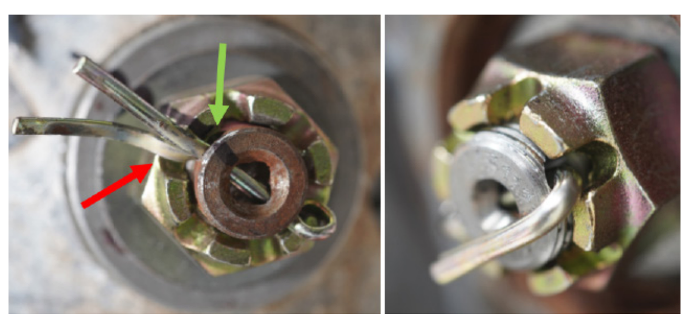

Figure 7
Left rear axle cotter pin showing post-installation misalignment of the axle cross hole and castellated nut slot (left). Right rear axle cotter pin showing undisturbed factory-installed alignment (right).

cotter pin segment in the foreground aligns with the axle transverse hole (green arrow), while the cotter pin segment in the background aligns with the castellated nut slot (red arrow); the head of the left cotter pin is also deformed. This is consistent with the threaded driving axle stub turning ~10° clockwise relative to the castellated nut after the cotter pin had been installed. Like the chipped wheel fracture surface shown in **Figure 6**, this is an indication that the axle and wheel damage occurred while the vehicle was in motion.

The circumferential crack of the left rear aluminum wheel hub disabled the rigid drive axle assembly at the wheel such that the wheel had some limited freedom of movement independent of the axle. Thus, the tire and wheel had to be ratchet-strapped to a fixed rigid frame to remove the wheel's lug nuts without causing further wheel hub damage. The CV joint boot was removed, and, as expected, the end of the main shaft that originally was attached to the CV joint inner race was fractured. There was also superficial post-fracture damage to the aluminum wheel fracture surface in the form of burnishing. After removal of the cotter pin, castellated nut, brake assembly, and wheel, several components were reassembled for visual clarity (**Figure 8**).

The burnished regions on both sides of the mating conical cast aluminum wheel hub fracture surfaces are from high points rubbing against each other (see **Figures 8** and **9**, red arrows). Also shown with a yellow arrow in **Figure 9** is the polished precision cylindrical interface surface for the wheel bearing; the blue arrow shows the splined internal recess for interaction with the driving end of the axle assembly, which is the outer race "bell housing" of the CV joint.

The physical evidence of burnishing is consistent with the fracture occurring during travel of the vehicle. There was also major abrasion damage to the disc brake assembly, consistent with the left rear wheel hub wobbling as it rotated. The largely axially symmetric conical wheel hub fracture surface is consistent with a centered inboard to outboard axial force being applied to the wheel hub, rather than a bending moment being applied by a local rim strike. Other than shape and post-fracture damage observations, no detailed fractography was performed on the cast aluminum wheel hub, since there was no macro evidence of a fatigue break at the aluminum hub. The wheel bearing at the center of **Figure 8** between the CV joint outer race at right and the fractured wheel hub at left spun freely. Consequently, it was not further examined.

The left rear CV joint, detached from the wheel assembly and with the damaged flexible rubber boot removed, is shown from the inboard side in **Figure 10** (left). Although covered with grease, many details are apparent. From exterior to interior is the bell housing (outer race), the cage, the inner race with six cavities for hardened steel ball bearings with the balls removed, the retaining circlip near the bottom, and the fractured stub of the left rear drive axle in the center. **Figure 10** (right) shows the degreased inner race from the outboard side and the axle stub in the splined inner recess, which is not properly positioned fully outboard.

The splined male end of the axle main shaft contains

Figure 8
Left rear-threaded axle stub, aluminum wheel hub fragment, bearing, CV joint outer bell. Red arrows indicate representative burnished surfaces; blue arrow shows the installation point of the fractured main axle shaft.

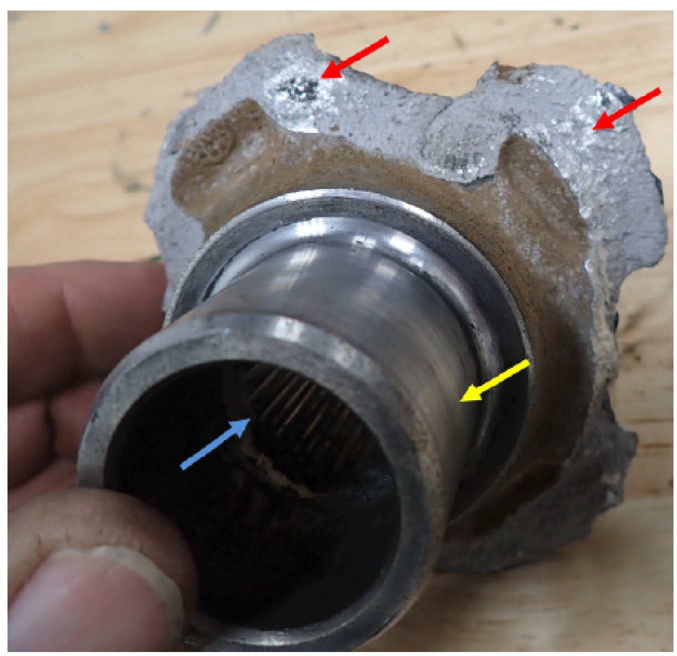

Figure 9
Central detached fragment of aluminum wheel hub, shown from inboard side.

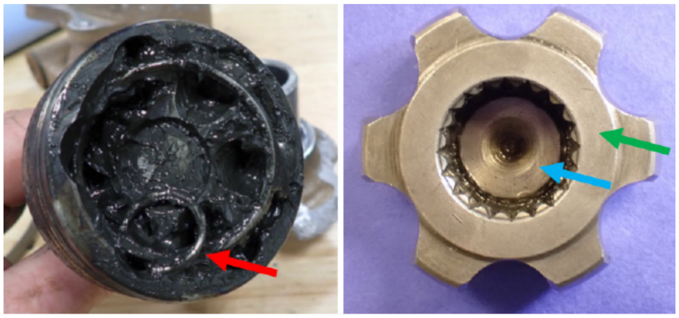

Figure 10
Left: Inboard view of CV joint bell housing showing fractured end of the main axle shaft and retaining circlip (red arrow). Right: Outboard view of degreased inner race; the stub end of the main axle is inappropriately inboard as the outboard face of the axle shaft (blue arrow) should be above flush of the outboard face of the inner race (green arrow).

a groove that accepts a retaining circlip. During assembly, the shaft end with circlip is pressed into the mating female splines of the inner race. This lightly compresses the circlip flush within the recess during installation. At full shaft insertion, the circlip then expands to provide axial fixation for the shaft to prevent the axle main shaft from displacing back inboard. However, that fixation either never occurred as the shaft was not inserted sufficiently or was otherwise unsuccessful, as **Figure 10** shows in the right photo. The circlip was marked with circumferential witness marks consistent with hard loading against the spline surfaces, suggesting that it was loaded coming back out of the subject inner race.

Figure 11 shows that the fatigue break occurred at the end of the main axle shaft at the outboard side of the circlip groove nearest the inner race. The fracture surface developed at the region of greatest axle bending moment and minimum cross section. The entire axial width of the circlip groove was present on the longer inboard axle shaft fragment (**Figure 11**, right). As a rotating cylindrical member, the fatigue crack progressed semi-uniformly planar to the shaft axis from outside to inside. This also ensured rotary compressive loading of the circlip as the axle shaft and the end past the groove became misaligned; a light in color witness mark of this compression is visible in **Figure 11** (left) — see green arrows.

The arc-like impressions on the main face of the outboard main shaft fragment are consistent with the interfacing rim of the detached inboard axle shaft pressing against the outboard stub during rotation, producing the fracture of the aluminum wheel hub with an inboard to outboard force. The light-colored groove end perimeter in **Figure 11** (right, red arrows) is no longer sharp but presents an

Figure 11
Left: Inboard end of CV inner race and fractured axle end showing a circlip compression mark and multiple arc-shaped impressions from the detached axle main shaft. Right: Outboard side of fractured axle shaft showing classic topographic macro features of fatigue fracture.

irregular beveled interface of the groove wall at the fracture surface. This was caused by cold work compression of this inboard edge against the outboard axle stub center segment during vehicle travel. The fracture surface on the inboard axle shaft fragment is better preserved for macro features of fatigue (**Figure 11**, right). Notable features include[3-5]:

A. The overall planar fracture surface that is perpendicular to the shaft axis.

B. The ratchet marks that initiated the planar crack perpendicular to the shaft axis once the axle shaft had backed off sufficiently for the circlip groove to be exposed past the splined region;

C. Radial spaced arc-like markings of crack progression from exterior to interior; and

D. An identifiable point of final fracture near the shaft centerline. These macro features were plainly visible with low power optical microscopy and did not require scanning electron microscope (SEM) examination.

Witness marks about the circlip were consistent with the axle main shaft having been inserted some distance into the inner race, but these marks could not confirm that the main shaft had been fully inserted with circlip expansion at the factory during half shaft assembly. On the main splined surface of the axle were circumferential compression marks documenting bending loading on the axle as the end moved incrementally inboard relative to the CV joint inner race (**Figure 12**). These marks strongly indicate that the shaft was, at least, nearly fully inserted — though perhaps not fully inserted — which would be one potential failure mode mechanism of the shaft backing out. The axle

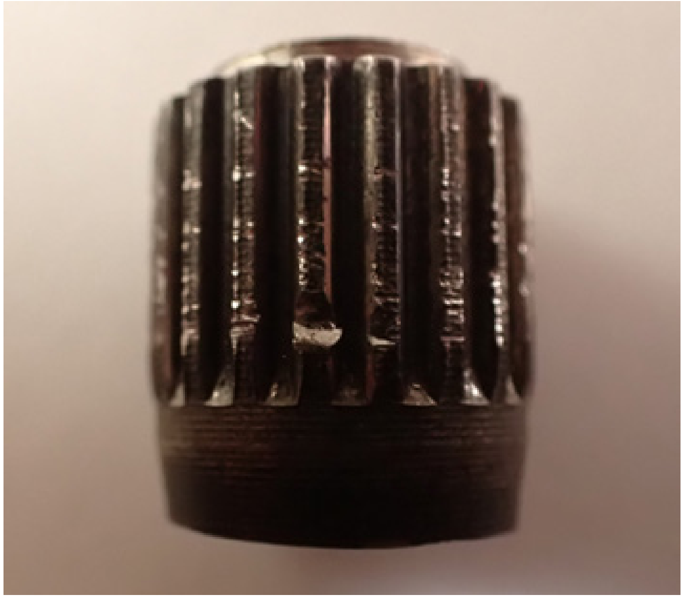

Figure 12
Sawn-off end of main axle stub, which fractured at circlip groove (top), showing circumferential compression marks developed while it backed out of the mating splines of the inner race.

fragment shown in **Figure 12** is the profile view of the segment shown in **Figure 11** at right.

Wheel Hub Demonstrative Testing

In any engineering investigation, it is critical to guard against confirmation bias — the processing of new information solely using an established paradigm[6]. The competing paradigms in this instance are either that the operator error caused the overturn and drive train damage or that the drive train damage self-manifested and initiated the loss of control, overturn, and resulting fatality. In this instance, the lead investigator (author) had personally inspected and analyzed hundreds of overturned vehicles that collectively have not presented an instance, much less a pattern, of a "severe wheel strike" in a barrel rollover causing an axle shaft failure in single overload or, more importantly, in fatigue loading, which is itself conceptually implausible as shaft fatigue failures require thousands to millions of shaft revolutions to manifest fracture.

Although the physical evidence strongly indicated that the fatigue failure preceded the overturn — and that the detached fractured axle shaft pressed against the displaced mating stub CV inner race and caused the wheel hub fracture in an outboard direction — demonstrative destructive testing was performed to investigate how a cast aluminum wheel hub fracture would present geometrically in both posited loading directions. Two aluminum rear wheel hubs of the type that were used on the incident UTV design were purchased from an on-line salvage retailer and axially loaded using a manual arbor press to develop a concentrated active load on one side and a diffuse reactive load on the other, thus producing outside-in and inside-out loading fracture (**Figure 13**). Note the wheel studs and brake disc attached to the black aluminum wheel hub.

The general shape of the fracture surface from the inboard-to-outboard loading produced an angular wheel hub fracture surface, reasonably matching the incident wheel hub (**Figure 14**). While the incident hub was rotating at least 5 revolutions per second at the initiation of yaw and of loss of control, the fracture is a form of "Hertzian cone" in which the principal tensile stresses within the brittle material subjected to focal compressive loading ensures an angular, conical crack progression[7]. As an analogy to the instant fracture, a lead pellet that is discharged from an air rifle into common annealed window glass will produce an entry hole the same diameter as the pellet, a conical fracture downstream of impact through the glass thickness, and, finally, a larger damage diameter hole at the exit plane.

Figure 13
Exemplar wheel hub and arbor press used to apply a concentrated inboard force against the wheel hub.

Figure 14
Incident wheel hub (left); Tested wheel hub given inside-to-outside loading (right).

The inboard concentrated load produced a conical fracture surface that diverged from inboard to outboard. The outboard concentrated load produced a conical fracture surface that diverged angularly from outboard to inboard.

The outcome of these rudimentary demonstrations was unsurprising for several reasons. First, an inboard-directed wheel impact force is not resisted by the axle, but rather by the suspension A-arms shown in **Figures 1** through **3**. That is, hard cornering action by any UTV or passenger vehicle pushing a tire/wheel/wheel hub assembly toward or away from the vehicle centerline direction will be resisted inboard of the wheels by the suspension (not the drive axle), which "floats" axially as enabled by the DOJ joint.

Pushing on a UTV tire or wheel inboard produces no compressive or tensile stress on the drive axle. This is easily seen when comparing two-wheel drive and four-wheel drive vehicles — in that the deletion of a drive axle does not require a change to the suspension, as the suspension resists the loading in all directions. Second, as a counterfactual thought experiment, suppose excessive slop existed in the mounts of the incident UTV A-arms that allowed the tires and wheels to objectionably move inboard and/or outboard. The half shaft could, in this hypothetical case, be loaded axially by a wheel strike. However, a wheel strike during barrel rollover would displace the wheel assembly inboard against the half shaft (**Figure 15**).

In this diagram, the components mating to the CV joint end of the half shaft are not shown. What is shown is the driving outer race "bell" end, the ball bearings as brown spheres, the inner race in yellow, the main axle in blue, the retaining circlip in red, the flexible rubber boot in green, and the boot clips in gray. The red arrows show the impact force that could potentially be transmitted to the axle, which is resisted by the black arrow that is traceable to the inboard mounting end of the axle assembly at the transaxle. The combined impact force (red) will tend to move the inner race (yellow) toward the right, while the resisting force will tend to move the axle and circlip to the left. This would act to seat the outboard end of the main axle shaft to the CV joint inner race — not to overcome the fixation of the circlip and move the main axle shaft inboard. Thus, a conceptual free body diagram of an inboard directed wheel strike loading path further indicates that a substantial wheel strike would not cause the damage observed in the incident overturned UTV.

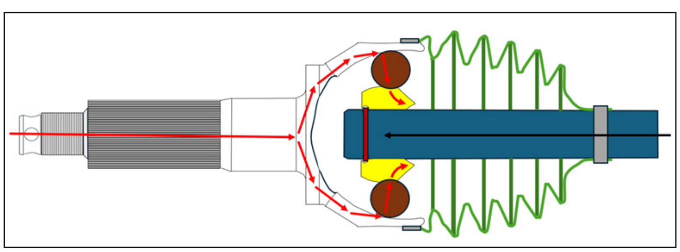

Figure 15
Free body diagram of wheel force from outboard to inboard against the axle.

Summary and Conclusions

The failure at this UTV's left rear wheel assembly initiated with a progressive axial inboard repositioning of the main axle shaft with respect to the CV joint inner race over time during vehicle travel. The inboard positioning is physically documented by damage to the retaining circlip and circumferential witness marks, which plastically indented the splined surface of the outboard end of the main axle shaft. After the circlip groove became fully exposed inboard of the CV joint inner race, the maximum bending moment and minimum area were at the outboard face of the axle shaft's circlip groove. This groove also contained a sharp stress-enhancing inner edge that ordinarily would be unproblematic, since that groove was never designed to receive bending stresses. Fatigue cracks initiated as documented by circumferential ratchet marks. The crack progression was from exterior to interior as is universal in rotating shafts with bending loading.

Once fractured, the axle and wheel spun independently, as documented by the damaged flexible CV joint boot. During travel, the loose main axle shaft fracture surface edge pressed against its mating outboard fracture surface and pushed the outboard drive components outboard against the cast aluminum wheel hub. The brittle aluminum wheel fractured due to a concentrated inboard-to-outboard loading, producing a Hertzian cone fracture surface. The tire/wheel/hub component was then only lightly attached to the suspension and brake assembly. The brake disc, including its mounting bolts, continued to rotate and impacted on the mating brake components that were still properly affixed to the bearing carrier, causing scouring and torque about the rear wheel. This braking action at the left rear wheel initiated suddenly and without warning. It induced the counterclockwise vehicle yaw and overturn.

The subject half shaft, with approximately 2,000 miles of usage, was original to the vehicle. Upon leaving the factory, the left rear axle shaft may not have been fully seated within its mating CV joint inner race, but this was not revealed by the inspections. It could also be that, for some other undetermined reason, the main axle shaft backed out of its properly seated initial position as the retaining circlip was unable to prevent the displacement. No definitive cause of the initial displacement of the axle shaft in the inboard direction was determined. Still, as the half shaft was not a component that was intended to be adjusted, maintained, repaired, or even inspected by the vehicle owner (beyond visual inspection the flexible joint boots for damage or grease leaks), user error could reliably be ruled out. The fact that the two occupants of the incident UTV were approaching a left-hand turn at the time of overturn was merely a remarkable coincidence.

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