Dynamic and Static Testing of Vehicles as Anchors

Bureau of Reclamation

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Background

The Bureau of Reclamation (Reclamation) has been using forms of rope access since early in the agency's history. For decades, wire-cored manila ropes and boatswain's chairs were the accepted equipment that allowed workers to access otherwise inaccessible parts of Reclamation structures. Installed anchors were usually 1-1/2" schedule 40 steel pipe installed in a hole usually drilled with a pneumatic impact drill. Occasionally, drill steel itself was used, but due to its tendency to become brittle and crystallize, it was frowned upon for safe anchors for most Reclamation work. Two anchors were usually required, and the 7/8" diameter rope was secured to the anchors with clove hitches.

As Reclamation transitioned to modern rope access techniques in the late 1990s, the need for safe, reliable anchors became more critical than ever. In June 2013, Reclamation's Technical Service Center published a Technical Memorandum No. MERL-2013-29 titled Rope Access Anchors: Research and Testing of Concrete Anchor Bolts. In this report, concrete anchor bolts (also typically used in natural rock) were evaluated and tested specifically for rope access and fall protection anchors.

Concrete anchor bolts are not the only choice for anchors. Structural anchors, such as concrete or steel that are "unquestionably" strong are often used. Another choice of anchor is to use a vehicle as a "deadweight" or sliding ballasted anchor. This type of anchor is typically only chosen when a suitable anchor bolt or structural anchor is not able to be utilized, although a vehicular anchor has its benefits. One benefit is that a vehicular anchor does not rely on the same site conditions as a concrete anchor bolt or structural anchor. A concrete anchor bolt relies on the compressive strength of the concrete for its strength. With Reclamation's aging infrastructure, there have been instances where the quality of the concrete was found to be questionable and not a preferable choice for an anchor bolt. The integrity of a structural anchor can similarly be called into question. For example, a structural steel anchor that appears "unquestionably" strong may have interior corrosion, or may have been recently painted and hiding potential corrosion. In contrast to a vehicular anchor, concrete anchor bolts and structural anchors both rely on existing site conditions that are not easily observed. The only site condition a vehicular anchor relies on is the surface it sits upon, which can readily be visually inspected. Reclamation's aging infrastructure and remote locations have urged Reclamation to consider the practicality and reliability of vehicles as anchors.

In March 2005, Reclamation performed static testing on two different vehicular anchors in a variety of positions and conditions. The primary conclusion of this testing showed that the strongest configuration was a transverse (sideways) loading connected to the middle of the vehicle's side frame. The testing also showed that only the heavier of the two vehicles (Chevrolet Suburban), exceeded a 5,000 lbf static force; therefore the testers recommended to only use a vehicle as an anchor with a Gross Vehicle

Weight Rating (GVWR) in excess of 8,000 lbf. Although a vehicle's GVWR does not directly reflect a vehicle's unloaded weight, the GVWR is easily found posted on the vehicle itself. With the advent of the interwebs, the deadweight of a vehicle is easily found, and should be considered.

Methodology

The inspiration for the methodology of this research came from the Principle Investigator's work on the ANSI Z359.18 subcommittee for anchorage connectors. Reclamation is a voting member and is actively involved with the American National Standards Institute (ANSI) Z359 committee that creates standards for fall protection (including rope access). ANSI Z359 has recently (2017) published "Z359.18 – Safety Requirements for Anchorage Connectors for Active Fall Protection Systems". This standard identifies several types of anchorage connectors and specific testing methods for each type. One type of anchorage connector, Type D, is allowed to deform when it is tested. This research assumes that a sliding vehicle is a Type D anchorage connector.

For Type D anchorage connectors, the standard first requires a performance test, which is designed to produce an approximate 5,000 lb dynamic load on a perfectly rigid anchorage connector. Since by definition Type D anchorage connectors are not rigid, it is understood that some energy will be dissipated by the anchor itself; therefore a load somewhat less than 5,000 lbs is anticipated. The load from the performance test is then multiplied by a factor to determine the static test load requirement. This factor is based on the number of users that are allowed to connect to an individual anchorage connector. In this case, that would be a single vehicle.

This research project intends to approximate the ANSI Z359.18 test procedures for a Type D anchorage connector to determine the suitability of vehicle as an anchor and to determine the number of users that can attach to a vehicle of a given weight. For simplicity, only one test surface was used and the same test sled was used with different weights added on. The results from these tests are not intended to be assumed for other scenarios and should not be substituted for onsite testing or site-specific judgement. A competent person and/or a qualified person as defined in ANSI Z359 should be consulted before using a vehicle as an anchor.

Test Setup

In order to perform drop testing on a vehicular anchor in a laboratory environment, two pulleys were required to redirect the vertical force generated by the falling test mass to a horizontal force onto the vehicular anchor. One pulley was located toward the top of the test tower and the other was anchored to the ground. The test vehicle was placed on the smooth concrete of the lab floor, facing perpendicular to the test tower. Heavy-duty nylon rigging straps with sewn terminations were rigged to the side frame of the test vehicle with a heavy-duty shackle. Connected to the shackle was a load cell, which was connected to the test lanyard. The test lanyard ran horizontally a couple feet from the floor to the lower pulley, then was redirected near vertical to the upper pulley. From the upper pulley, the test lanyard was connected to another load cell with a shackle, which was connected to the test weight. A quick release mechanism connected the test mass to a separate bridge crane until the test mass was released. All connectors in the test setup were heavy-duty shackles. See Figure 1 for a schematic diagram of the test setup.

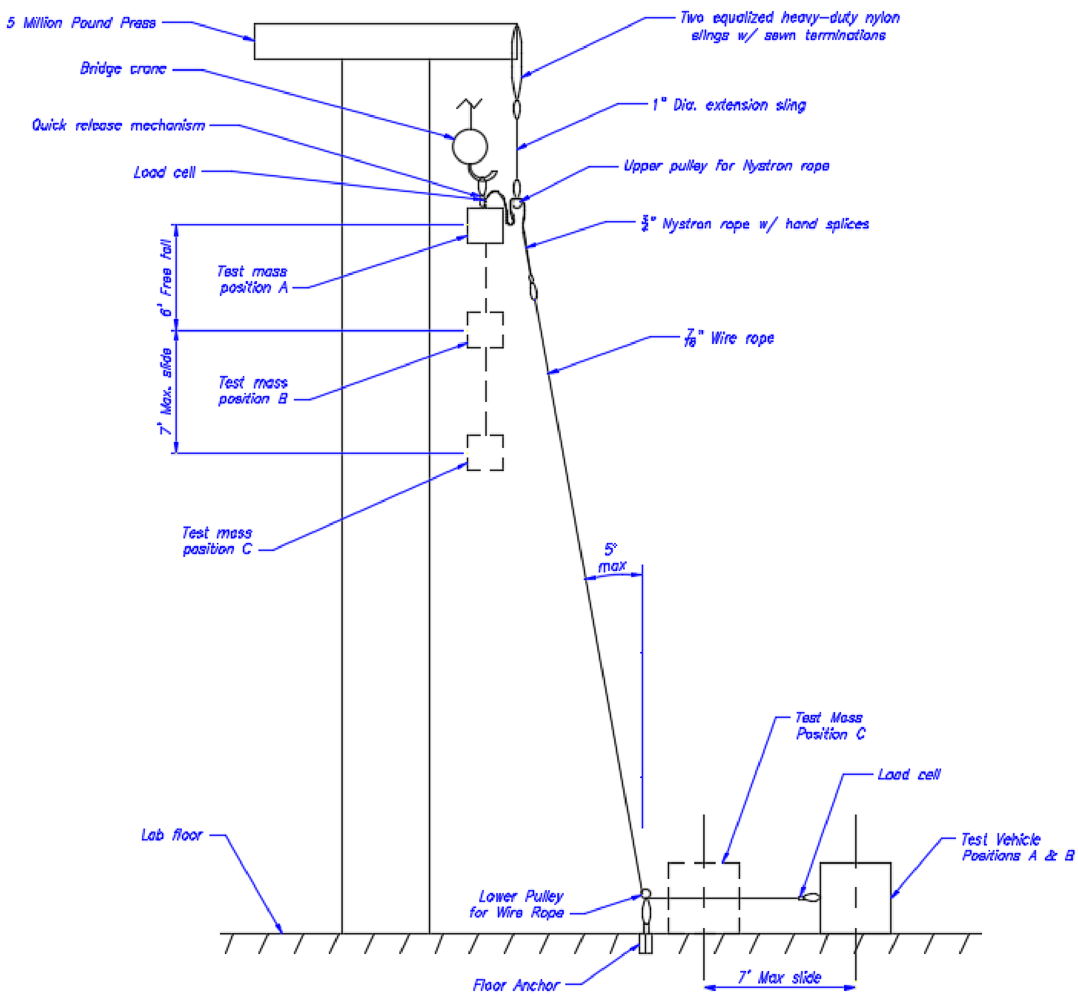

Figure 1 - Drop Testing Schematic

Test Vehicle

Due to purchasing restrictions, a vehicle mockup was fabricated using the axles and wheels from a 2004 Jeep Cherokee. Tube steel side frames were bolted and welded to the axles and angle iron was welded laterally to support a plywood platform on top of the frame. This setup allowed for a quick change in various weights to be added on top of the plywood platform to test different weights of the test vehicle. Lumber 2x4's were jammed in between the front tires and the frame to inhibit the test vehicle from turning. All four wheels were chocked with masonry bricks. For each test setup, a variety of dead weights were secured on top of the plywood platform with cam straps. See Figure 2.

Figure 2 – Test Vehicle Shown Fully Loaded (Test Setup #3) During Static Testing

Test Lanyard

A key component to the ANSI Z359.18 standard is the test lanyard. According to the standard, the lanyard has no maximum length requirement, but it must not stretch more than 8.0 inches when statically loaded to 4,500 lbf. In order to meet this requirement and due to the need for a relatively long test lanyard, a ¾” diameter Nystron rope manufactured by Samson Rope Technologies, Inc. (Samson)[1] was connected in series with 7/16” diameter wire rope. Although the ANSI Z359.18 requirement could have easily been achieved using wire rope alone, the stiffness would have been far too conservative to achieve meaningful results. The Nystron rope was chosen for its relative stiffness compared to other ropes, which allowed for a longer section of rope to be chosen. The Nystron rope included a hand splice at each end, and the wire rope was terminated with forged wire rope clips and thimbles. The test lanyard was not statically tested to verify it met the requirements of ANSI Z359.18. Instead, calculations were used to verify this requirement.

For ¾” Nystron rope, Samson indicates the average strength to be 23,000 lbf and the elastic deformation at 20% of this strength to be 4.50% stretch[1]. Conveniently, 20% of 23,000 lbf is approximately equal to the ANSI Z359.18 required 4,500 lbf; therefore, 13 feet of Nystron rope at 4.50% elongation should stretch approximately 7.0 inches.

For the remainder of the test lanyard, 7/16” EIP wire rope with 6x19 fiber core construction was chosen for its strength and availability. At a strength of 20,400 lbf[2], a load of 4,500 lbf would be approximately 22.1% of the strength. The modulus of elasticity is 12,000,000 psi[3].

Applying the following equation and converting to inches yields 1.3 inches of wire rope stretch at 4,500 lbf.

$$\text{Changes in length (ft)} = \frac{\text{Change in load (lb)} \times \text{Length (ft)}}{\text{Area (inches}^2\text{)} \times \text{Modulus of Elasticity (psi)}}$$

Combining the stretch with the Nystron rope gives 8.3 inches of stretch, which is just outside of the ANSI Z359.18 required maximum of 8.0 inches of stretch at 4,500 lbf. This was deemed to be adequate for the purposes of this testing.

Test Tower

The test tower used was Reclamation's custom-built Five Million Pound Press. It is one of the biggest compression test machines in the world and was primarily used to test concrete samples for what was the largest dams that had been built at the time. It can also be used for tension testing. Rumor has it that when a 6 inch diameter cylinder of steel was tensioned to failure, all the windows shattered. For the purposes of this testing, the Press is only used as a static structure to be connect the upper pulley.

Test Mass

According to the ANSI Z359, the test mass is required to be 282 lbf. This seemingly arbitrary number is derived from a worker with a maximum weight of 310 lbf (including equipment). Testing has shown that a factor of 1.1 be used to compensate for the fact that the test mass is rigid, whereas a human being is not. For this testing, the test mass was constructed of two pieces of scrap steel bolted together. With the addition of shackles, the test mass weighed 303 lbf.

Quick Release Mechanism

The quick release mechanism was a homemade three ring release, consisting of three different sized steel rings that are arranged to decrease the load on a release pin. It is similar to a three ring release used by skydivers to release a loaded parachute. The three ring release system was activated by someone on the ground pulling a string connected to the release pin.

Load Cells

Two of Rock Exotica's Enforcer load cells were used to measure dynamic forces during the drop testing. One load cell was connected between the Test Mass and the Nystron rope and the other was connected between the vehicle anchor sling and the wire rope. The two load cells were used to measure the losses in the system. These losses are expected to be much less than a "normal" vehicular anchor where the rope would be redirected over an edge.

To measure static forces, a 10,000 lbf Dillon load cell was used.

Bridge Crane

The laboratory bridge crane runs along the ceiling above the test tower and was used to raise the test mass to the proper height.

3 Ton Hoist

For the static testing, one side of a 3 ton hoist was connected to the Dillon load cell at the test vehicle and the other side was connected to the floor anchor.

Results

Three test setups were each tested three times dynamically and three times statically. Although not statistically significant, three iterations of each test generally demonstrates consistency and is in accordance with methodologies outlined in ANSI Z359. The dependent variable in each test setup was the amount of weight placed on top of the test vehicle. To simulate the disproportionate weight of an engine in an actual vehicle, a large weight (1,730 lbf) was placed near the front of the test vehicle for all of the test setups. In addition to the "engine" weight, test #1 had all four of the other dead weights evenly distributed along the plywood platform of the test weight. Test #2 had the "engine" weight in the front of the test vehicle as it was in test #1 with two of the other dead weights evenly distributed. Test #3 had only the "engine" weight located in the front of the test vehicle as it was in the other two tests.

For the dynamic tests, the test mass was raised to the same height as the upper pulley and released with the quick release mechanism. Due to the unbalanced weight on top of the test vehicle, only the rear end of the vehicle moved during any of the tests. The distance the rear tires moved was recorded as the sliding distance. The static testing setup was identical to the dynamic testing; however, the testing was terminated once the test vehicle began to move. Table 1 shows the maximum recorded dynamic forces at the test weight and at the test vehicle and how far the rear tires slid during those tests. Table 1 also compares the maximum recorded static force (at the test vehicle).

Table 1 – All Dynamic and Static Test Results for Three Test Scenarios

Test #		Test Vehicle Weight (lbf)	Test Surface	Max. Dyn. Force @ Test Weight (lbf)	Max. Dyn. Force @ Vehicle (lbf)	Max. Static Force @ Vehicle (lbf)	Sliding Distance (inches)
1	a	4675	Lab Floor	2670	2144	2266	0
	b			2930	2198	2234	1
	c			2918	2148	2198	0
2	a	3800	Lab Floor	3080	2284	1630	3
	b			2890	2212	1626	2.5
	c			2896	2144	1652	3
3	a	2925	Lab Floor	2970	2206	1088	7
	b			2968	2192	1078	7
	c			2974	2266	1072	6.5

Figure 3 shows the results from Table 1 graphically. It's important to note that for each of the three iterations of a test setup, the measured values did not differ greatly from one another, which gives confidence in at least the precision, if not the accuracy, of the measurements.

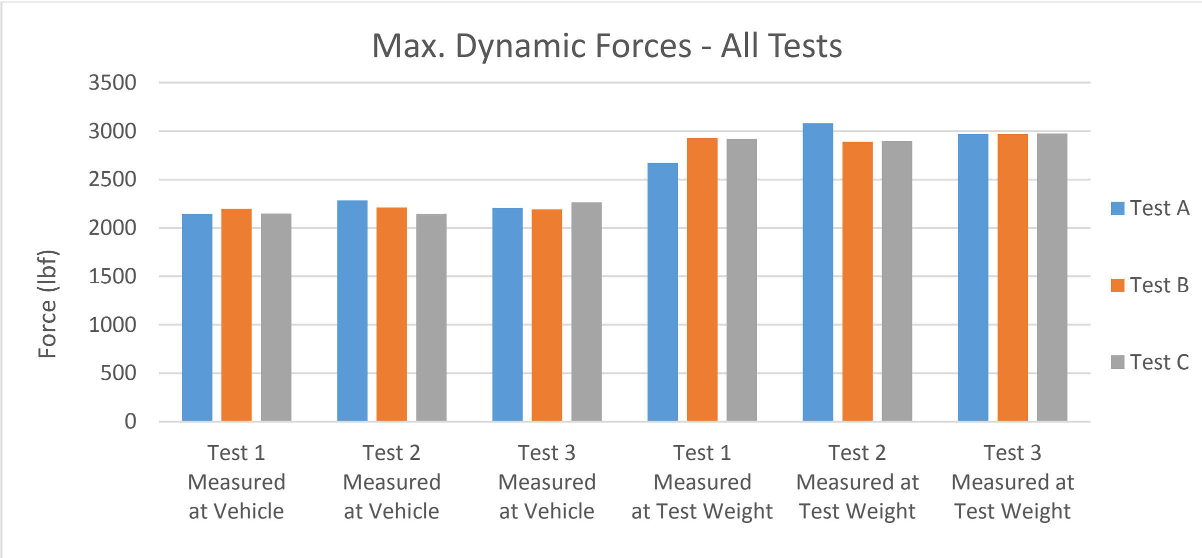

Figure 3 - Maximum Forces Measured for All Three Dynamic Test Setups

Figure 4 shows the averages of the maximum recorded forces for each test setup. As expected, the dynamic forces at the test weight are consistently higher than at the test vehicle. This is due to the energy losses in the test lanyard and the pulleys. The losses in the test lanyard are intentional to gain a repeatable result in the measured force at the test vehicle; therefore, this is the more significant of the two dynamic forces and is more applicable to be compared to the static forces. It is interesting to note that the dynamic forces change very little with the change in the weight of the test vehicle; however, the static forces decrease proportionately with the decrease in weight of the test vehicle. While the dynamic forces remain nearly the same in all three test setups, the sliding distances shown in Table 1 increase as the weight of the test vehicle decreases. This shows that the energy is absorbed by the sliding of the test vehicle instead of a higher impact force.

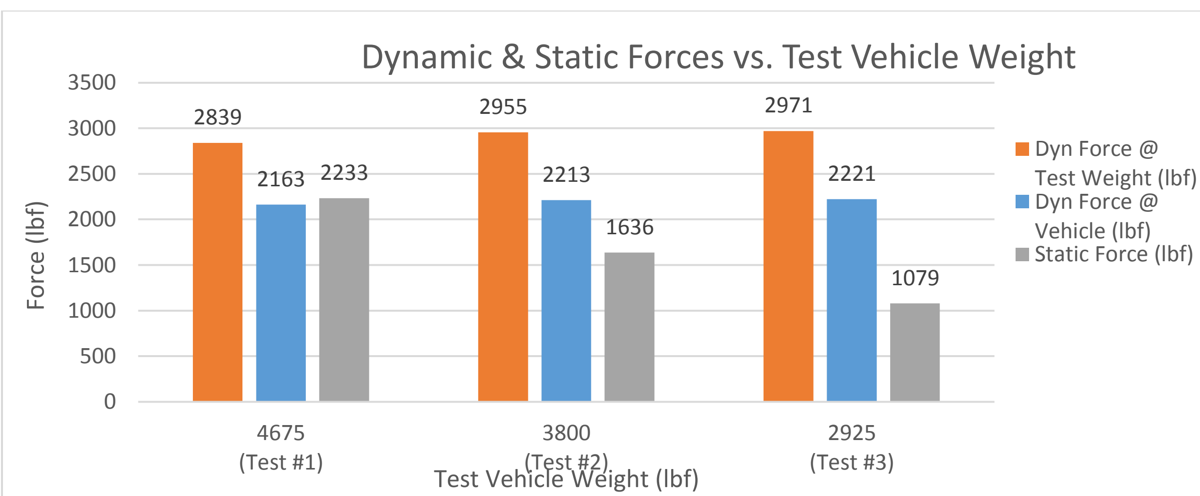

Figure 4 – Averaged Dynamic and Static Forces for Three Test Setups

Table 2 and Figure 5 shows the static testing Reclamation has done on actual vehicles compared with the current static testing on the test vehicle. The past testing was conducted on a 6,000 lbf Chevrolet Suburban and a 4,600 lbf Ford Explorer on smooth concrete and on asphault. Even though the past testing included many different test arrangements, only the tests that anchored to the side of the vehicle with a lateral (sideways) pull test were included. Although the past testing and the current testing are not exactly “apples to apples”, it is interesting to observe the wide range of calculated static friction coefficients. Since the laboratory floor is essentially a very smooth concrete, the past testing of the Explorer on the smooth concrete is similar the current test #1. Both tests were on concrete and both vehicles weight approximately the same; however, there is still a fairly large gap in the calculated friction coefficients, 0.70 for the Explorer and 0.48 for test #1.

Table 2 – Past Static Testing on Actual Vehicles Vs. Current Static Testing on Test Vehicle

Test Type	Test #	Test Vehicle Weight (lbf)	Test Surface	Average Static Force (lbf)	Average Sliding Distance (in)	Static Friction Coefficient	Dynamic Friction Coefficient
Past Testing	Suburban	6000	Smooth Concrete	5380	X	0.90	X
			Asphault	5950	X	0.99	X
	Explorer	4600	Smooth Concrete	3200	X	0.70	X
			Asphault	4260	X	0.93	X
Current Testing	1	4675	Lab Floor	2233	0.33	0.48	0.46
	2	3800		1636	2.83	0.43	0.58
	3	2925		1079	6.83	0.37	0.76

Table 2 also compares the static friction coefficients with the dynamic friction coefficients. As expected, the calculated static friction coefficients remain relatively the same as the test vehicle weight changes. The calculated dynamic friction coefficients drastically change as the test vehicle weight changes, which means these must not be accurate depictions of dynamic friction coefficients. This is most likely due to the dynamic nature of the drop test. Dynamic friction coefficients are not typically measured with a non-constant force such as a drop test, but with a constant force moving an object along a surface. The change in the calculated dynamic friction coefficients was due to all the dynamic forces at the test mass staying nearly the same and all the forces at the test vehicle staying nearly the same, even though the weight of the test vehicle changed. Interestingly, the dynamic forces are not dependent on the weight of the test weight, but likely due to the dynamic force acted upon it by the weight of the test mass and the distance it was dropped. Changing either the weight of the test mass or the distance it was dropped would likely change the measured dynamic forces at the test weight and at the test vehicle.

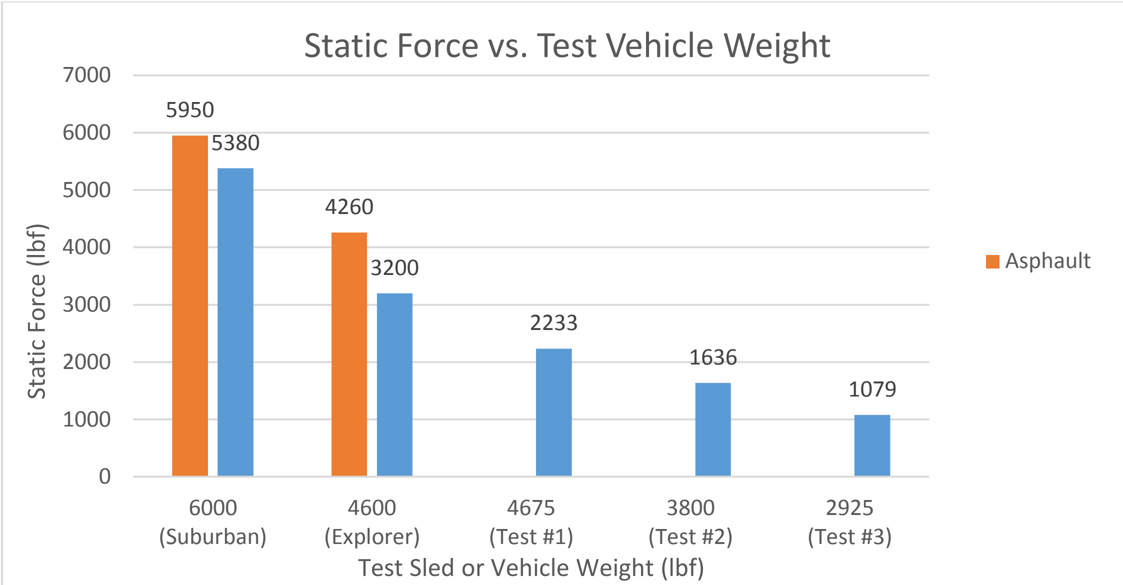

Figure 5 - Past Static Testing on Actual Vehicles Vs. Current Static Testing on Test Vehicle

Figure 6 shows photos during the drop testing pre and post drops.

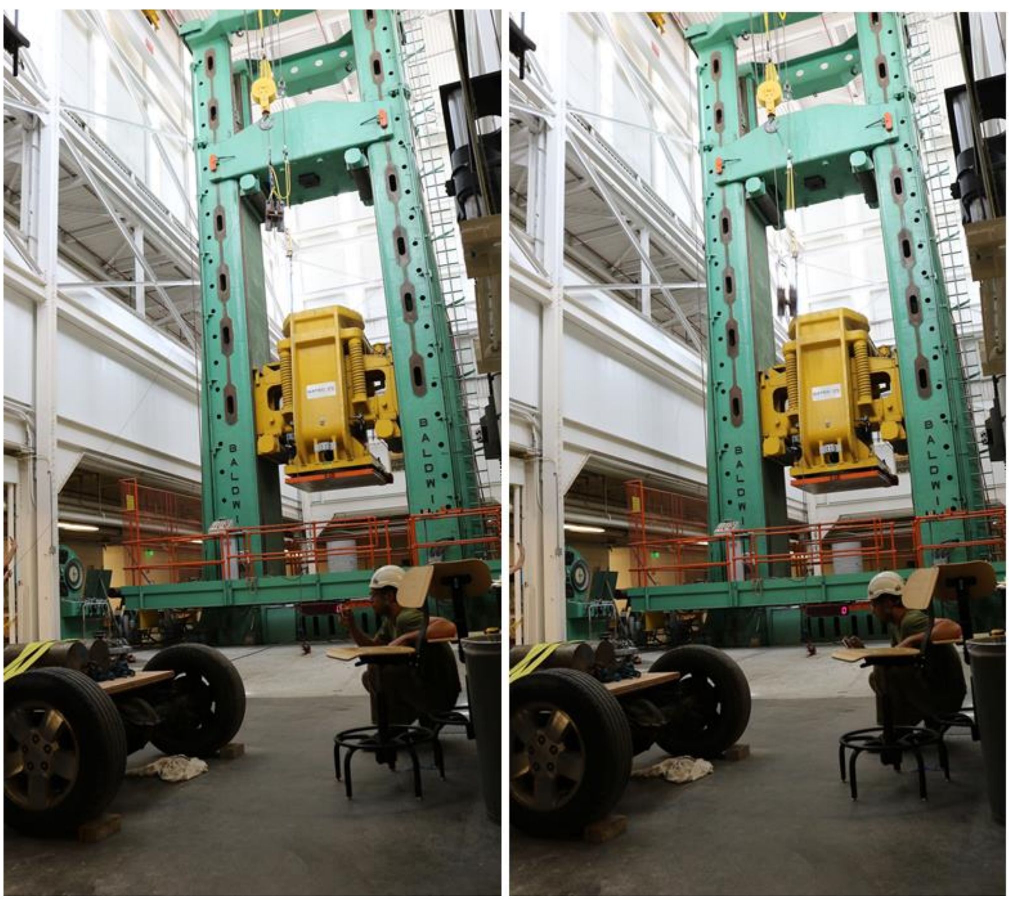

Figure 6 – Drop Testing Setup: Pre-Drop (Left) and Post-Drop (Right)

Conclusion

Vehicular anchors are cool.

References

1. Samson Rope Technologies, Inc.
   a. http://www.samsonrope.com/
2. Webrigging supply
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