Axle Failures Revisited

by Tom Norman

Many of you are aware of rear axle failures occurring in MT19 Series A and B motorcars. The first indication that I had of axle problems was in April 1995 when fellow NARCOA member Jim Britten sent me a copy of Fairmont Service Data Sheet #411. This Data Sheet advised inspection of the rear axle center bearing and bearing support for severe wear conditions that could cause rear axle deflection to such an extent, that after time, it fatigues and breaks.

Basically what Fairmont recommended was to start up the engine, put it in low gear with the brakes on, let out the clutch and observe the axle deflection at the center bearing. If the deflection exceeded 1/8" all worn components were to be replaced. Fairmont also recommended a Service Group (138583) be applied to all cars in service. The Service Group included a new center bearing bracket and a new shoulder bolt that hinges the center bearing to the center bearing bracket. The new center bearing bracket is mounted behind the axle (rotated 180 degrees around the axle to the rear) and the spring is discarded.

I followed the Data Sheet recommendations, and also installed the Service Group. Then on an excursion in August 1997, my axle broke. It had 12,200 miles on it. Why did it break? The Service Group went in at 8,170 miles and axle deflection was measured annually, and was within Fairmont's specifications. It could be that the old axle had been stressed too much and should have been replaced, however, I still felt that my axle was "safe" as the deflection before I installed the Service Group was within tolerances. Around the same time, other operators were experiencing broken axles, including one on an MT19-A that Mike Paul had just sold. Working with Mike, we submitted four failed axles to a metallurgist for analysis.

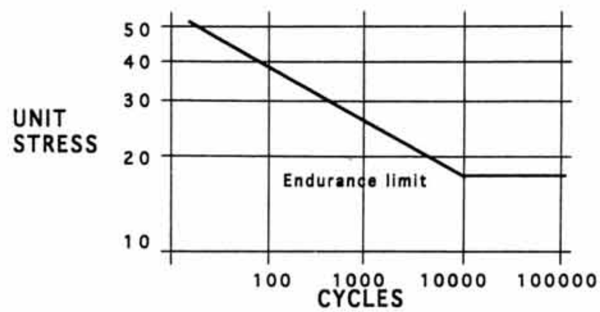
While waiting for the metallurgist's report, I searched for more information on axles. Motorcar Operators West had axle articles in their newsletter *Lineup* dating from 1993. The *Lineup* Volume 6, Number 5, October 1997, reprinted these articles along with a new one by Don Massy calculating stresses in the axles. NARCOA's ***THE SETOFF*** published Fairmont Service Data Sheet #411 in the May/June 1995 and July/Aug 1997 issues. (Back issues of ***THE SETOFF*** are available from Joel Williams, PO Box 82, Greendell, NJ 07839; back issues of the *Lineup* are available from Gene Volz, 1024 O Street, Rio Linda, CA 95673). The consensus of opinion in these articles was axle failure due to bending fatigue. The bending fatigue could be caused by play in the wheel bearings, bearing guides, and guide bushings; play in the center bearing and center bearing bracket; deflection at the drive sprocket as the chain transfers power; and/or deflection of the axle by the center bearing. The deflection of the axle by the center bearing was assumed to be caused by three items. One, the center bearing could be out of alignment with the wheel bearings in a static situation. Two, the spring in the center bearing kept the axle restrained in the middle, as the axle ends moved vertically in the MT19's sprung wheel bearings. Three, the axle would be pulled of center with respect to the wheel bearings, as the center bearing pivots about a hinge point (rather than mimic the wheel bearings vertical axis movement). These problems, diagnosis, and corrections were addressed in the above articles. All of the above mentioned movements cause the axle to experience bending as it rotates. This is called rotational bending fatigue. Circumferential fatigue cracks start at the outer edge of the axle and progress inward, and as the axle flexes, these cracks open and close smoothing the fracture surface. The spread of the cracks looks like an extremely thin hacksaw has cut into the axle as it rotates. Eventually at overload the axle breaks in two, leaving a bright jagged crystalline surface. However when the metallurgist's report returned, two of the axles had exhibited unidirectional bending fatigue failure. The other two axles had the fracture surface marred too badly to determine the failure mode. Of the two axles that exhibited unidirectional bending fatigue, if the keyway is positioned at 12:00 o'clock, the initiation occurred at 3:00 o'clock on one axle and 6:00 o'clock on the other. According to the metallurgist "the crack initiates at one location on the surface and propagates through the cross section normal to the direction of applied maximum stress. Based on the spacing of striations and their orientations the failure mode is classified as low-stress, high-cycle unidirectional bending fatigue." It is a completely different fracture structure as compared to rotational bending fatigue failures. "With rotational bending fatigue...crack initiation occurs at a number of different locations around the circumference of the shaft. As the small individual cracks propagate toward the center of the shaft, overload ultimately occurs and the fracture surface has a star appearance.

How can the axle experience one directional bending as it rotates? The only possibility that I can visualize is the axle is already bent, between the wheel bearings and the center bearing. Let's say the high spot is at 12:00 o'clock (looking at a cross section of the axle). The center bearing will adjust vertically so there is no stress in the axle. The center bearing moves in the vertical axis since the center bearing is hinged at the center bearing bracket. As the high spot on the axle rotates to 3:00 o'clock the center bearing restrains the axle, deflecting it forward. The axle high spot rotates to 6:00 o'clock, the center bearing adjusts down for no stress. The axle high spot moves to 9:00 o'clock, the center bearing deflects the axle rearward. So two unidirectional stresses occur per revolution. The maximum stress is applied at the high spot of the axle inside the center bearing.

One other possibility that I did consider for unidirectional bending fatigue was when the spring is used with the center bearing, any deflection due to suspension movement would occur at one point on the axle. This assumes the spring restricts the center bearing movement in the vertical axis. However, when the stress is repeated it is not applied at the same specific point on the axle, but rather at a random location dependant on rotation of the axle when the shock occurs. Theoretically over time the axle would see the stress applied over the entire circumference, which I think would exhibit a rotational bending fatigue pattern.

Grabbing my *Machinery's Hand Book*, I found recommended allowable stresses for shafts with keyways. Shafts subject to simple bending should be limited to flexural stress of 12,000 psi, or if torsion only, the torsional stress should be limited to 6,000 psi. If a shaft experiences both, the limit should be 6,000 psi. I calculated torsional shearing stress based on the maximum torque available from the Onan B48G, assuming no transmission losses and perfect adhesion. The torsional stress was 4,716 psi, within design limits. Next I calculated flexural stress in the axle at the center bearing. The stress was calculated for an 1/8" deflection, Fairmont's maximum allowed deflection per Service Data Sheet #411. This flexural stress was 11,045 psi, over the design limits. I also measured axle deflections at the center bearing in two motorcars with the cars in gear but braked, while releasing the clutch. The deflection was measured vertically and horizontally both in forward and reverse gear. These measurements ranged from 0.020 to 0.177", resulting in a flexural stress of 1,744 to 15,622 psi. The maximum flexural stress possible, would be with axle end movement due to spring suspension action, assuming the center bearing remains stationary. This is hypothetical, but the 1/2" deflection does demonstrate that a maximum flexural stress of 44,177 psi could occur, but unlikely. A more realistic picture is to assume the axle on a normally loaded car is half way between the maximum spring deflection, so that the axle will deflect up or down 1/4". The flexural stress then would be 22,088 psi. I believe the high stresses from this suspension action is one reason for Fairmont's removal of the center bearing spring with the Service Group installation. If we look at stress from a bent axle (my definition of bent axle is a bend between the wheel bearing assemblies at the center bearing) a bend of 1/32" = 2,761 psi, 1/16" = 5,523 psi, and 1/8" = 11,045 psi.

Another consideration is the endurance limit of the shaft. The shaft material has an endurance limit, defined as the highest unit stress that can be sustained in a very large number of repetitions without failure. An example of a unit stress/cycles graph (called an S-N graph) showing unit stress and cycle would be:

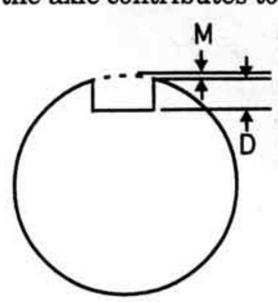


In the above graph, the unit stress and cycles are in units of 1,000. A stress of 38,000 psi predicts a failure at 100,000 cycles, while stresses under 18,000 psi (the endurance limit) should see unlimited cycles. This graph illustrates the endurance limit principle, but is an example only. It is not the S–N curve for the axle steel.

How many cycles are we looking at? Unidirectional bending, at the center bearing, caused by a bent axle would occur twice each revolution. Based on my motorcar's mileage of 12,000 miles that calculates to 30,244,000 cycles! If we assume an axle deflection at each rail joint staggered every 39 feet, we have 3,249,000 cycles, or if we assume good track with a bad joint every 100 feet we end up with 633,000 cycles. It appears that a bent axle will cause at least 10 times the cycles as caused by suspension action. But what about an axle deflected by worn bearings or distorted frame. We can assume the deflection would occur while the car is under power, and chain force is pulling the axle. Assuming the car is under load 75% of the car's mileage, then we can approach 11,351,000 cycles. That brings us back to the metallurgist's conclusion of low stress, high cycle unidirectional fatigue failure. My axle failure was unidirectional bending fatigue, but it is also possible to account for axle failure from rotational bending fatigue, because of the high cycles.

The metallurgist recommended: (1) eliminate the applied stress, (2) go to a larger diameter axle, eliminating the center bearing, or (3) use a higher strength steel, specifically AISI 4340, hardened to 38 to 40 Rc. There are problems with each solution. We can maintain our cars to lower the stress, but we can't eliminate it. I had inspected my rear axle and center bearing and maintained deflection as recommended but still had a failure. Going to a larger axle diameter would require a new drive sprocket hub and possibly bearing modifications including new bearing housings and guides. The higher strength steel will improve endurance limits, but can still ultimately fail with the applied stress. The key is to keep the applied stress under the endurance limit of the new steel.

By this time I had observed 7 axle failures on MT19 Series A and B motorcars. All the axles broke in a plane perpendicular to the shaft center line at the keyway, usually in line with the sprocket. The shafts were AISI 1045 steel, with a tensile strength of 90,000 psi. These axles are 1-3/16" in diameter, same as on M9 and M19s. Why axle failures on MT19s only? Engine horsepower and torque at the rear axle is higher on MT19s, but still within design limits for the AISI 1045 steel. The other obvious difference is belt drive verses chain drive. The design change for the Onan engine and chain drive required a relocation of the center bearing to 6-1/4" to the right of the car centerline, as opposed to 1-1/4" on the belt cars. This put the sprocket and keyway much closer to the center bearing. On a belt car the centerline of the pulley and center bearing are 5-1/2" apart, while the distance between the sprocket and center bearing centerline is only 1-3/4". Unidirectional bending fatigue suggests the maximum stress is at the center bearing, but the weakest part of the axle is the keyway, and the keyway is substantially closer to the center bearing on the MT19 than on a belt car. The biggest change between the M9/M19 axle and the MT19 is in the keyway depth. The keyway depth (see drawing below) on M9/M19s is 0.049". Initially this depth was used on MT19's when the car was introduced in 1966. However around 1975 this depth was increased to 0.125". I believe this change was due to sprocket hub problems. The original sprocket hub was secured by set screws. If theses set screws loosened, the hub rocked back and forth on the axle until the keyway was wallowed out. I believe Fairmont went to the deeper keyway to prevent this problem, but kept the old style hub. Apparently this did not cure the problem as they changed to the "QD" tapered hub by 1985. This solved the loose hub problem but I believe that retaining the deep keyway in the axle contributes to axle failures.



KEYWAY DEPTH

M = 0.0133" for a 1-3/16" diameter axle with a 1/4" wide keyway

MOTORCAR	KEYWAY DEPTH
M9, M19	0.049"
MT19 Series A 1966-1975	0.049"
MT19 Series A 1975-1985 and MT19 Series B	0.125"
AISI 4340 Axle with "QD" HUB	0.0625"

Consolidating this information, my solution for a new axle was to machine one using AISI 4340 steel hardened to 38 to 40 Rc. I also cut the keyway to a depth of 0.0625", half the depth of the old axle, and much closer to the M9/M19 axle at 0.049". The 0.0625" depth allowed me to utilize 3/16" by 1/4" keystock to make the new key, while retaining the QD hub originally machined for a 1/4" square key. I'm not worried about this keyway depth, especially with the QD taper lock type hub. M19AAs with the twin cylinder Fairmont engine use the shallower 0.049" keyway depth, same as other M19s. The maximum torque at the rear axle for the RKB twin is 106.8 ft–lbs, not that far from the Onan B48G of 128.9 ft–lbs.

The selection of AISI 4340 steel gives a material much better suited for our axle. AISI 1045 steel provides medium strength and toughness at a low cost. With ever increasing weights, poor railroad maintenance, and increased mileage (and thus cycles) on MT–19's, it appears that we should use a material with better endurance strength. AISI 4340 is a tough, shock resisting steel, that when heat treated offers the highest combination of tensile and endurance strength along with ductility. In fact AISI 4340 is recommended for diesel engine crankshafts. By heat treating the steel to 38 to 40 Rc, the tensile strength is improved, yet the material is still machinable. The tensile strength of AISI 4340 is 170,000 psi as compared to 90,000 psi for the AISI 1045 steel.

The endurance limit for the AISI 1045 and 4340 steel can be estimated at 40% to 60% of the ultimate tensile strength. Using the lower percentage we arrive at an endurance limit of 56,666 psi for the AISI 4340, 1.89 times the endurance limit of 36,000 psi for the AISI 1045 steel. Using a safety factor of 3 to account for notch sensitivity and stress concentrations in the keyway, we don't want to exceed an applied stress of 22,667 psi for the AISI 4340, compared to 12,000 psi for the AISI 1045. The AISI 4340 material provides a substantial increase in endurance limit.

I was able to find AISI 4340 cold finished steel bars, but in an annealed condition. This required sending the material to be heat treated to 38 to 40 Rc. When returned, the bars are warped because of heat treating and need to be straightened. Because of this, I used 1-1/4" diameter bars, and after straightening, I had the material centerless ground to the correct diameter. The final step was machining the axle tapers, threads and keyway. Options to further reduce keyway stresses are to radius the fillets to 0.010" and/or shot peening.

So the bottom line is, I felt that for my new axle, using heat treated AISI 4340 steel, and a 0.0625" keyway would give the best performance. Unidirectional bending fatigue is just one mode of failure. If we have sloppy bearings, bushings, improperly adjusted chains, and/or overloaded cars, rotational bending (cont. on pg. 8)

(**Axle** cont. from pg. 7)
fatigue will occur. Every MT19 owner must carefully and routinely inspect his/her axle. The question is not if your old axle will break but when!

Other things I look for:

1. Eliminate as much play as possible in the center bearing bracket, by re–bushing the bracket or using a new bolt.

2. Be sure there is minimal play in the wheel bearings, bushings and bushing guides.

3. Be sure the axle is straight. I remove the axle and mount in spare wheel bearings (or v–blocks) on a lathe bed, then measure with a dial indicator at each end and at 12" spacings as I rotate the axle. If it isn't straight, I put it in a hydraulic press and correct it. I try for a total indicator reading at the axle center of no more than 0.007".

To check your axle on the motorcar, raise the car and place on jack stands, disconnect the chain and unbolt the center bearing bracket, so nothing restricts the axle center. Now rotate the axle and observe the movement at the center bearing location. You want this to be zero, and I look for 0.007" on a new axle, but I think you can live with 1/32" on an old axle. This is the static deflection. Measure the dynamic deflection as per #5 below.

4. Remove the center bearing spring and throw it away. Use the center bearing unsprung. Fairmont recommends mounting the center bearing bracket to the rear of the axle. Definitely remount the center bearing if you change the axle. Mike Paul points out that putting the center bearing pivot ahead of the axle makes the axle unstable with respect to a pulling force on the axle in the direction of the pivot. To use his analogy "it's like trying to put a marble on top of a sphere and make it stay there. With the pivot rearward of the axle, its like putting the marble inside the sphere and trying to make it stay on the bottom of the sphere. The former is very unstable, the latter very stable."

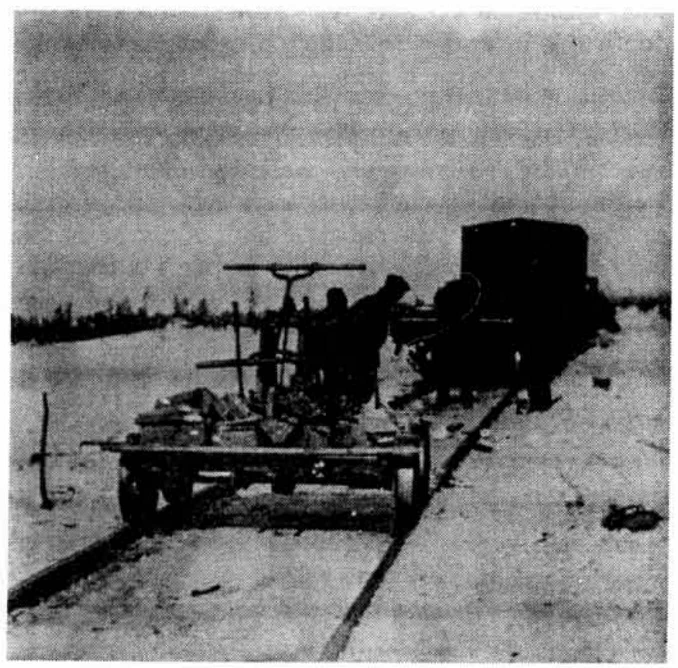
5. Check for play at the center bearing per Fairmont's Service Data Sheet #411. Fairmont isn't concerned until axle deflection is 1/8", but try to keep under this.

6. If you don't have the QD tapered hub on your old axle, change to it with the new AISI 4340 axle.

7. When bolting up the center bearing bracket, do it without the chain on the sprocket. Be sure that the center bearing bracket does not deflect the axle. Usually the car is on jack stands, in order to access the center bearing. To be really accurate, pry up the rear axle wheel bearings and place a 1/4" shim between the wheel bearing and the lower frame. This places the axle in a neutral position, with the springs compressed half way simulating a normally loaded car. In this position the axle centerline and the center bearing pivot centerline are in the same horizontal plane, and the center bearing will pivot equally upward and downward with suspension movement. I have even used a dial indicator to minimize actual deflection. Ideally the indicator should not read a change after mounting the center bearing, and then again after connecting the chain.

8. Make sure the chain tension is adjusted correctly. It should not deflect the axle to a great degree. The chain is tightest when the wheels are lifted off the rail, so check it then. Rick Tinsley has forwarded information from a Diamond Chain catalog that recommends slack span tension be adjusted to allow 4% to 6% mid–span movement for horizontal drives.

A note to MT14 motorcar owners. I have also observed four rear axle failures on MT14s. All failures occurred at the sprocket location. These failures appear to be rotational bending fatigue. Since the MT14 is not sprung like the MT19s, I can't see that unidirectional bending fatigue is a problem. However, the three rear axle bearing assemblies must be aligned to eliminate axle deflection. I would recommend checking the axle for straightness by unbolting the center bearing and unhooking the chain similar to #3 above. If the axle is straight, proceed by mounting the center bearing so that no deflection occurs on your dial indicator. It might require shimming and/or elongating the bearing housing mounting holes in the frame. Other sources for flexing stress can occur from excessive play in worn bearings or frame flexure from an overloaded motorcar.



An early real—photo of a handcar, tools, crew and worktrain, somewhere in Montana in the winter. TAYLOR COLLECTION