Tram Brakes

ME 493 Final Report - Year 2010

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Executive Summary

The project sponsor, Zdenek Zumr, operates a funicular tram at his residence. The tram was intended to haul people and cargo up the steep slope to the residence. The tram operates on a single pull cable and at the inception of this project had no means of controlling the cart should the pull cable break or the winch malfunction. An emergency braking system is required to keep people and cargo safe in the event of a cable or winch malfunction.

The goal of this project is to provide an emergency braking system for the tram cart that will activate automatically in the event of a cable or winch malfunction. The braking system will stop the descent of the cart automatically and allow for a manual, controlled descent to be performed by an occupant of the cart if needed. The braking system must be reliable, be able to operate after long periods of non use, and operate without destruction of major braking system components when used.

The Product Design Specifications were established by early February, and detailed design was completed by late April. Prototype production took place during May, with installation and testing occurring in late May. Documentation, including bill of materials (BOM), operating and maintenance instructions (O&M), and assembly drawings are ready to be delivered to the project sponsor. A final presentation was given on June 2nd, and this Final Report is due June 7th, 2010.

The external search conducted by the design team used the internet and an on-site visit to the Portland Aerial Tram to aid in producing concepts during the design team's internal search and concept brainstorming processes.

The internal search process produced seven feasible concepts. These concepts fall into 3 basic categories: direct cable friction systems, brakes on a solid member, and brakes controlling the rotational motion of a shaft with rotation caused by an independent cable looped around a pulley connected to the shaft.

The concept in which a brake caliper applies braking force directly to a secondary cable was selected. A provision for manual operation of the caliper by an occupant of the tram cart was added to the system to satisfy the project sponsors requirements.

The braking system was completed using less than $ 300.00 of the $ 1,000.00 budget, was tested on schedule, and the project sponsor has agreed that all design specifications have been met.

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Introduction

The project sponsor, Zdenek Zumr, owns and operates a funicular tram at his residence. Since the tram operates on a single pull cable, an emergency braking system is required to prevent the tram cart from descending down the track with loss of control in the event of a cable or winch gearbox malfunction. The tramway, as viewed from the residence is shown in Figure 1.

Figure 1: Tramway as viewed from upper landing. Tramway is approximately 77 feet long and descends at a 30 degree slope from the residence to the street.

The solution developed consists of a mechanical brake caliper that, in the event of an emergency, would clamp down on a secondary static cable to safely arrest the cart and its contents.

Mission Statement

An emergency braking system for a funicular tram located at the project sponsors residence is to be designed and prototyped. The braking system is to operate automatically in the event of a pull cable or winch gearbox malfunction. The braking system should either stop the tram cart, or allow the cart to descend to the bottom of the tramway at a controlled velocity of no more than 2 ft/sec. If the braking system is to stop the tram cart, a provision for manual operation of the brake may be included to allow an occupant on the cart to descend to the bottom of the tramway. The braking system must be reliable, mechanical (non-electrical), and operate without the destruction of major braking system components. Documentation of the mechanism, including Bill of Materials (BOM), operating and maintenance instructions (O&M), and Assembly Drawings are to be delivered with the prototype.

Main Design Requirements

The design team determined that the following requirements were highly important to the success of the project:

- Brake system will automatically stop the cart (total combined weight < 800 lbs) in an emergency
- The system should have a manual brake release on the cart
- Stopping acceleration will not be greater than the acceleration experienced at startup
- All components must be mechanical
- The braking system should capture the cart to the track while still allowing for the cart to be removed easily when necessary
- The minimum factor of safety for all brake system components must be at least 2

An exhaustive list of design requirements is listed in the PDS provided in Appendix G.

Top Level Design Alternatives

Internal search, External search, and brainstorming provided seven top level design concepts to the design team for concept evaluation. The top level concepts fell into three basic categories: direct friction applied to a structural member, direct friction applied to a secondary cable, and brakes controlling the rotation of a shaft whose rotation was caused by movement of the cart.

Two methods of direct friction applied to a structural member were discussed. The first, brake calipers mounted to a steel T-section, is shown below in Figure 2.

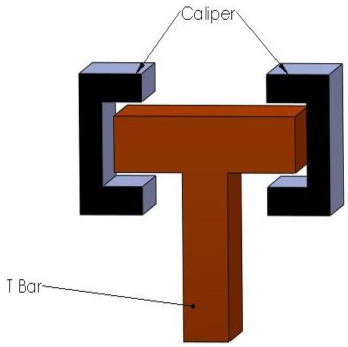


Figure 2: Direct friction to structural member, caliper on T-bar concept

Braking would be accomplished in this concept by applying some type of activation force to the calipers in the event of an emergency, causing the calipers to clamp down onto the T-section beam. The second method in this category utilized the internal surfaces of a C channel as the braking surfaces.

Two methods of direct friction applied to a secondary cable were discussed. The first method was a system similar to a rock climbing apparatus known as a Petzl Stop Descender, shown in Figure 3, which would use a pinching action to control the descent of the cart under emergency conditions.

Figure 3: Petzl Stop Descender used to control descent during rock climbing

The second concept in this category was the caliper on cable method. A brake caliper mounted directly on a cable, as shown in Figure 4, would be used to control the descent of the cart.

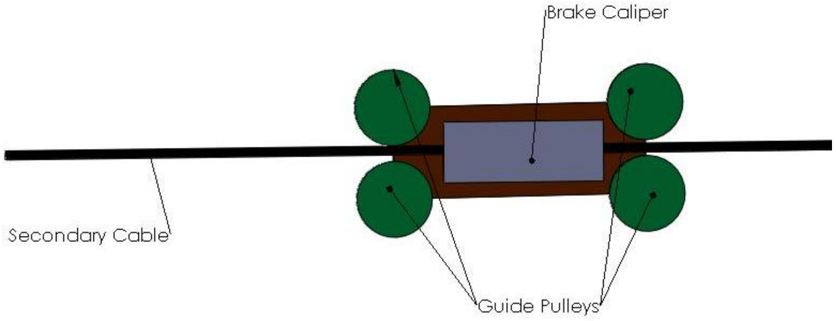


Figure 4: Cable On Caliper concept sketch

Three methods of brakes controlling the rotation of a secondary shaft were discussed. These three options were all relatively complicated, and expensive to install initially. All three options were ruled out during the decision making step of the process, and due to their complexity none of the options is pictured here.

Construction of a decision matrix based on PDS requirements lead to the choice of the brake caliper mounted directly to a secondary cable as the top level design for this project. Reliability was given the most weight in the decision making process, and the concept chosen should be highly reliable due to the simplicity of the concept. Other important PDS constraints met by the caliper on cable concept are listed below

- the system is completely mechanical
- the system operates in a non-destructive manner to major system components
- installation and maintenance costs are low
- the tram cart is captured to the track by a secondary cable

This concept also allowed for a relatively simple manual override system to be designed and installed.

Final Product Design

The final design of the product utilizes a secondary cable stretched from the top to the bottom of the tramway. The secondary cable passes through a mechanical brake caliper which is attached to the tram cart. A linkage set connects the winch pull cable to the caliper, and a spring is utilized to apply braking force to the caliper in the event of an emergency. Figures 4, 5 & 6 provide models of the complete braking system. The braking system features three distinct sub-units: the caliper assembly, the caliper activation assembly, and the cable guides.

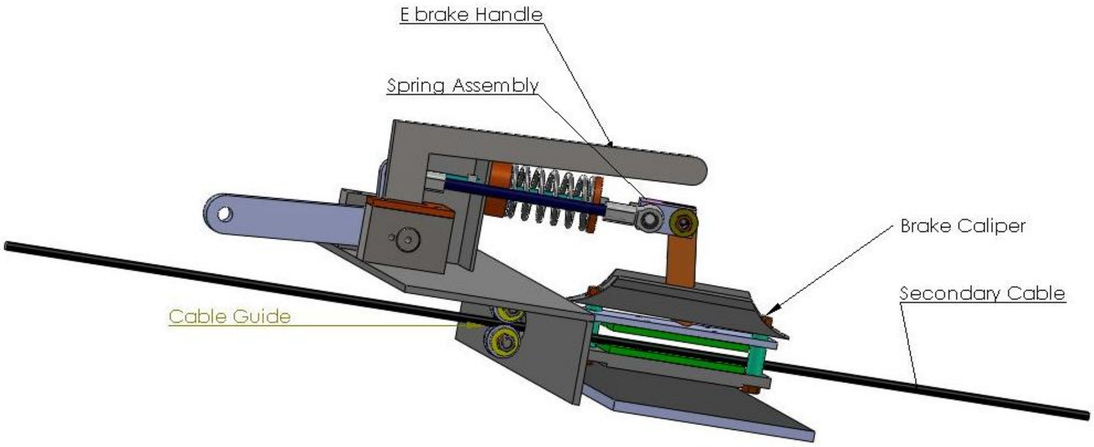


Figure 4: Model of the complete caliper on cable design. (side view)

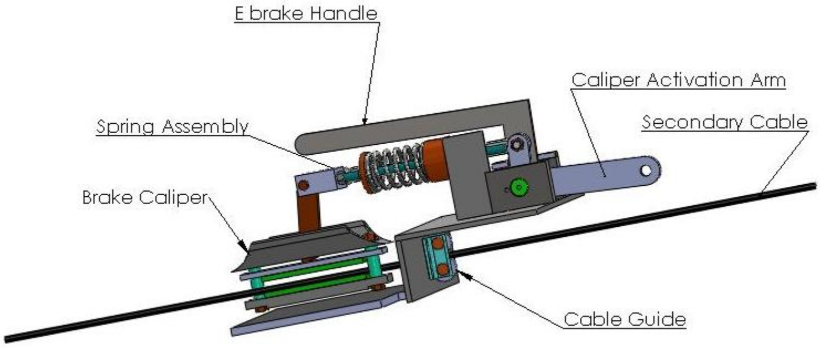


Figure 5: Model of the complete caliper on cable design. (opposite side view)

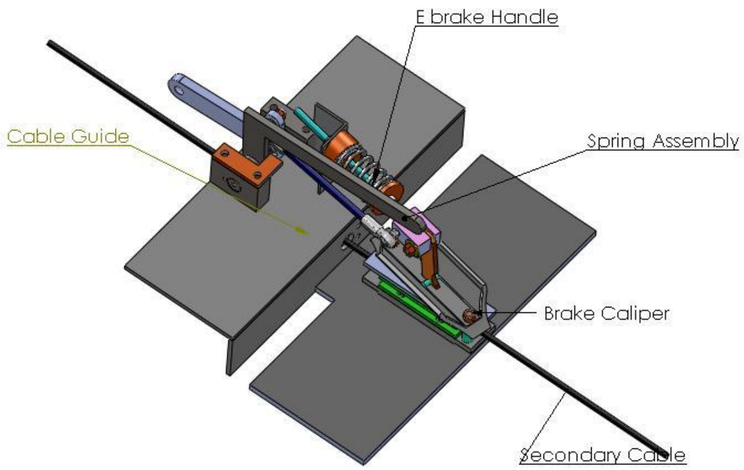


Figure 6: Model of the complete caliper on cable design. (top view)

The Caliper Assembly: The caliper assembly is composed of the caliper itself, the spring mechanism, and the rod connecting the caliper lever to the caliper activation assembly. The mechanical caliper selected was originally intended to be used as a transfer case brake for a Toyota pickup, and was purchased in the form shown in Figure 7.

Figure 7: Transfer case brake as purchased.

Modifications had to be made to the caliper so it would function with the tram cart and the cable. These modifications involved manufacturing a new bottom plate that would allow the caliper to mount to the cart. New brake pads were also machined out of aluminum to replace the brake pads that came with the caliper because the original friction material the brake pads were constructed with could not withstand the abrasion the cable would inflict on the pads during an emergency stop. Aluminum was selected as the material for the new pads because it would be tough enough to withstand the abrasion of the cable to some degree without causing damage to the secondary cable. Figure 8 displays the modified caliper, which operates by a cam action generated by rotating the activation lever about the activation pin which causes a force to be exerted on the top brake backing pad. Grooves were machined in the brake pads to provide a path for the cable to travel, and to increase the surface area of the cable contacting the brake pad to lower the stress exerted on the brake pad during caliper operation.

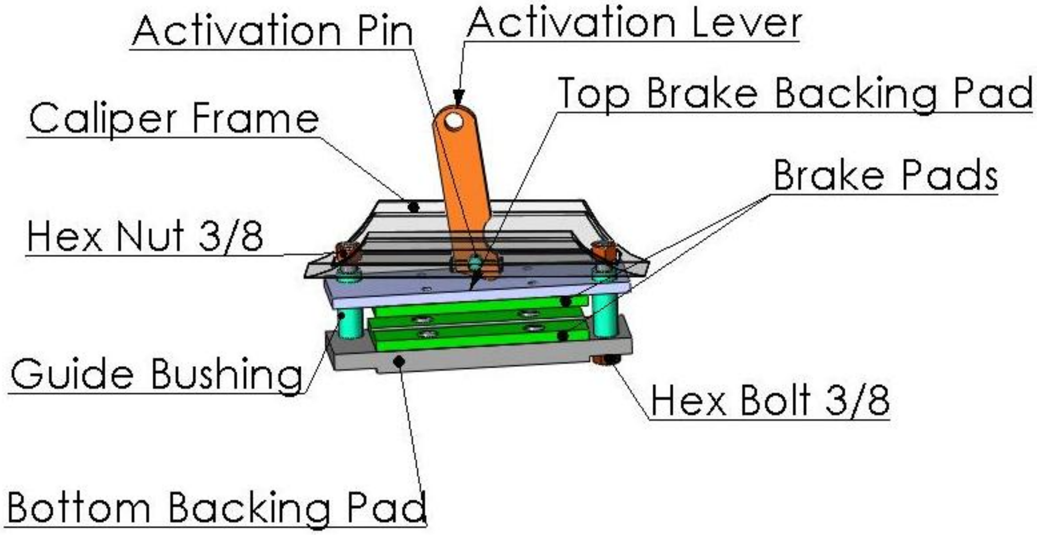


Figure 8: Modified caliper assembly

The spring mechanism shown in Figure 9 was designed to ensure that the caliper will always be clamped down on the secondary cable when pull cable tension is lost. The spring mechanism consists of a spring mounted between two retaining washers. One of the washers is mounted on the cart frame, and the other is attached to a rod which connects through a clevis to the caliper activation lever. An experiment was conducted to determine the spring force needed to be applied to the caliper to provide the necessary tension in the braking cable to stop the cart. According to the caliper experiment described in Appendix C, approximately 80 pounds of force is required to be applied to the caliper activation lever to compress the caliper on the cable with enough force to stop the fully loaded cart. A spring was selected that would supply this force, while still maintaining the required range of motion for the caliper lever to allow the system to operate properly.

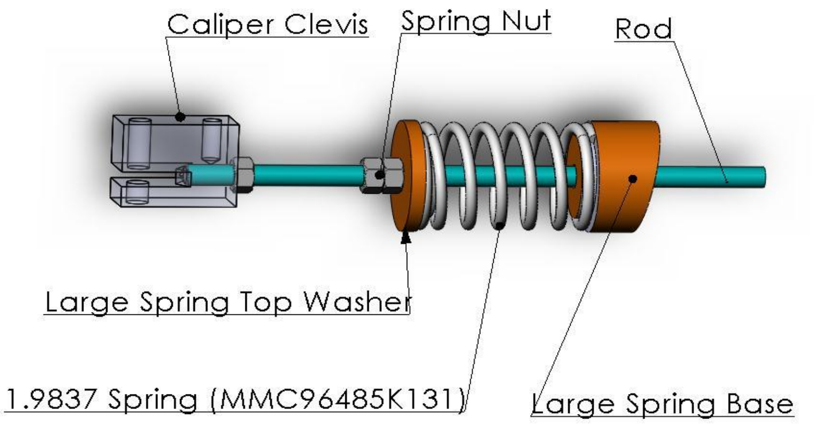


Figure 9: Spring Mechanism

The rod that connects the caliper lever to the pull pin lever is just a simple threaded rod with ball joints on both ends. Ball joints were selected because the rod has to translate smoothly though a fairly large angular displacement in all three dimensions. The caliper lever acts in a plane that is approximately eleven degrees off the plane that the brake activation pivot arm translates through. This angular deviation is in addition to the difference in height and the radius of motion between the two levers. The translational demands on the connecting rod were substantial enough that the design team agreed that ball joints were the most appropriate type of connecting feature to use in this application. The connecting rod is shown in Figure 10 on the next page.

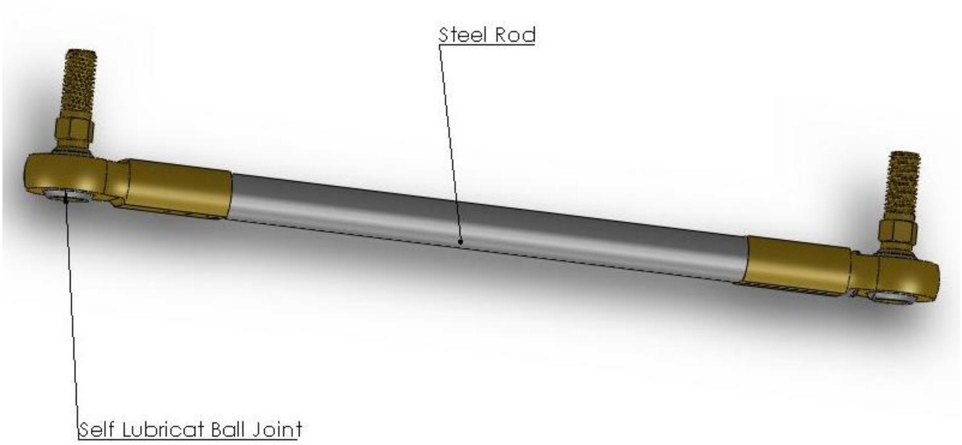


Figure 10: Connecting Rod Assembly

The Caliper Activation Assembly:

The caliper activation assembly connects the pull cable to the cart, deactivates the caliper when the pull cable is tensioned, and allows for the brake to be manually released when pull cable tension is lost. The assembly shown in Figure 11 is composed of four primary components: the brake lever pin, the bearing blocks, the E-brake handle (manual release handle), and the brake activation pivot arm.

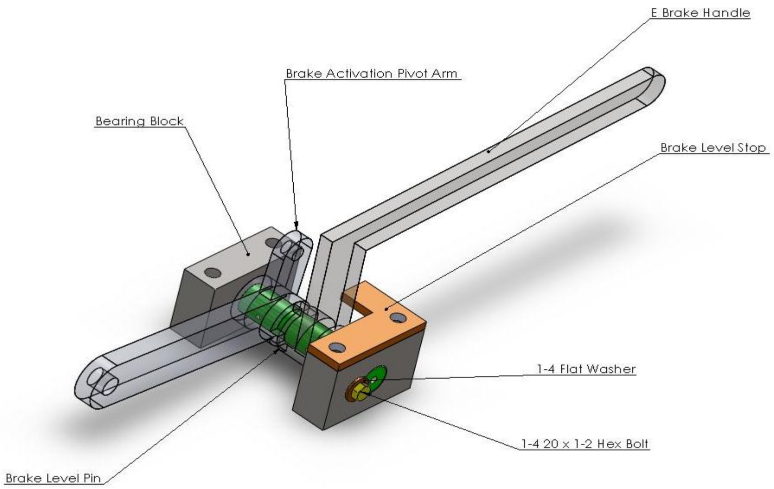


Figure 11: Caliper Activation Assembly

The brake lever pin is a critical component which was engineered to have a 7/8 inch diameter to withstand the cyclical bending load that will occur on the steel cylinder during normal operation. The bending on the shaft is caused by the pull cable load acting on the three inches of exposed shaft between the bearing block inside edges. To provide independent lubrication to the levers rotating on the shaft, both ends of the shaft are drilled and fitted with grease zerks. Radial holes were drilled through the shaft at two locations on the shaft, one under each lever, to provide a path for the grease from the zerk fittings to the moving components, as shown in Figure 12.

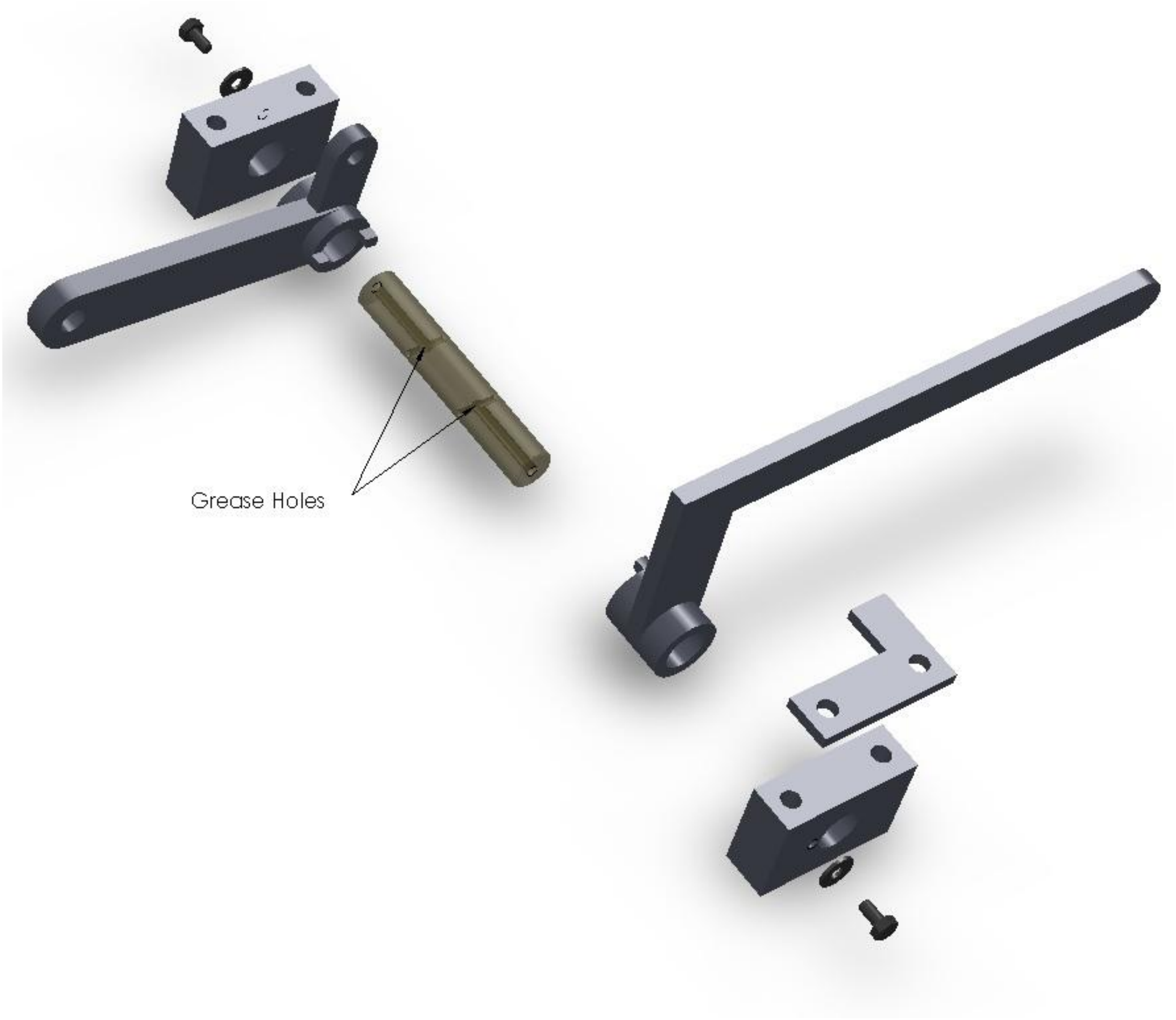


Figure 12: Exploded view of caliper activation assembly, showing grease holes in pin

The bearing blocks are each one piece, and machined from steel bar stock. Each bearing block attaches to the cart frame with two 3/8 inch bolts which mount through vertical holes drilled through the blocks. The bearing blocks also feature a drilled and tapped hole located just outside the shaft hole. These holes receive ¼" bolts and flat washers that capture the shaft between the two blocks when assembled, and function as inexpensive shaft retainers.

The block located on the same side of the assembly as the manual release handle is equipped with an L-shaped section of stainless steel plate. The short leg of this L extends out towards the release handle. This piece of material establishes a lower limit for the travel of the release handle.

The manual release handle allows a passenger on the cart, after a pull cable or winch malfunction, to release the brake caliper and return the cart to the bottom of the track in a controlled manner. It is made out of two sections of flat steel bar stock that were welded into an L-shape. This section was then welded onto a piece of steel bar stock that was machined to slide over the brake lever pin (shaft). The unit was designed such that the hole though the tube was perpendicular to center plane of the handle unit. The tube also had material removed from the end that was to be positioned toward the center of the shaft so that what remained were two tabs ¼ inch long with approximately square cross sections located diametrically opposite from each other similar to those shown in Figure 13 on the brake activation pivot arm.

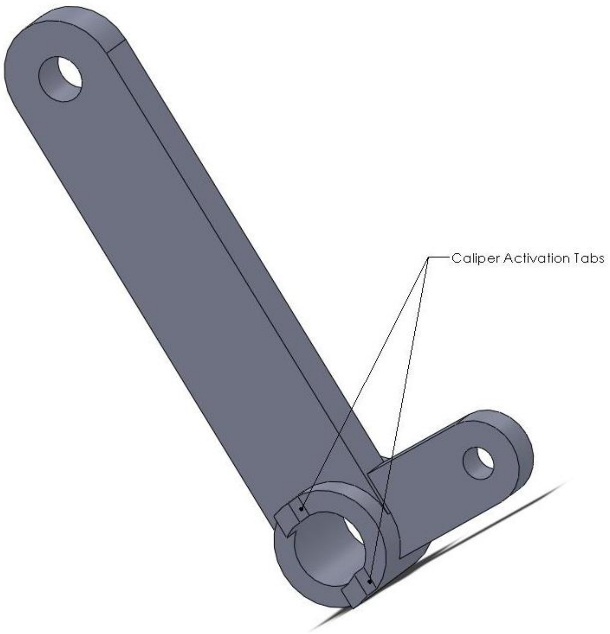


Figure 13: Brake Activation Pivot Arm with caliper activation tabs shown

These tabs mate with two identical tabs on the brake activation pivot arm when the caliper is engaged and the release handle is pulled to open the caliper. The manner in which the tabs engage allows the brake activation pivot arm to move independently of the E-brake handle, but also gives the E-brake handle the capability of moving the brake activation pivot arm in emergency conditions.

The brake activation pivot arm, shown in Figure 13, is the most important component of the caliper activation assembly. This component engages and disengages the caliper based on whether there is tension in the pull cable or not. The lever has two arms, one connects to the pull cable and the other connects to the caliper through the rod and ball joints. The brake activation pivot arm uses pull cable tension to overcome the pressure exerted on the caliper by the spring. Preliminary calculations indicated that an empty cart moving downhill would not provide adequate tension in the pull cable to overcome the spring force exerted on the brake activation pivot arm with a 1:1 arm length ratio. Due to the critical nature of this factor on the performance of the system the tension in the pull cable was measured. The minimum steady state force in the cable was found to be 40 lbs. The ratio of mechanical advantage needed was determined to be 3:1 to overcome the spring pressure when compressed to normal operating conditions. Therefore, the pull cable arm is three times longer than the caliper arm because this difference in length creates the 3:1 mechanical advantage required to ensure the pull cable will always have enough tension to keep the caliper open during normal operating conditions. The brake activation pivot arm was machined out of steel. The two arms are welded onto a section of tube that, like the manual release handle, fits over the shaft. As shown in Figure 13, this tube has two square tabs milled out of the end facing the middle of the pull pin assembly that mate with the tabs milled into the release handle to allow independent and dependent operation of the two levers as needed.

Cable Guides

Two cable guides were installed on the cart. The purpose of the cable guides is to guide the cable through the cart without exposing the cable to the sharp edges of the holes the cable passes through, and to keep the secondary cable lined up with the groove machined into the brake pads. A picture of the upper cable guide as installed on the cart is shown in Figure 14.

The stainless steel guide rollers are press fitted with brass bushings that spin on steel stand-offs, as shown in Figure 15.

Figure14: Upper cable guide as installed on cart

The guide roller stand-off is machined slightly wider than the guide roller, and is clamped between the guide roller washer and the guide roller bracket. The stainless steel guide rollers should spin against the steel guide roller washer and the guide roller bracket without galling due to the difference in materials, and the use of lubrication.

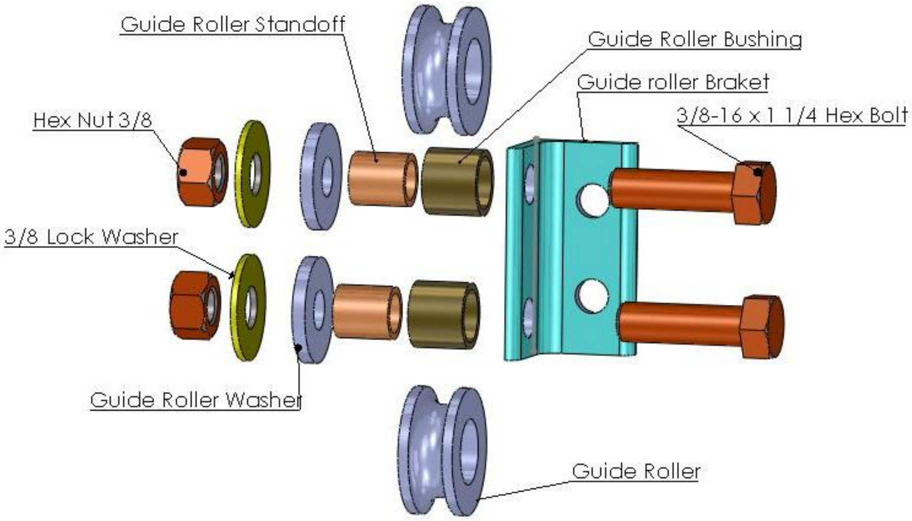


Figure 15: Exploded view of cable guide assembly

To aid in the ability to remove the cart from the track, the secondary cable was installed by the project sponsor with a turn buckle for cable tension, as shown in Figure 16.

Figure 16: Secondary cable tensioning turn-buckle and pull cable as installed

To comply with the PDS requirement for ease of cart removal from the tramway, the design team created a special cable clamp, shown in Figure 17, for the lower end of the secondary cable which does not require the cable to be bent around in a loop. The reasoning behind not requiring a loop in the cable is that a straight cable end can easily pass through all system components to allow ease of cart removal from the tramway when required. The cable clamp produced and installed in this system is shown in Figure 18.

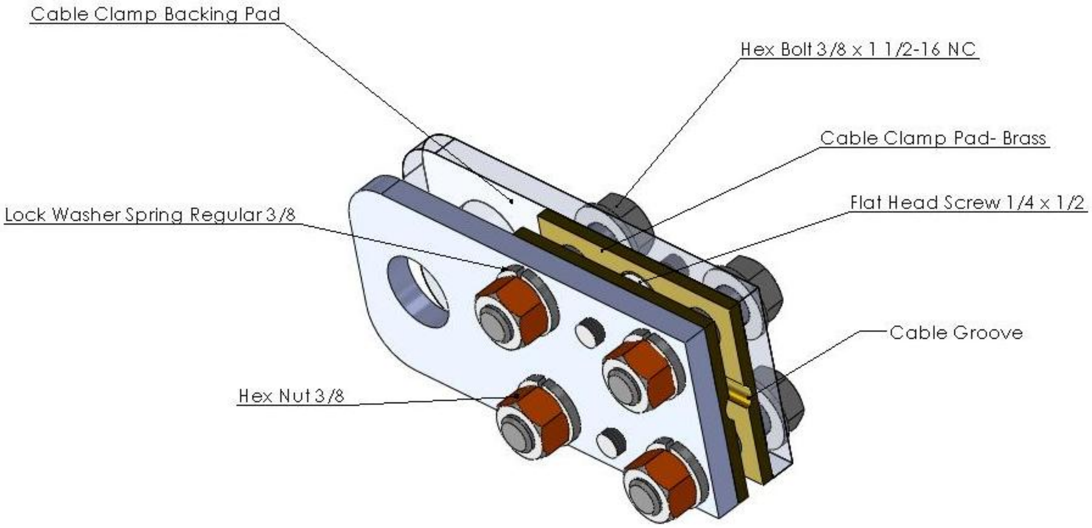


Figure 17: Lower cable clamp with groove for straight cable clamping

Figure 18: Lower cable clamp and anchor as installed

The straight cable is inserted into the cable groove shown in Figure 15, and when the four 3/8 bolts are tightened, the secondary cable is securely held in place.

Final Product Evaluation

Final product evaluation was performed by testing and analyzing the prototype. The product design specifications (PDS) for this system provided several required attributes that the final product would be required to have. The most important of these were listed in the Main Design Requirements section of this report. The design, as tested, functioned as it was designed to. This claim is substantiated by several means, namely practical tests and experiments, engineering analyses, and by physical inspection.

Three of the major PDS requirements listed earlier can be demonstrated to have been met by visual inspection of the design of the system. The requirements that can be visually inspected for conformance are:

- The system will have a manual release on the cart
- All components must be mechanical
- The system must attach the cart to the track while still allowing the cart to be removed when necessary

The solution designed includes a mechanical release handle as described in the previous section, and shown in Figure 19.

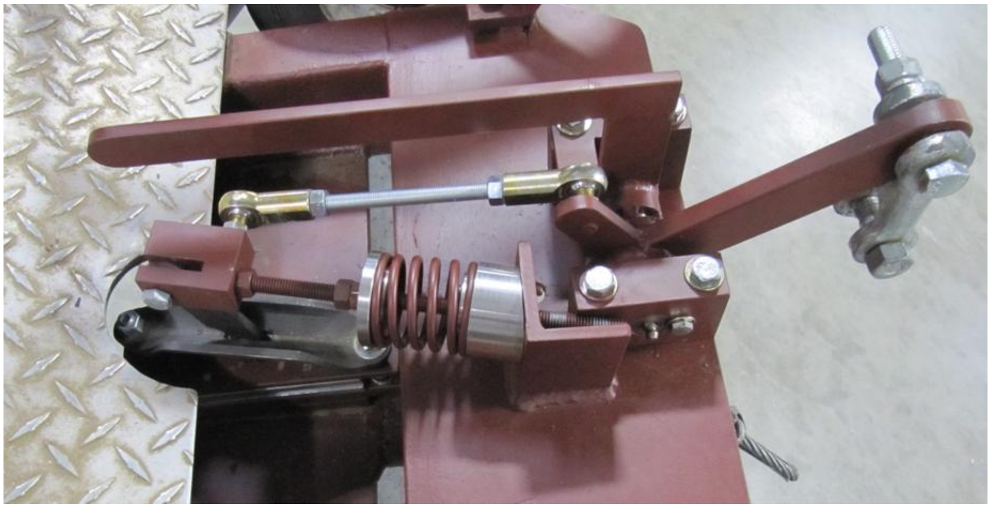


Figure 19: Tram brake assembly as installed on tram cart.

During the testing process the handle always function properly. This fulfills the first requirement listed above. The second requirement is also met because the braking system is purely mechanical. This might seem to be an overly simple requirement that should not have been given special attention in this document, but due to the degree to which the cart is exposed to the elements and the fact that the cart moves along a track, it is imperative that electricity is not relied upon to stop the cart in an emergency. The secondary cable fulfills the third requirement listed above. Because the brake cable passes through the cart frame as shown in Figure 16 above, and is deflected slightly upwards as it does so, it serves as a means of capturing the cart to track. This deflection in the cable imparts a force normal to the track that ensures the cart wheels will stay in contact with the rails under all but extreme situations.   Ease of cart removal is provided for by the special lower cable clamp shown in Figure 18.

The functionality of the brake system is the main concern of two of the three remaining PDS requirements discussed in this document. These requirements are:

- The brake system will automatically stop the cart (weighing up to 800 lbs) in an emergency
- Stopping acceleration will not be greater than the acceleration experienced at startup

Both of these requirements have been met. This was demonstrated by the testing done with the completed system on the track at the project sponsor's residence. With the brake system fully set up and configured for use, multiple tests were conducted with different loads on the cart ranging from zero additional weight to a weight approximately equal to the maximum cargo capacity specified in the PDS document (600 lbs.). The initial tests consisted of simply running the tram up and down the track under with various loads to ensure that the brake system would not impede normal operation. It did not, and there was not a noticeable difference in the way the cart traveled along the track when compared to the way things were before the brake system was added. The next round of testing comprised of trials that examined the effectiveness of the brake in a situation where the pull cable failed. This event was simulated by removing the pull cable from the shackle attaching it to the pull cable lever arm and replacing it with a length of string. The cart was then loaded and the string was cut. Every trial conducted proved to be successful. At most the cart glided one or two inches down the track before being brought to a stop. A dynamic test was also conducted, where the cart was set up as described previously with the string connecting the cart to the pull cable and then the pull cable winch was allowed to free spool for a few seconds before being stopped. Once the winch was locked, the string snapped and the brake system brought the cart to a smooth and quick stop. Travel down the track after the point of caliper engagement was minimal. This test was conducted with the maximum amount of weight loaded onto the cart and the result was a success. The project sponsor found the stopping acceleration to be acceptable during all testing performed. This testing process demonstrates that the design team has successfully met the functional requirements discussed earlier.

The final major requirement in the PDS document was that the entire system be designed with a minimum safety factor of 2. This was taken into account in the engineering analyses that were performed during the detailed design portion of this project. These analyses can be found in the Appendices C. Due to the available standard sizes of material stock and the fact that most of the material used to machine components for this system was donated, most of the safety factors for the components as they were built for this project are greater than 2. The actual safety factors for the components are listed in Table 1 on the next page.

Table 1: Actual safety factors of components as built

Component	Minimum Factor of Safety
Activation Lever	10.82
Pull Cable Bolt	5.03
Pillow Block Bolts	5.65
Activation Shaft	2.33
Brake Cable	4.18
Connecting Rod	17.67
Activation Tabs	108.00

Additional requirements of the PDS that were met by visual inspection are: all hardware to be zinc or Cd plated, exposed steel surfaces were painted, where possible off-the-shelf parts were used, the system was designed to minimize components wear, all lubrication point are easily accessible, and the e-brake handle is conveniently placed to allow easy operation.

This project fell within the allotted $1,000.00 budget with the overall project cost as shown in Appendix I totaling $ 293.58. The major reason for cost containment on this project was that much of the material was donated, as was the tooling used to make the components. Appendix I provides a complete list of expenditures for this project.

In conclusion, the braking system that was designed and prototyped fully meets the requirements as specified by both the project sponsor Zdenek Zumr, and the elements recorded in the PDS document. The final product is an emergency brake system that will arrest Mr. Zumr’s funicular tram in the event of a pull cable or winch failure. The system was designed and prototyped on schedule and under budget. Testing has proven that the design works as it was designed to. This project was a success based on acceptable performance of the system, and the fact that the PDS requirements were met. In addition, our sponsor has reviewed the final product and approved the entire system based on his own inspection of the prototype, and witnessing the operational testing of said prototype. A statement of approval from our project sponsor is provided in Appendix J.

Appendix A: Detailed Description of Design, Manufacturing, and Assembly

The braking system design is comprised of four distinct sub-units: the caliper assembly, the caliper activation assembly, the spring force assembly, and the secondary cable routing components. This appendix describes the individual systems initially, and then the combination of the systems into the final assembly.

Caliper Assembly

A completely mechanical brake caliper was selected for this project due to the reliability needed of a system which may remain stationary for many years, but yet be called upon to work without fail in the event of an emergency. The mechanical caliper selected was originally intended to be used as a transfer case brake for a Toyota pickup, and was purchased in the form shown in Figure A-1.

Figure A-1: Transfer case brake caliper as purchased.

The caliper functions by rotation of the activation lever about the activation pin. The activation pin rests in a pocket formed into the upper frame. The end of the activation lever has a cam profile that contacts the upper brake backing pad. The upper brake backing pad slides on the bushings when the activation lever is rotated which causes a compressive force to be exerted on the cable between the brake pads. The components described above are annotated in the exploded view shown on page A-2.

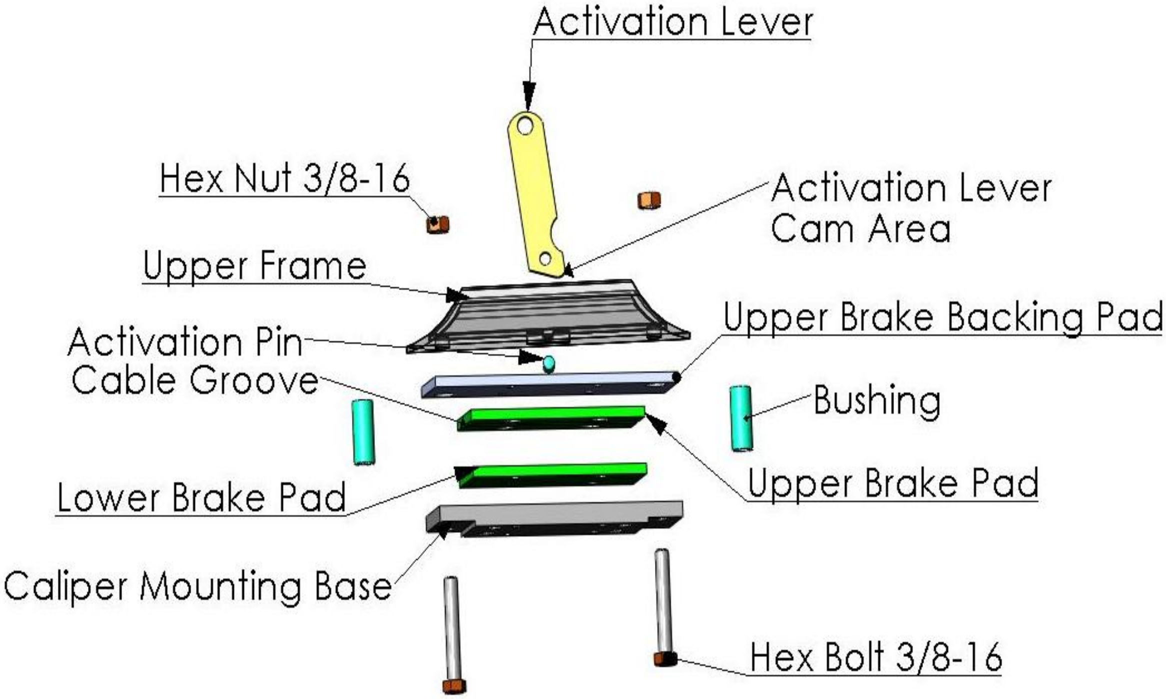


Figure A-2: Exploded view of modified brake caliper. The springs and brake pad retaining screws are not shown for clarity.

Modifications had to be made to the caliper to enable it to function as desired. These modifications involved discarding all original caliper parts except for the upper frame, activation lever, activation pin, bushings, and springs. New components were manufactured to complete the caliper assembly. A new caliper mounting base (bottom plate), drawing # 17, which provides for mounting of a new brake pad, and provides the ability to mount the caliper to the cart was designed. A new upper brake backing pad, drawing # 18, was designed to accept the new upper brake pad. Aluminum brake pads, drawing # 19, were designed to be used in this application. Aluminum was chosen for the brake pad material to provide a wear surface for the cable to run against during brake system operation, instead of secondary cable damage being caused by the use of a steel brake pad. A groove was machined into the brake pad to increase the contact surface area of the cable against the brake pad thereby reducing stress, as well as to provide a guided path for the cable to follow through the caliper. Each brake pad is attached to its respective backing pad with four ¼-20 flat-head Phillips screws. The ¼” screws were used in this application because all hardware was donated, and the ¼” flathead screw was the smallest screw available in the donated supplies. These screws act in shear in this application, and the shear strength of a single ¼” bolt is much greater than the load that could be applied by this system. Since four bolts are used per brake pad, no analysis was performed on these screws, and they were tightened to a torque value of 66 in-lbs per Appendix H.

The modified caliper was used to test the concept as described in Appendix C. No initial estimate of the force generated in the cable as it was being pulled through the closed caliper was available initially, and the prototype pads for testing were not originally going to be the brake pads used in the final assembly, so the bolt size to mount the caliper to the test fixture were intentionally oversized to eliminate the possibility of failure during testing. Due to time constraints, the initial test prototype lower backing pad for the caliper was used in the final assembly. The bolts used to mount the caliper to the cart, ½-13 x 1 ½” are significantly larger than those that would normally be required. The caliper was tested at forces on the activation lever 1.5 times those used in the final product without any sign of failure. Though analysis should have been performed on the caliper mounting bolts, none was performed due to time constraints, and the original lower backing plate with four ½”-13 mounting bolts was used in the prototype to mount the caliper to the cart. Tightening torque should have been analyzed as well, but standard bolt torque values from Appendix H for ½”-13 grade 2 non-lubricated bolts were

Figure A-3: Brake caliper mounting to the cart as viewed from the bottom.

used, and the caliper mounting bolts were tightened to a torque value of 50 ft-lbs. The grade 2 specification was used because the lower backing plate was constructed from mild steel bar stock. The caliper mounting holes in the cart frame were slotted slightly to allow the caliper cable groove to be lined up with the secondary cable during final assembly to prevent brake pad wear due to caliper misalignment. Figure A-3 shows the caliper as mounted to the cart from the bottom side.

The 3/8-16 x 3" bolts that hold the caliper together were also tested in the experiment performed, which was previously mentioned. These bolts were tightened to 30 ft-lbs per Appendix H. No analysis was done on these bolts for the same reasons given for the caliper mounting bolts.

Caliper Activation Assembly

The caliper activation assembly connects the pull cable to the cart, deactivates the caliper when the pull cable is tensioned, and allows for the brake to be manually released when pull cable tension is lost. The assembly shown in Figure A-4 is composed of four primary components: the brake lever pin, the bearing blocks, the E-brake handle (manual release handle), and the brake activation pivot arm.

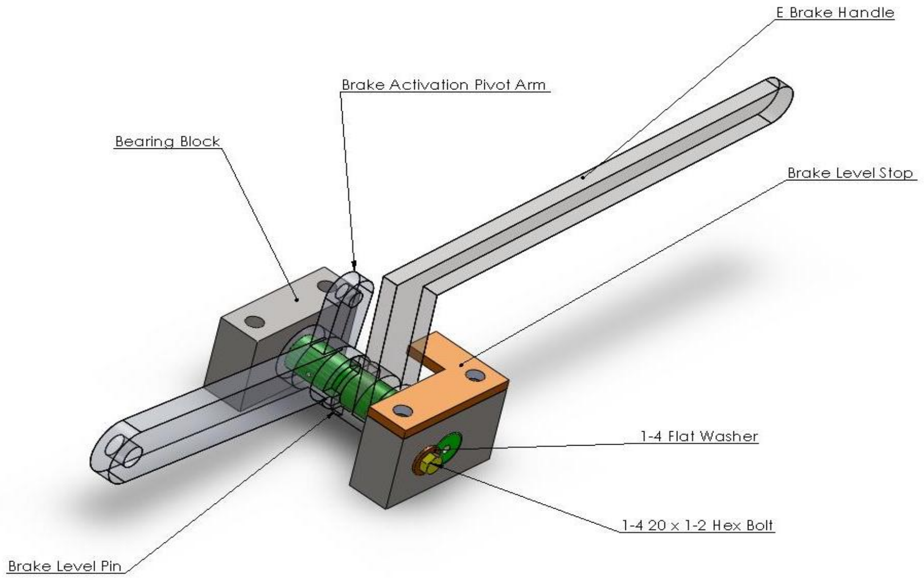


Figure A-4: Caliper Activation Assembly

The brake lever pin is a critical component which was engineered to have a 7/8 inch diameter to withstand the cyclical bending load that will occur on the steel cylinder during normal operation. The minimum tension in the pull cable during dynamic conditions was measured to be 40 lbs. This measurement was performed using a 200lb spring scale connected between the cart and the pull cable. It was noted during testing that the transient start-up load was approximately 3.5 times the steady state dynamic load. The bending on the shaft is caused by the pull cable load acting on the three inches of exposed shaft between the bearing block inside edges. The brake lever pin was sized to withstand the cyclical loading in the transient state.

The brake activation pivot arm and the E-brake handle work both independently and dependently on the brake lever pin. Both pieces rotate on the brake lever pin, and are contained laterally by the bearing blocks. Two sets of diametrically opposed caliper activation tabs as shown in Figure A-5, on both the brake activation pivot arm and the E-brake handle provide the ability of this system to function as required.

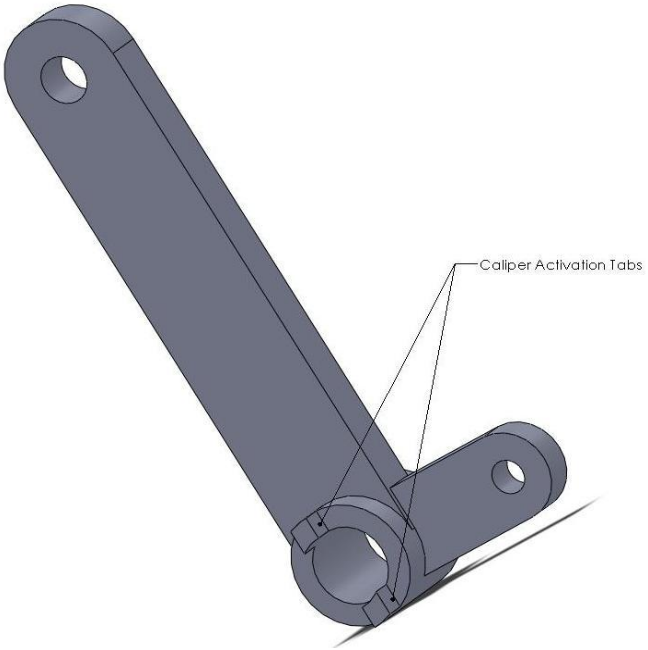


Figure A-5: Brake Activation Pivot Arm with diametrically opposed caliper activation tabs

These tabs allow the brake activation pivot arm to move independently of the e-brake handle based on pull cable tension, but also provided for the ability to release the caliper manually by pulling up on the E-brake handle through dependent engagement of the caliper activation tabs.

The brake activation pivot arm engages and disengages the caliper based on whether there is tension in the pull cable or not. The lever has two arms, one connects to the pull cable and the other connects to the caliper through the rod and ball joints (yet to be discussed). The brake activation pivot arm uses pull cable tension to overcome the pressure exerted on the caliper by the spring (yet to be discussed). Calculations indicated that an empty cart moving downhill would not provide adequate tension in the pull cable to overcome the spring force exerted on the brake activation pivot arm with a 1:1 arm length ratio. Due to the critical nature of this factor on the performance of the system the tension in the pull cable was measured. The minimum steady state force in the cable was found to be 40 lbs. The ratio of mechanical advantage needed was determined to be 3:1 to overcome the spring pressure when compressed to normal operating conditions. Therfore, the pull cable arm is three times longer than the caliper arm because this difference in length creates the 3:1 mechanical advantage required to ensure the pull cable will always have enough tension to keep the caliper open during normal operating conditions.

The E-brake handle was incorporated in this design to provide a manual means of overriding the automatic braking system. This ability was deemed necessary in the event a passenger was on the cart during an event that led to brake system activation. Through the use of the E-brake handle, an occupant of the cart can descend to the lower landing of the tramway in a controlled manner. The E-brake handle engages the caliper activation arm as previously described to make the controlled descent possible. A brake lever stop was provided to act as a rotation limiting device to maintain the rotational position of the E-brake handle in an aesthetically pleasing position while not in use.

The bearing blocks provide containment of the brake lever pin, caliper activation arm, and E-brake handle. These blocks also provide for mounting of the assembly to the cart frame. The brake lever pin is contained between the blocks by bolts with flat washer that protrude past the brake lever pin bores on the outside edges of the bearing blocks as shown in Figure A-4. The brake lever stop mounts to the top of the bearing block on the same side as the E-brake handle.

The brake lever pin was machined from steel bar stock. The raw bar stock was tightened in a three jaw chuck on an engine lathe. The tailstock end of the bar was center drilled, and a live center was mounted in the tailstock to prevent deflection of the shaft during the turning process. The shaft was turned to diameter in the lathe, the shaft was cut to length with a parting tool, and both ends were then chamfered with a 45° tool per drawing #24. To provide independent lubrication to the levers rotating on the shaft, both ends of the shaft were drilled and fitted with grease zerks. The #3 holes were drilled to depth using the lathe tailstock, and the holes were tapped to ¼-28 to accept grease zerk fittings. Radial holes were drilled through the shaft at two locations on the shaft, one under each lever, to provide a path for the grease from the zerk fittings to the moving components, as shown in Figure A-6.

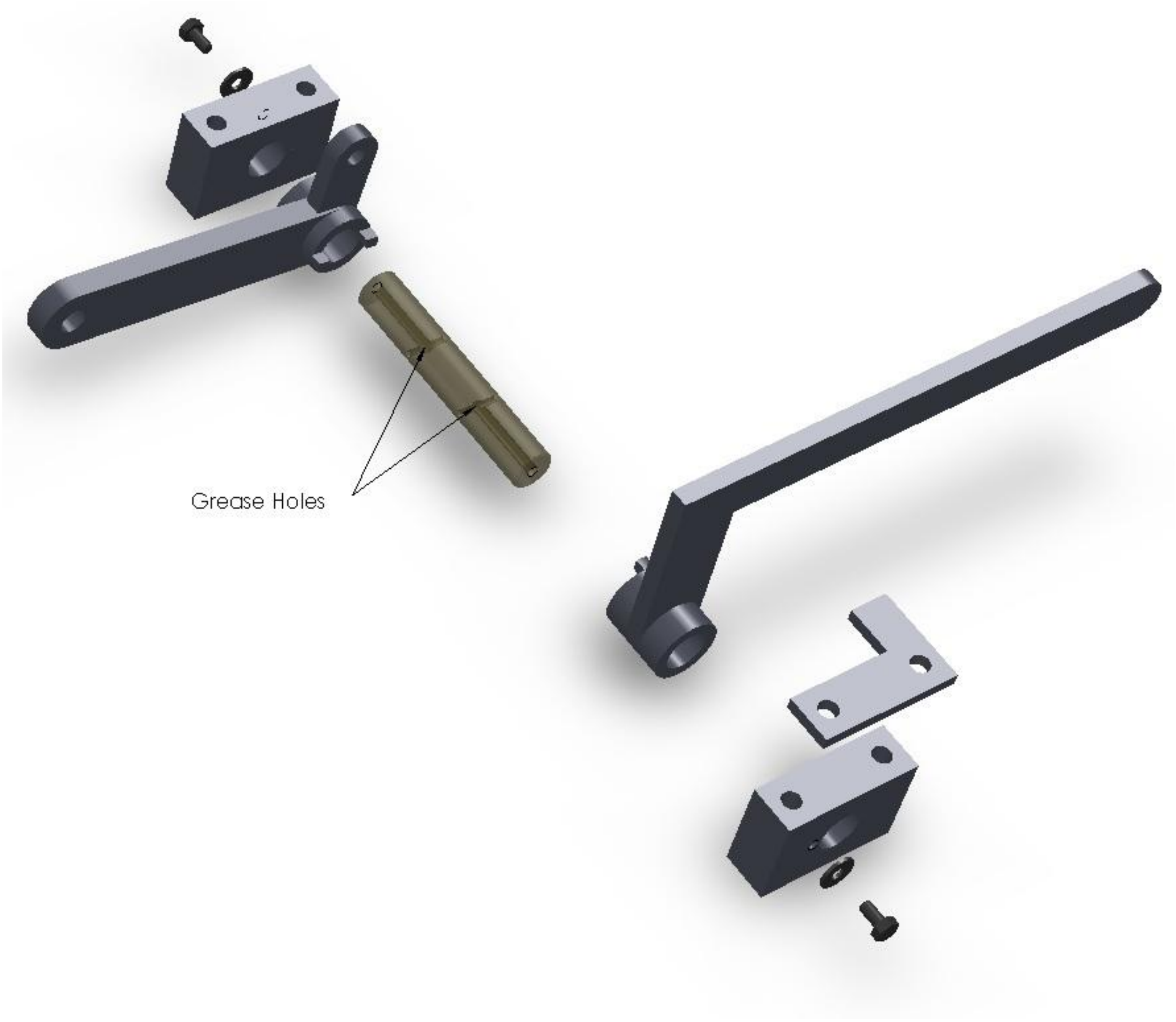


Figure A-6: Exploded view of caliper activation assembly, showing grease holes in pin

The radial holes were drilled through the shaft using a vertical mill.

The bearing blocks were machined from 3”x1.5” steel flat bar. Pieces slightly more the 2” long were cut from the bar stock. The blocks were squared in a vertical mill. Each block was placed in a vise on the mill. A 6” diameter, 10 insert face mill was installed in the mill spindle. The blocks were placed on parallels to allow the surface which needed to be cut to extend past the top of the vise. Since the flat bar was 1.5” thick, and the part only needed to be 1” thick, approximately 0.450” of material was removed from the side of each block. The blocks were de-burred, then rotated so that the previously cut side was against the stationary vise jaw. A round pin was placed between the clamping vise jaw and the block, and the vise was tightened. Material was removed from the block until cleanup of the surface was attained. The process of rotating the block was continued until the width and height dimensions were attained, with the clamping pin not being needed for the fourth surface. The blocks were then rotated, and squared to the mill table to allow the length dimension to be cut squarely to the block. The brake lever pin holes were center drilled, for hole location accuracy, drilled through, and reamed to size per drawing # 20. The ¼-20 holes for pin retention were center drilled, tap drilled with a #7 drill, the holes were chamfered for thread relief, and then tapped to ¼-20. The mounting holes were center drilled, and drilled through with a 25/64 drill.

The brake activation pivot arm is composed of three pieces, the pull cable bar, the caliper bar, and the center tube. The pull cable bar was made by cutting a piece of ½”x1.5” flat bar to length. The bar was milled to 1 3/8” wide. An adjustable milling cutter known as a criterion head was adjusted to cut a 1.375” diameter hole, and the end of the bar that mounts to the tube was cut with a profile to match that of the OD of the tube. The hole for the pull cable was drilled to 17/32” per drawing #12. The end of the bar was rounded using an 18” disc sander. The caliper arm was cut to length from 5/16” x 1” flat bar. The criterion head previously mentioned was used to generate the round profile on the tube end. The other end was rounded using the 18” disc sander. The arm was fitted with 3/8-24 threads to connect to the caliper rod. The tubular center section was made from 1 ¾” steel bar stock. The OD of the bar was turned to size, and the center was drilled within 0.05” of finished diameter. The bore diameter was finished with a small boring bar. The piece was cut to length using a parting tool. The diametrically opposed tabs were cut into the end of the part on a vertical mill with a ¾” endmill. The two arms were ground to fit the contour of the tube appropriately, glass beaded to remove surface impurities and metal scale, and were TIG welded to the tube by an expert welder.

The E-brake handle was manufactured in much the same manner as the brake activation pivot arm per drawing #11.

The brake lever stop was sawed from a section of ¼” x 2” Stainless Steel flat bar. A 3” length was cut using a horizontal band saw. The 25/64 diameter holes were drilled on the mill. The L-section was cut out on a vertical band saw. The part was finished using a vertical belt sander.

Spring Force Assembly

The spring mechanism shown in Figure A-7 was designed to ensure that the caliper will always be clamped down on the secondary cable when pull cable tension is lost. The spring mechanism consists of a spring mounted between two retaining washers. One of the washers is mounted on the cart frame, and the other is attached to a rod which connects through a clevis to the caliper activation lever. An experiment was conducted to determine the spring force needed to be applied to the caliper to provide the necessary force in the braking cable to stop the cart. According to the caliper experiment described in Appendix C, approximately 80 pounds of force is required to be applied to the caliper activation lever to compress the caliper on the cable with enough force to stop the fully loaded cart under any condition. A spring was selected that would supply this force, while still maintaining the required range of motion for the caliper lever to allow the system to operate properly.

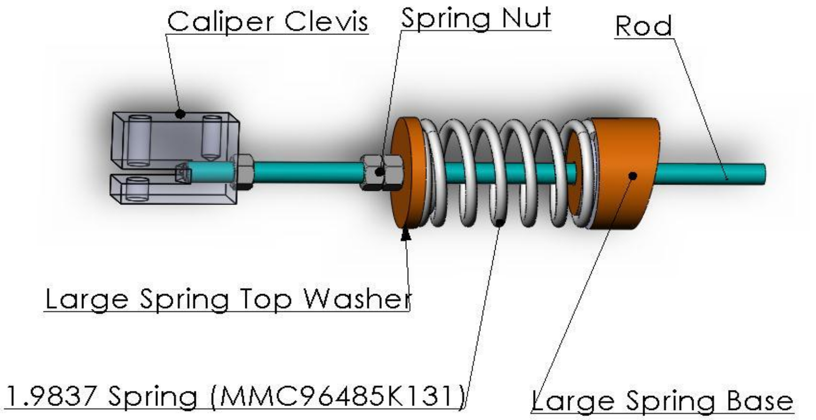


Figure A-7: Spring force assembly

The caliper clevis connects the spring force assembly to the caliper, and also provides a mounting location for the connecting rod that connects the caliper to the caliper activation assembly.

The spring washers were machined from 2 1/16” Stainless Steel bar stock. The top washer was turned to size in an engine lathe per drawing #14, and the center hole was drilled using a 7/16” drill in the tailstock. The washer was cut to length with a parting tool. The spring base OD, overall length, and center hole were cut in the same manner as the top washer, per drawing #?. The angled base was cut by placing the spring base into the mill vise at the appropriate angle, and facing the base to the appropriate overall length. The mounting holes were drilled and counter-bored with the spring base resting on the face previously milled to allow the hole to be perpendicular to the mounting surface.

The caliper clevis was cut from a piece of 2” square stock. The piece was cut to length in a horizontal band saw. The perimeter was milled to drawing #10 specifications in a vertical mill. The groove for attachment to the caliper was placed such that the caliper activation lever makes contact with the shank of the 3/8 bolt connecting the caliper activation lever to the caliper clevis. The bolt used, tightens into the clevis by running out of thread, thus leaving only the shank of the bolt exposed to the caliper activation lever, and preventing the clevis from collapsing when the bolt is tightened. The groove for the caliper activation lever was cut using a ¼” endmill, and the groove was cut in a manner which provides additional relief to allow for the large degree of angular travel that occurs between the caliper clevis and caliper activation arm. The mounting point for the spring assembly is in plane with the caliper activation assembly, and was drilled and tapped to 3/8-16 in the vertical mill. The hole for the caliper connecting rod was fitted with 3/8-24 threads, and the hole was made in the vertical mill.

Assembly of the components was performed after the caliper was installed. A relief was cut into the spring assembly side bearing block to allow for clearance of the threaded rod for the spring assembly. The spring base was secured to the spring base mount location on the cart using ¼-20 socket head cap screws torqued to 96 in-lbs per Appendix H standard torque specifications for dry grade 5 bolts. An 8.75” section of 3/8-16 threaded rod was cut and the spring, top washer, and (3) 3/8”-16 nuts were placed on the threaded rod. One end of the rod was placed through the spring base, and the other end was threaded into the caliper clevis. One

3/8 nut was used to jam nut the threaded rod to the caliper clevis. The other two nuts were left loose for final adjustment of the spring tension after cable installation.

Secondary Cable Routing

The braking system required the installation of a secondary cable. The chosen design fulfills a PDS requirement of securing the cart to the tramway by passing the cable through (2) structural members, one at each end, of the cart. The secondary cable, upper attachment point, upper cable clamps, secondary cable tensioning device, and lower attachment point were provided by the project sponsor. The design team was tasked with providing cable guides to guide the secondary cable through the cart, and a special cable clamp for the lower attachment point which did not require the cable to be bent into a loop.

The cable guides designed for this project served two purposes, to guide the cable through the structural members of the cart without exposing the cable to the sharp edges of the holes the cable passes through, and to keep the secondary cable lined up with the groove machined into the brake pads. For this project a guide was installed at both the upper and lower ends of the cart. A picture of the upper cable guide installed on the cart is shown in Figure A-8.

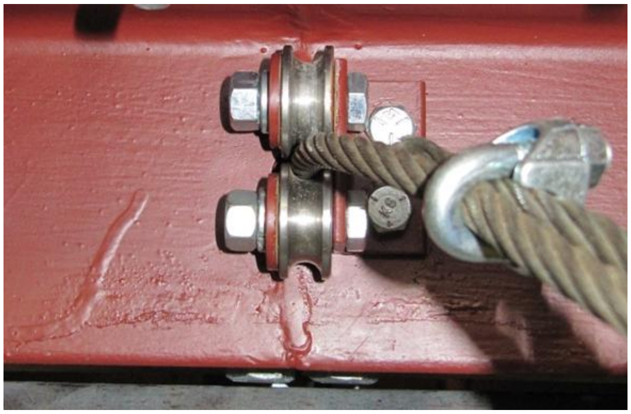


Figure A-8: Upper cable guide as installed on cart

Two stainless steel guide rollers per cable guide capture the cable. The guide rollers are fitted with brass bushings that spin on standoffs sandwiched between the mounting bracket and a special washer. The guide roller stand-off is machined slightly wider than the guide roller, and is clamped between the guide roller washer and the guide roller bracket. The stainless steel guide rollers should spin against the steel guide roller washer and the guide roller bracket without galling due to the difference in materials, and the use of lubrication.

The upper attachment point for the secondary cable was installed by the project sponsor. The turn-buckle for tensioning the secondary cable, and the upper attachment point are shown in Figure A-9.

Figure A-9: Secondary cable tensioning turn-buckle and pull cable as installed

To comply with the PDS requirement for ease of cart removal from the tramway, the design team created a special cable clamp, shown in Figure A-10, for the lower end of the secondary cable which does not require the cable to be bent around in a loop.

Figure A-10: Lower cable clamp and anchor as installed

The rationale behind not requiring a loop in the cable is that a straight cable end can easily pass through all system components to allow ease of cart removal from the tramway when required.

An exploded view of the cable guide assembly is shown below in Figure A-11.

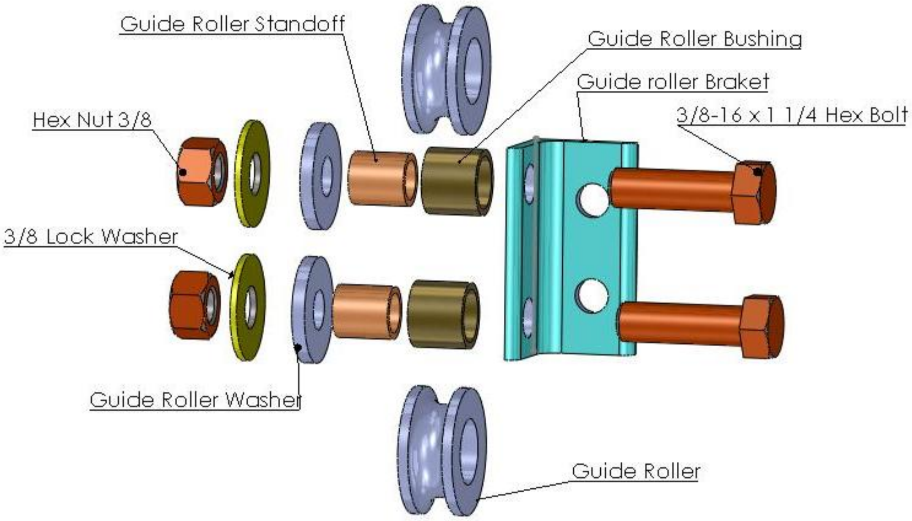


Figure A-11: Exploded view of cable guide assembly

The guide roller bracket was cut to length in the horizontal band saw from 1” angle iron. The holes were drilled in the mill to the sizes and locations provided on drawing # 22. The guide roller standoffs were turned from steel bar stock on an engine lathe. The OD was turned to diameter and the center hole was drilled per drawing # 7. The part was cut to length with a parting tool. The guide roller bushings were machined from brass bar stock on an engine lathe. The same process used to make the standoffs was also use to make the bushings, except the ID was turned to size with a small boring bar per drawing #23. The guide rollers were machined from stainless steel bar stock on an engine lathe per drawing # 15. The OD was turned, and the part was faced using a turning tool. The bore was drilled to 19/32, and finished with a small boring bar. The cable groove was cut with a specially ground radius tool. The full radius tool was plunged in to the part to the appropriate depth. The width of the part was cut with the part off tool. The guide roller washers were cut from 1.25” steel bar stock per drawing # 16 on an engine lathe. The OD was turned to print, the center hole was drilled using the tailstock, and the width was finished with the parting tool.

The cable guides were assembled using grade 5 hardware. The brass bushings were pressed into the guide rollers on an arbor press. A coating of grease was applied to the inside of the bushing, and the standoffs were slid inside the bushing. The 3/8" bolts were fitted into the guide roller brackets, the guide rollers with standoffs were slid on, the guide roller washers were installed, and the lock washers and nuts were installed. Both cable guides were mounted to the uphill sides of the respective structural members at the top at bottom ends of the cart, and the mounting bolts were torqued to 17 ft-lbs per Appendix H

The special lower cable clamp consists of two identical pieces bolted together with 3/8-16 bolts, as shown in Figure A-12.

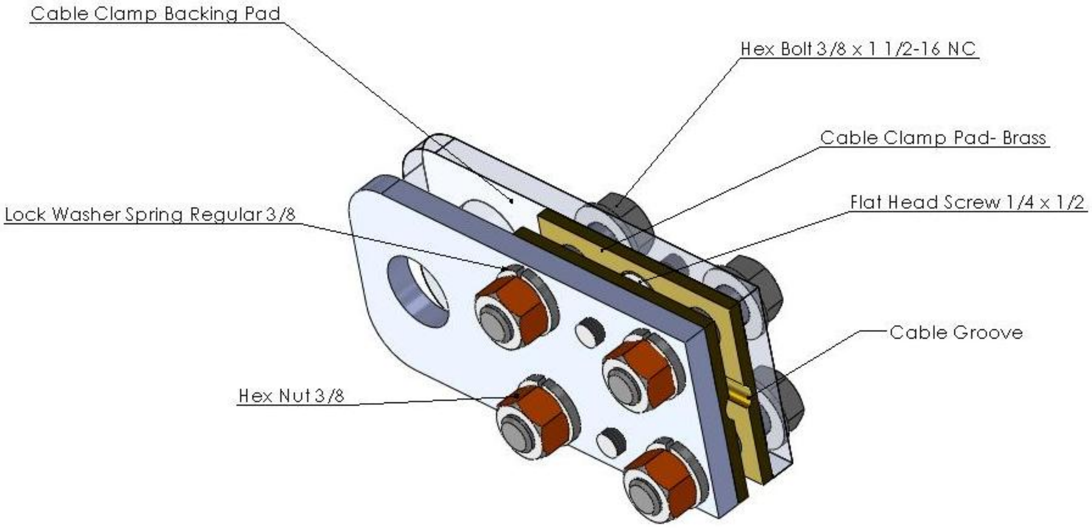


Figure A-12: Lower cable clamp with groove for straight cable clamping

The clamp functions in much the same manner as the caliper except instead of cam action compressing the brass pads onto the cable, bolts are used to obtain compression. No engineering analysis was done on this component. The concept was proven to be valid during the caliper experiment, and much greater compression is exerted by the bolts than by the caliper cam. In addition, the only force acting on this component is the secondary cable tension generated by the turnbuckle. The clamp will not see any load generated by the braking system. For these reasons, engineering analysis was not done on this component.

Since the clamp will reside in the lower well of the tramway, and could potentially be submersed in water, the cable clamp backing pads were made from ¼”x2” stainless steel bar stock, and the cable clamp pads were made from 1/8” brass sheet stock. The clamp backing pads were sawed to length in the horizontal band saw. The pad mounting holes, 3/8 bolt holes, and the ¾” mounting hole were created on the vertical mill per drawing #3. The cable clamp pads were machined in the same manner as the brake pads per drawing #2.

The pads were assembled to the backing plates using (2) ¼-20 x ½” flat head Phillips screws per pad, and the assembly was loosely assembled with the 3/8” hardware shown in the exploded view in Figure A-12.

Final Assembly

With the caliper assembly and spring force assemblies installed previously, the caliper activation assembly can be installed. Both ¼”-20 x ½” bolts and flat washers can be installed into the bearing blocks prior to mounting. First, the spring assembly side bearing block is installed. Mounting the first block is accomplished using (2) 3/8-16 hex head cap screws with flat washers on the topside, and lock washers & hex nuts on the bottom side. The brake lever pin, with grease zerks installed, is then slid into the bearing block. The brake activation pivot arm and E-brake handle can then be slid onto the brake lever pin, and the second bearing block can be installed. The brake lever stop is held in place by the mounting bolts for the second bearing block which also uses 3/8-16 bolts with flat washers on the top with lock washers and nuts on the bottom side. The four 3/8-16 bolts were tightened to 30 ft-lbs per Appendix H specifications for dry grade 5 bolts. Grease should be applied to both grease zerks on the ends of the brake activation pin until grease is visibly seen squirting out both ends of the respective lever. Significant pressure may need to be applied to the grease gun due to the tight fit of the levers on the shaft. This condition is normal.

Once the caliper activation assembly is installed, the connecting rod between the caliper assembly and the brake activation assembly can be installed. The ball joints are threaded onto each end of a 5 ½” long 3/8-24 threaded rod equipped with jam nuts. One ball joint is screwed into the small arm on the brake activation pivot arm, and the other is screwed into the caliper clevis, and both ball joint studs equipped with lock washers can then be tightened securely. The ball joint studs may need to be cut to length for proper fit prior to assembly. Figure A-13 provides a picture of the assembly as it should appear when properly installed.

Figure A-13: View of braking system properly installed.

With the cart mounted to the tramway, and the pull cable attached to the long side of the brake activation pivot arm, the secondary cable is threaded through the upper cable guide, the caliper, and the lower cable guide, and pulled through to the lower cable mount. The lower cable bracket is then installed on the cable, and the cable clamp bolts tightened to 30 ft-lbs per Appendix H. The lower clamp is then secured to the lower cable attachment eyebolt using suitable hardware. The secondary cable turnbuckle can then be tightened to tension the secondary cable. The secondary cable should be tensioned to the point at which it no longer sags onto the track when the cart is resting at the bottom landing.

The caliper can be aligned with the cable by making sure the caliper is compressed on the cable, loosening, and then re-tightening the caliper mounting bolts. This will ensure the brake pads do not wear during normal operation of the cart.

The spring in the spring assembly can be adjusted when there is no tension on the pull cable. The easiest way to accomplish a condition with no tension in the cable is to allow the car to rest in the lower well and operate the winch in a downward direction until the pull cable is slack. With no tension on the pull cable, the nuts on the threaded rod for the spring force assembly can be tightened into the upper washer until the spring is compressed to a length of 2”. The second nut can then be used as a jam nut against the first nut as shown in figure A-13.

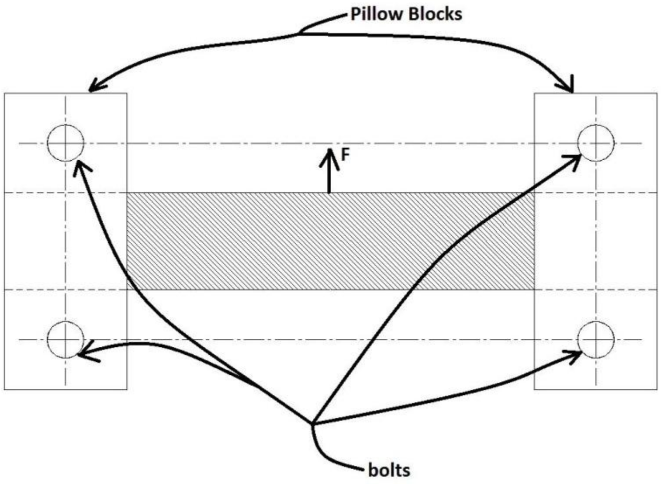
At this point the system is installed and ready for use.

Appendix B: Analysis

Pillow Block Bolts Failure Analysis

Summary Section

The objective of this analysis is to determine the diameter needed for the bolts holding the pillow blocks down to meet the required safety factor for all plausible modes of failure. The following figure shows the system configuration.



<u>The result of this analysis will be the minimum diameter of the pillow block bolts needed to satisfy the required safety factor. This analysis indicates that the bolts must be at least .223 inches in diameter to satisfy the minimum safety factor requirement.</u>

Formulation Section

Definition of Symbols:

d = diameter of the individual bolts
τ_Y = yield strength
F= maximum pull force imparted on the shaft
SF = Safety Factor

Given:

τ_Y = 16000 psi
SF = 2
F= 1250 lbs.

Find:

Required diameter of the bolts

Assumptions:

The forces and number of loading cycles will be low enough that fatigue can be neglected. Because of the symmetry of the system bending stress can also be neglected.

Solution:

Shear failure will require the largest diameter.

$$\tau = \frac{F}{A} = \frac{F}{4(.25\pi d^2)} = \frac{1250}{\pi d^2} = \frac{397.89}{d^2}$$

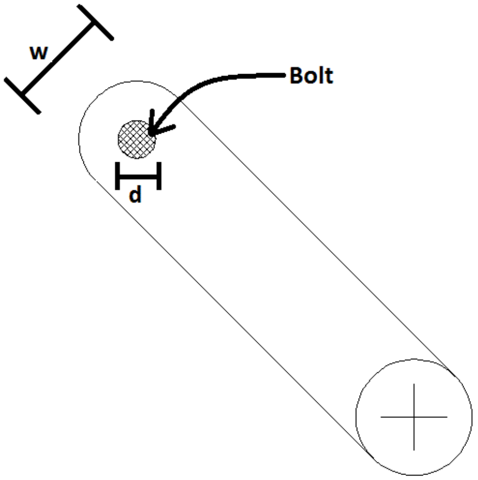
$$d = \sqrt{\frac{397.89 * SF}{\tau_y}} = \sqrt{\frac{397.89 * 2}{16000}}$$

$$\boxed{d = 0.223 \text{ in}}$$

Caliper Activation Lever Failure Analysis

Summary Section

The objective of this analysis is to determine the sizes of both the caliper activation lever and the pull cable bolt necessary to prevent failure with a safety factor of 2 as required by the PDS. The arm is to be made from 3/8 inch thick steel plate. The bolt is to be galvanized steel. The following drawing shows the basic system configuration.



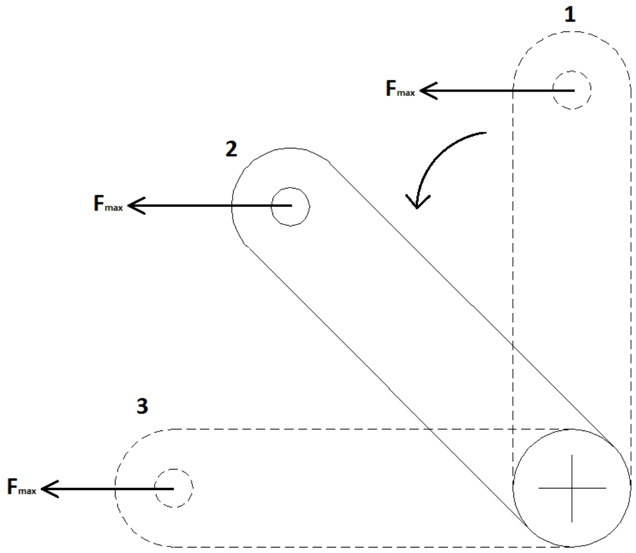
The result of this analysis will be the minimum dimensions of the lever and the minimum diameter of the bolt to satisfy the required safety factor. This analysis indicates that the bolt must be at least 0.315 inches in diameter and the lever must be at least .523 inches wide if it is to be .375 inches thick.

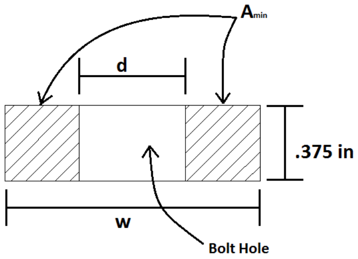
Evaluation

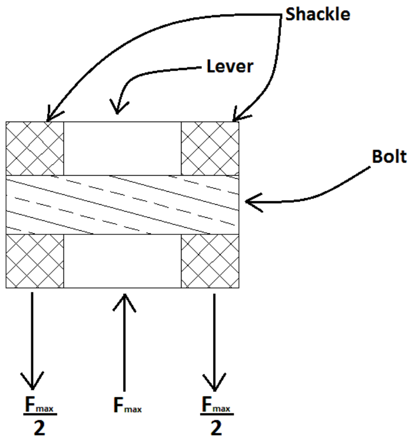
This analysis returns the bare minimum value for the bolt diameter and lever width. Because there is no realistically important weight limit for this system the final parts could be machined to be much more substantial.

Formulation Section

Schematics:







Definition of Symbols:

A_{min} = minimum cross sectional area
w = width of the lever
d = diameter of the bolt
S_y = yield strength
F_{max}= maximum pull force imparted by the cable on the lever
T_L = thickness of the lever
SF = Safety Factor
$A_{min,B}$ = minimum bearing area
$A_{min,S}$ = minimum cross sectional area for shear loading
σ_B =Bearing Stress
σ_T =Stress due to tension
τ_B = Shear Stress in the bolt
τ_Y = Yeild stress in shear
$d_{min,B}$ =minimum bolt diameter for bearing load
$d_{min,S =}$ minimum bolt diameter for shear load

Given:

S_Y = 32000 psi
T_L = 0.375”
SF = 2
F_{max}= 1250 lbs.

Find:

Required width of lever, required diameter of bolt

Assumptions:

Stress is minimal in the lever except when it is loaded axially. Failure of the lever in tension will occur at the maximum width of the bolt hole where cross sectional area is smallest. This device will be subjected to so few load/unload cycles that fatigue failure can be neglected.

Solution:

Failure of the bolt due to bearing stress:

$$\sigma_B = \left(\frac{F_{max}}{A_{min\,,B}}\right) = \frac{S_y}{SF}$$

$$A_{min\,,B} = T_L * d_{min\,,B} = .375 d_{min\,,B}$$

$$A_{min\,,B} = \left(\frac{F_{max} \ * SF}{S_y}\right) = \left(\frac{1250 * 2}{32000}\right) = .078\ in^2$$

$$d_{min\,,B} = \frac{A_{min\,,B}}{.375} = \frac{.078}{.375}$$

$$\boxed{d_{min\,,B} = 0.208\ in}$$

Failure of the bolt due to shear stress:

$$\tau_B = \left(\frac{.5 * F_{max}}{A_{min,S}}\right) = \frac{\tau_y}{SF}$$

$$\tau_y \approx \frac{S_y}{2} = \frac{32000}{2} = 16000$$

$$A_{min,S} = \left(\frac{F_{max} * SF}{\tau_y}\right) = \left(\frac{.5 * 1250 * 2}{16000}\right) = 0.078 \text{ in}^2$$

$$d_{min,S} = \sqrt{\frac{A_{min,S} * 4}{\pi}} = \sqrt{\frac{0.078 * 4}{\pi}}$$

$$\boxed{d_{min,S} = 0.315\ in}$$

Failure of the lever in tension:

$$A_{min} = .375(w - d)$$

$$\sigma_T = \left(\frac{F_{max}}{A_{min}}\right) = \frac{S_y}{SF}$$

$$A_{min} = \left(\frac{F_{max} * SF}{S_y}\right)$$

$$.375(w - d) = \left(\frac{1250 * 2}{32000}\right)$$

$$(w - d) = \frac{\left(\frac{1250 * 2}{32000}\right)}{.375} = .208 \text{ in}$$

$$d = d_{min,S} = .315 \text{ in}$$

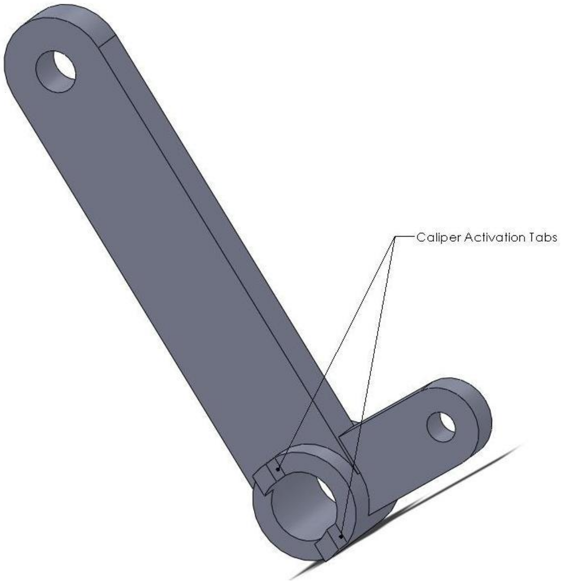
$$w = .315 + .208$$

$$\boxed{w = 0.523 \text{ in}}$$

Caliper Activation Tabs Failure Analysis

Summary Section

The objective of this analysis is to determine the minimum area needed to satisfy the minimum safety factor requirement specified in the PDS. The tabs will be steel and made by removing material from the end of a 1 inch tube section. Two tabs will be machined into the tube; they will have opposite sides parallel and have equal area.



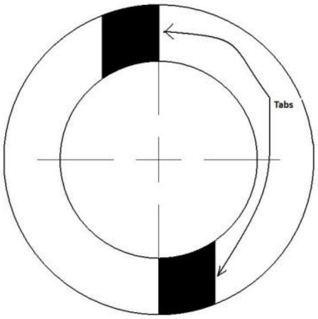
The result of this analysis will be the minimum area of the activation lever tabs to satisfy the required safety factor. This analysis indicates that the tabs must be at least 0.011 square inches in area.

Evaluation

This analysis returns the minimum value for the tab's cross sectional area. This area is so small that machining these tabs to this size would be much more difficult than making the tabs larger.

Formulation Section

Schematics:



Definition of Symbols:
A = cross sectional area
F_1= Force imparted by the rod on the lever
F_2= Force needed on the tab to release the caliper
SF = Safety Factor
τ = Shear stress in the tab
τ_Y = Yield stress in shear

Given:
τ_Y = 16000 psi
SF = 2
F_1= 100 lbs
D=2 in
d= 1.125 in

Find:
Minimum area of tab to satisfy safety factor of 2

Assumptions:
The load on the tabs can be is uniform enough that it can be condensed to a point load. The tabs are not tall enough to fail due to bending stress. Shear is the only mode of failure that warrants consideration.

Solution:

$$\tau = F_2(SF)A$$

$$A = \frac{F_2(SF)}{\tau}$$

$$F_1D = 2F_2d$$

$$F_2 = \frac{F_1D}{2d} = \frac{(100)(2)}{(2)(1.125)}$$

$$F_2 = 88.89\ lb$$

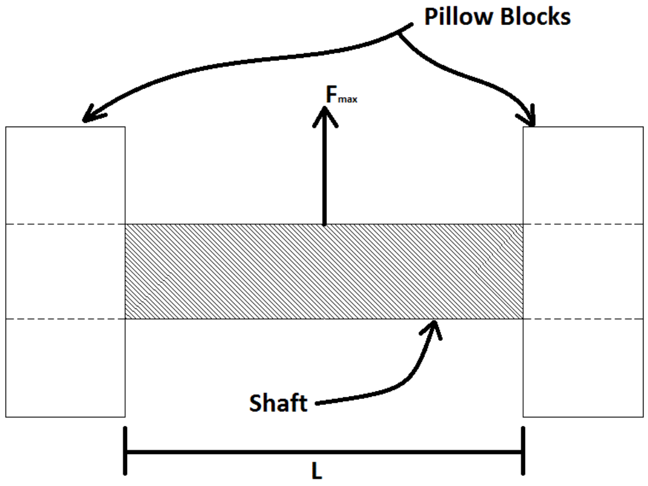
$$A = \frac{F_2 * SF}{\tau} = \frac{(88.89 * 2)}{16000}$$

$$\boxed{A = .011\ in^2}$$

Caliper Activation Shaft Failure Analysis

Summary Section

The objective of this analysis is to determine the size of the caliper activation shaft necessary to prevent failure with a safety factor of 2 as required by the PDS. The shaft is to be machined from steel. The following drawing shows the basic system configuration.



The result of this analysis will be the minimum diameter of the shaft required to satisfy the required safety factor. This analysis determined that the required minimum diameter of the shaft is 0.842 inches.

Evaluation

This analysis returns the bare minimum value for the shaft diameter. Because there is no realistically important weight limit for this system the final parts could be machined to be much more substantial, thus increasing the actual safety factor.

Formulation Section

Definition of Symbols:

S_y = yield strength
F_{max}= maximum pull force imparted by the cable on the shaft
SF = Safety Factor
σ_B =Bending Stress
τ_{max} = Maximum shear stress
d_B = minimum bolt diameter for bending load
d_S = minimum bolt diameter for shear load
$d_{Req.}$ =required minimum shaft diameter
A_s= Cross-sectional area of the shaft
R_A ,R_B = Reaction forces

Given:

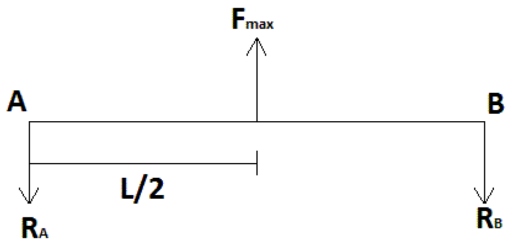
S_Y = 32000 psi
L = 3 in.
SF = 2

F_{max} = 1250 lbs.

Find:
d_{Req}

Assumptions:
No thrust loading occurs. Shaft can be modeled as a round beam with cantilevered ends. Fatigue failure can be neglected due to the very small number of loading cycles the shaft will experience over its lifetime.

Free Body Diagram:



Solution:

$$\Sigma F = 0 = F_{max} - R_A - R_B$$

$$F_{max} = R_A + R_B$$

$$\Sigma \mathrm{M_A} = 0 = \left(\frac{L * F_{max}}{2}\right) - (L * R_B)$$

$$R_B = \frac{\left(\frac{L * F_{max}}{2}\right)}{L} = \frac{\left(\frac{3 * 1250}{2}\right)}{3}$$

$$R_B = 625 \text{ lb}$$

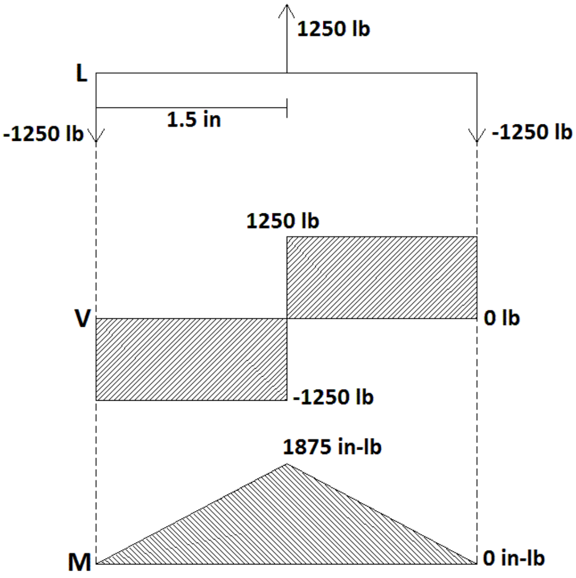
$$R_A = 1250 - 625$$

$$\mathrm{R_A} = 625 \text{ lb}$$

Multiplying the three forces determined to this point by the required safety factor give the forces that will be used for the rest of the analysis:

$$F_{max} = 2500\ lb, R_A = 1250\ lb,\ R_B = 1250\ lb$$

Loading, Shear, and Bending Diagram:



$$V_{max} = 1250\ lb$$

$$M_{max} = 1875\ in \cdot lb$$

$$\tau_{max} = \frac{4V_{max}}{3A_s} = \frac{4 * 1250}{3 * .25\pi {d_S}^2} = \frac{2122.1}{{d_S}^2}$$

$$d_S = \sqrt{\frac{2122.1}{S_y}} = \sqrt{\frac{2122.1}{32000}}$$

$$d_S = 0.258 \text{ in}$$

$$\sigma_B = \frac{My}{I} = \frac{32M}{\pi d^3} = \frac{32(1875)}{\pi {d_B}^3} = \frac{19099}{{d_B}^3}$$

$$d_B = \sqrt[3]{\frac{19099}{S_y}} = \sqrt[3]{\frac{19099}{32000}}$$

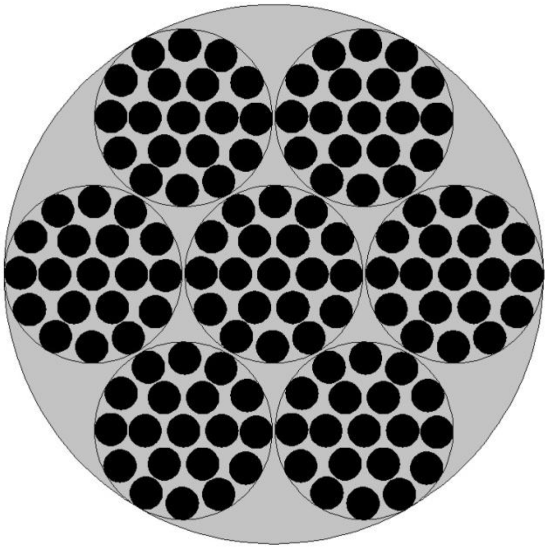
$$d_B = 0.842 \text{ in}$$

$$\boxed{d_B > d_S \therefore\ d_{Req.} = d_B = 0.842 \text{ in}}$$

Brake Cable Failure Analysis

Summary Section

The objective of this analysis is to determine if the brake cable that was donated by the sponsor will be strong enough to satisfy the minimum safety factor requirement in the PDS. The cable is steel and has a standard 7x19 winding pattern; nominally it is 7/16" in diameter. The following drawing represents a cross sectional view of the cable. The black areas are the actual steel strands while the gray areas represent the open space in the cable.



<u>The result of this analysis will be a determination of the adequacy of the donated brake cable to satisfy the required safety factor. This analysis determined that the cable has an actual safety factor of 4.18 which is greater than the required safety factor of 2.</u>

Evaluation

According to this evaluation the cable will satisfy the minimum safety factor requirement in the PDS.

Formulation Section

Definition of Symbols:

S_y = yield strength

F_{max}= maximum pull force imparted by the cart on the cable

SF_C = Safety Factor of the cable

σ =Stress in the cable

A_C= Estimated cross-sectional area of the cable

Given:

S_Y = 32000 psi

F_{max} = 390 lbs.

Cable is steel with a standard 7x19 winding pattern

Strand diameter is .022 inches

Find:
Actual safety factor of cable

Assumptions:
The cross sectional area of the cable can be approximated by summing the cross sectional areas of the strands that comprise the cable.

Solution:
Approximate cross-sectional area of the cable:

The cable is made up of 7 bundles with 19 strands per bundle. The approximate area can be calculated as follows:

$$A_C = Strand\ area * \#of\ bundles * \#\ of\ strands\ per\ bundle$$

$$A_C = .25\pi(.022^2)(7)(19)$$

$$A_C = .051\ \mathrm{in}^2$$

This approximate area can then be used to find the actual safety factor of the cable.

$$\sigma = \frac{F_{max}}{A_C} = \frac{390}{.051} = 7647.1\ \mathrm{psi}$$

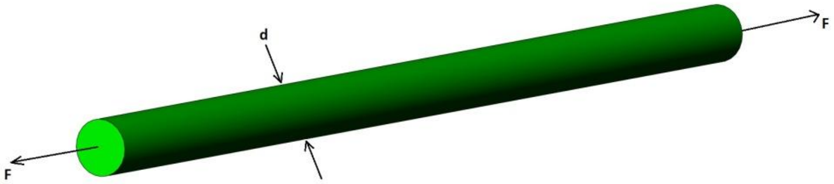
$$SF_C = \frac{S_y}{\sigma} = \frac{32000}{7647.1}$$

$$\boxed{SF_C = 4.18}$$

Connecting Rod Failure Analysis

Summary Section

The objective of this analysis is to determine the diameter needed to make the connecting rod meet the required minimum safety factor for all reasonably plausible modes of failure. The rod that will be used is threaded steel. The following drawing shows the system.



The result of this analysis will be the minimum diameter of the connecting rod to satisfy the required safety factor. This analysis indicates that the rod must be at least 0.089 inches in diameter.

Formulation Section

Definition of Symbols:

d = diameter of the bolt
S_y = yield strength
F= maximum pull force imparted on the rod
SF = Safety Factor

Given:

S_Y = 32000 psi
SF = 2
F= 100 lbs.

Find:

Required diameter of the rod

Assumptions:

The forces and number of loading cycles will be low enough that fatigue can be neglected. It can also be assumed that buckling can be neglected.

Solution:

$$\sigma = \frac{F}{A} = \frac{F}{.25\pi d^2} = \frac{100}{.25\pi d^2} = \frac{127.324}{d^2}$$

$$d = \sqrt{\frac{127.324 * SF}{S_y}} = \sqrt{\frac{127.324 * 2}{32000}}$$

$d = 0.089$ in

Force applied to braking cable versus time to stop tram cart

Summary Section

The goal of this analysis is to provide the stopping force needed to be generated in the secondary brake cable by the brake caliper to stop the motion of the cart over a change in time. This analysis is needed to determine the average acceleration of the tram cart versus the tension created in the braking cable.

The results of this analysis will be used in combination with Appendix C to determine the input force needed to be applied to the brake caliper versus the force required to be applied to the brake cable by the caliper to keep stopping acceleration of the cart within acceptable limits.

The results will be expressed in graphical form with force in lbs corresponding to elapsed time in seconds.

Evaluation Section

The graphical results shown in Figure B-2 indicate that a minimum force of approximately 354 lb_f tension is required to be applied to the cable to stop the cart when the cart is fully loaded. This minimum is noted by the flattening of the slope of the the graph in Figure B-2. The force value of 354 lb_f needed to stop the fully loaded cart will most likely exceed the PDS allowable stopping acceleration when the tram cart is partially loaded. Mitigating factors for this issue may exist since the time for the cart to reach final velocity on empty startup is much less than when fully loaded, thereby increasing the possible acceleration value that can be used for the braking system when the cart has a load that is less than full capacity. Additional design review sessions with the product sponsor determined this is acceptable.

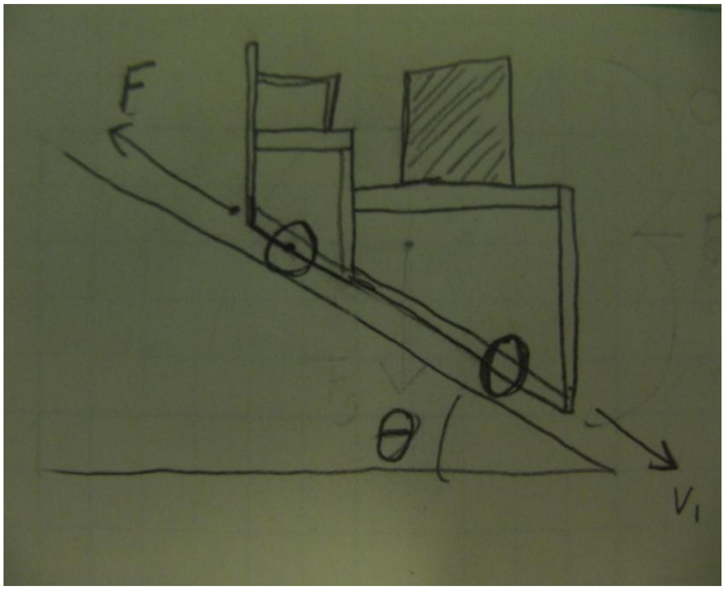
This analysis uses the principles of impulse and momentum. The analysis assumes that stopping of the tram cart occurs in a short enough period of time, and large enough changes in momentum occur that the forces involved can be called impulsive forces. The result also assumes the starting acceleration is 2 ft/sec by assuming the cart is at its final velocity of 1 ft/sec in 0.5 seconds as attempted to be measured with a stop watch.

Formulation Section

Given:

1. Initial velocity = v_1 = 1 ft/sec
2. Final velocity = v_2 = 0 ft/sec
3. W = weight of fully loaded cart (600 lbs cargo + 180 lb cart) = 780 lbs
4. Angle of departure from horizontal for tramway is Θ =26 degrees

Schematic:



Find:

Graphical result for force in braking cable versus time required to stop tram cart from initial velocity v_1 to final velocity 0 ft/sec.

Assumptions:

1. Stopping the tram cart occurs in a short period of time and large enough changes in momentum occur to be called an impulsive force. (Assumption required for use of this method)

Solution:

Applying the principles of impulse and momentum, the following equation can be used to solve for force in the braking cable, F, as a function of change in time, t.

$$mv_1 + \sum F\Delta t = mv_2 \qquad (0.1)$$

where:

m = mass of moving cart

v_1 = initial velocity

$\sum F\Delta t$ = sum of forces acting on cart multiplied by change in time

v_2 = final velocity

Equation (1.1) is displayed graphically in Figure B-1. The initial momentum is shown being added to the applied forces consisting of the force due to cable tension and the vector component of force due to gravity multiplied by time. The result is zero because the final velocity is zero.

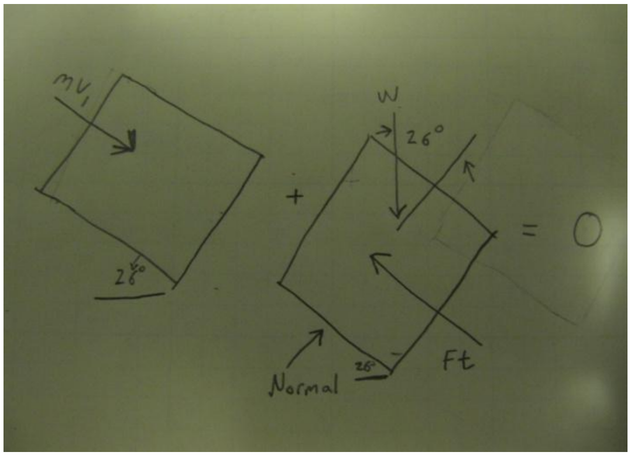


Figure B-1: Graphical representation of Equation (1.1)

For the purposes of this analysis, $t_1 = 0$, therefore $t = \Delta t = t_2$ = elapsed time of application of brakes to attain zero velocity.

Since each force is constant in magnitude and direction, the corresponding impulse is equal to the product of the force and time interval t.

The components of $\sum F\Delta t$ are given by the vector component of the gravitational force exerted on the cart multiplied by t, and the opposing braking cable tension generated over time t.

The components of $\sum F\Delta t$, assuming tension in the cable is negative force and downward momentum and gravitation forces are positive are given by

Gravitational force: (W * sin (26°)) * t

Stopping force in cable: -F*t

giving

$mv_1 + (W * \sin(26°)) * t - F*t = mv_2$

when the components are substituted for $\sum F\Delta t$ in Equation (1.1)

Substituting values for weight, mass, & velocity, into Equation (1.1) and solving for F as a function of t for gives

$$\left[F = 780\,lb * \sin(26°) + \frac{24.2\,lb \cdot \sec}{t}\right]$$

Figure B-2 is the graphical representation of tension in the cable versus time required to stop the tram cart with a 600 lb cargo.

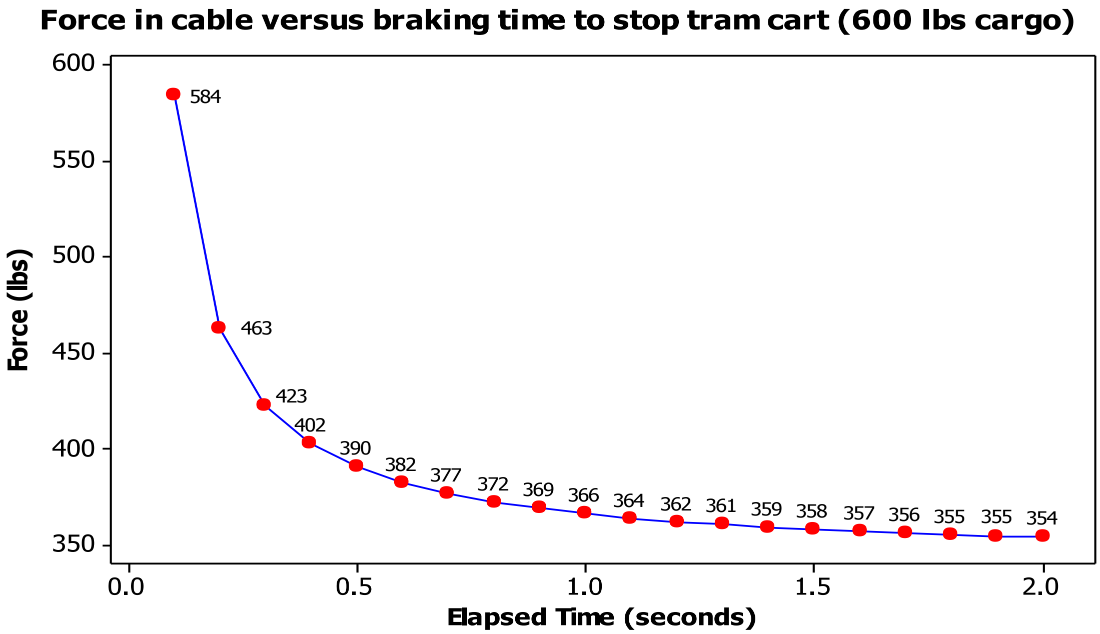


Figure B-2: Results of analysis with 600 lb cargo load on cart.

References:

[1]: Ferdinand P. Beer, E. Russell Johnston, Jr., William E. Clausen, Vector Mechanics for Engineers, Dynamics, 8th Edition, McGraw Hill, 2007, pp. 805-809

Appendix C: Experiments

Caliper Force Evaluation Experiment

Background:

The brake caliper, shown in Figure 1, purchased by the design team did not have any specifications available that provided information relating clamping force to input force. In order to fully arrest the loaded cart a minimum force of 355 pounds must be applied to the secondary cable by the caliper. This force will be generated by friction between the brake pads and the static brake cable. Because there was no information provided with the caliper, it was necessary to determine force needed to be applied to the caliper activation lever to produce a frictional force at least equal to the minimum force needed to arrest the cart's motion.

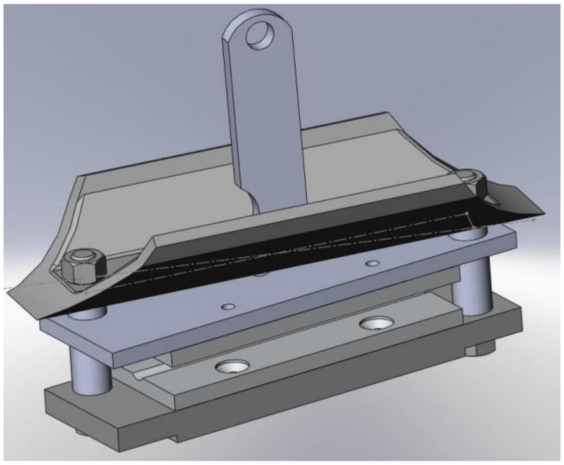


Figure C-1: The Brake Caliper

Apparatus:

The test apparatus for this experiment consisted of a hydraulic cylinder with a pressure gauge that was connected inline between a section of the brake cable and a mechanical hoist. The cylinder assembly is shown in Figure 2. The ID of the cylinder measured 1.570", and the OD of the shaft measured 0.786". The area of the annular ring inside the cylinder exposed to vertical force is 1.46 in^2. A correction factor of 1.46 is multiplied by the reading on the force gauge to obtain the actual force exerted on the cable. The force gauge made by Verson, with 50 lb increments, is shown in Figure 3. The caliper was securely mounted to a heavy piece of machinery in a vertical orientation as shown in Figure 4, and the brake cable section was run through it. A spring scale was connected to the caliper activation lever to allow measurement of the input force to the caliper.

Figure C-2: The Hydraulic Cylinder

Figure C-3: The Pressure Gauge

Figure C-4: The Caliper

Theory:

The spring scale will indicate the force applied to the caliper activation lever. The gauge on the cylinder will indicate the force on the cable as it is pulled though the caliper. Once the cable begins to move through the caliper the force can be read off the gauge. The value read from the gauge is multiplied by 1.46 to obtain the actual force in the cable. This is the total force that would be applied to the cart under normal conditions. Several tests will provide data to determine the average minimum force that needs to be applied to the caliper lever to produce the frictional force needed to stop the cart.

Data:

Three tests were done over a range of caliper input force values. The first two tests were done with a dry cable. The third test was conducted with a greased cable to simulate a worst case scenario. Table C-1 shows the corrected force values which account for the difference in area between the cylinders bore diameter and the ram diameter. This correction factor was determined to be 1.46, as previously outlined.

Table C-1: Corrected values of force in cable versus input force to caliper in lbs.

Caliper Lever Force	Non-Greased Cable		Greased Cable
	Trial 1	Trial 2	Trial 3
20	255.5	233.6	219
40	379.6	365	255.5
60	452.6	496.4	306.6
80	547.5	584	365
100	620.5	671.6	438
110			474.5

Results:

The third test shows that even in a absolute worst case scenario where the brake cable is coated in lubricant a force of 80 pounds applied to the caliper lever should be sufficient to produce a suitable force in the secondary by the caliper to stop the tram cart. Under normal conditions as simulated by trials one and two 80 pounds would be more than adequate to produce the types of forces required to stop the cart per analysis shown in Appendix B. This experiment also gave some insight to the durability of the aluminum brake pads used in the caliper. More than 3 feet of dry brake cable were pulled through the caliper with 110 lbs input force on the caliper activation lever, with the caliper under high clamping forces. Afterwards the cable was partially covered in aluminum dust but measurements of the brake pads showed that the material removed amounted to a layer less than 0.001 inches thick. This information validates that aluminum would be a suitable material to use for the brake pads in the final system, and that brake pad wear due to using the braking system to return the cart to the lower landing would not compromise the braking system during a one time use scenario.

Appendix D: Bill of Materials

Part Name/ Part Number	Quantity	Material	Make (M)/ Buy (B)	Drawing Number/ Source	Cost	Total
Hand Brake Assembly	1					
Bearing Block	2	Steel	M	20	Donated	Donated
Brake Activation Pivot Arm	1	Steel	M	12	Donated	Donated
Brake Lever Pin	1	Steel	M	24	Donated	Donated
Brake Lever Stop	1	Steel	M	21	Donated	Donated
E-Brake Handle	1	Steel	M	11	Donated	Donated
1/4"- 20 x 1/2" Hex Head Cap Screw Gr.5	2	Steel	B	N/A	Donated	Donated
1/4" Flat Washer	2	Steel	B	N/A	Donated	Donated
3/8" -16 x 3.5 Head Head Cap Screw Gr.5	4	Steel	B	N/A	Donated	Donated
3/8" Flat Washer	4	Steel	B	N/A	Donated	Donated
3/8 Spring Type Lock Washer	4	Steel	B	N/A	Donated	Donated
3/8-16 Hex Nut	4	Steel	B	N/A	Donated	Donated
1/4"- 28 Grease Zerk	2	Steel	B	N/A	Donated	Donated
Cable Clamp Assembly	1					
Cable Clamp Backing Pad	2	Stainless Steel	M	3	Donated	Donated
Cable Clamp Pad	2	Brass	M	2	Donated	Donated
Hex Bolt 3/8"-16 x 1 1/2"	4	Steel	B	N/A	Donated	Donated
Hex Nut 3/8" - 16	4	Steel	B	N/A	Donated	Donated
3/8" Flat Washer	4	Steel	B	N/A	Donated	Donated
3/8" Lock Washer Spring Type	4	Steel	B	N/A	Donated	Donated
Flat Head Screw 1/4 x 1/2	2	Steel	B	N/A	Donated	Donated
Parking Brake Caliper 5206- AP- 10024	1	Steel	B	All-Pro Off Road, Inc	$89.00	$89.00
Spacer 1/2"	1	Steel	M	8	Donated	Donated
Lower Backing Pad	1	Steel	M	17	Donated	Donated
Brake Pad Backing Plate	2	Steel	M	18	Donated	Donated
Brake Pad	2	Aluminum	M	19	Donated	Donated
1/4"- 20 x 3/4" Flat Head Phillips Screw	4	Steel	B	N/A	Donated	Donated
1/4"-20 x 1/2" Flat Head Phillips Screw	4	Steel	B	N/A	Donated	Donated
3/8"-16 x 2.5" Hex Head Cap Screw Gr.5	2	Steel	B	N/A	Donated	Donated
3/8" - 16 Hex Nut	2	Steel	B	N/A	Donated	Donated
3/8" Flat Washer	2	Steel	B	N/A	Donated	Donated
3/8 Flat Washer 0.562" OD	6	Stainless Steel	B	N/A	Donated	Donated
Spring Assembly	1					
Large Spring Base	1	Stainless Steel	M	1	Donated	Donated
Large Spring Top Washer	1	Stainless Steel	M	14	Donated	Donated
3/8" -16 x 8.75" Threaded Rod	1	Steel	M	N/A	Donated	Donated
Square Caliper Clevis	1	Steel	M	10	Donated	Donated
Spring MMC#96485K131	1	Steel	B	McMASTER-CARR.com	$8.40	$8.40
3/8" - 16 Hex Nut	3	Steel	B	N/A	Donated	Donated
3/8"- 16 x 1.75" Hex Head Cap Screw Gr.5	1	Steel	B	N/A	Donated	Donated
1/4" -20 x 1.5" Socket Head Cap Screw	2	Steel	B	N/A	Donated	Donated
Conneting Rod	1					
Self-Lube Bronze Race Ball Joint Rod End	2	Various	B	McMASTER-CARR	$7.03	$14.06
3/8 " - 24 x 5.5 " Threaded Rod	1	Steel	B	N/A	$2.46	$2.46
3/8" - 24 Hex Nut	2	Steel	B	N/A	Donated	Donated
3/8" Flat Washer Spring Type	2	Steel	B	N/A	Donated	Donated
Cable Guide Roller Assembly	2					
Guide Roller Bracket	2	Steel	M	22	Donated	Donated
Guide Roller Bushing	4	Steel	M	23	Donated	Donated
Guide Roller Washer	4	Steel	M	16	Donated	Donated
Guide Roller	4	Steel	M	15	Donated	Donated
Stand off	4	Steel	M	7	Donated	Donated
5/16" - 18 x 1/2" Hex Head Cap Screw	4	Steel	B	N/A	Donated	Donated
3/8" - 16 x 1 1/4" Hex Head Cap Screw	4	Steel	B	N/A	Donated	Donated
3/8 " Lock Washer	4	Steel	B	N/A	Donated	Donated
3/8" Hex Nut	4	Steel	B	N/A	Donated	Donated

Appendix E: Operation & Maintenance Manual

Operation Manual:

For system assembly instruction please see Appendix A. This operation manual assumes the system is fully assembled and adjusted prior to starting operation.

Automatic Operation:

- Under normal operation conditions the braking system will automatically engage in the event of pull cable breakage or loss of tension on the cable due to winch malfunction. Engagement of the braking system will result in stoppage of the tram cart
- Normal operation can automatically resume when tension is applied to the pull cable by the winch system.

Manual Operation

- Manual deactivation of the braking system is accomplished by lifting the E-brake handle after automatic operation of the braking system has occurred.
- The speed of descent is controlled by the amount the E-brake handle is lifted. Caution should be exercised to maintain a low rate of descent during manual operation by moderating the force applied to the E-brake handle.

Maintenance Manual:

Warning: This braking system is for emergency use only, and if proper maintenance is performed on the pull cable, the braking system should never need to be activated. A regular maintenance program for inspecting the pull cable is critical to prevent risk of injury to people or cargo that may use the tram associated with this braking system.

Warning: If the braking system is activated, the brake pads should be inspected for proper cable groove depth prior to further use of the tram system. Maximum groove depth is 0.140” for either brake pad. If groove depth is exceeded, replace brake pads prior to further use of the tram system.

Normal Maintenance:

Semi Annual PM:

- Inspect secondary cable for frayed or damaged areas. If any damage is found, replace secondary cable immediately. See Appendix A for secondary cable installation instructions.
- Grease (2) locations on brake lever pin. See Appendix A, Figure A-13 for grease Zerk locations. (Note: 2nd Zerk is on opposite end of brake lever pin)
- Grease (4) guide rollers. Loosen, and remove one guide roller bolt. Lift guide roller off cable. Slide standoff out of bushing. Inspect components for wear, if significant wear is observed, replace component. Otherwise, apply a liberal coating of a suitable water repellent grease to OD of standoff, ID of bushing, and sides of guide roller. Replace components as removed. Tighten bolt to 15 ft-lbs. Repeat procedure for the other (3) guide rollers.
- Grease cam point where caliper activation lever meets upper backing pad.
- Check for proper motion of E-brake handle and brake activation pivot arm by using E-brake handle to move brake activation pivot arm. If arms do not move freely, inspect for reason and perform necessary repairs.
- Inspect all other system parts for damage. If any damage is noted, replace component immediately.

Bi-Annual Maintenance:

- Perform all items in Semi Annual PM
- Check free length of activation spring. Free length should be 3” (nominal). If free length is less than 2.85”, replace activation spring. (See Appendix D for spring part #) If spring length is acceptable, re-tighten spring to a position 1” shorter than free length.

Appendix F: Single-stage, Multi-level Project Plan

ID	ℹ	Task Name	Duration	Start	Finish
1		**ME 492 - ME 493 Design Project**	**154 days?**	**Thu 12/3/09**	**Wed 6/2/10**
2		**PDS**	**58 days?**	**Thu 12/3/09**	**Mon 2/8/10**
3		**Talk to customers**	**48 days?**	**Thu 12/3/09**	**Wed 1/27/10**
4	▦	Interview Sponsor for PDS info	23 days?	Thu 12/3/09	Wed 12/30/09
5	▦	Speak to faculty advisor	8 days?	Wed 1/20/10	Wed 1/27/10
6		**Organize Customer needs**	**11 days?**	**Sun 1/17/10**	**Wed 1/27/10**
7	▦	Summarize customer need from PDS notes	2 days?	Sun 1/17/10	Mon 1/18/10
8	▦	Summarize information from Faculty advisor	8 days?	Wed 1/20/10	Wed 1/27/10
9		**Create PDS Template**	**3 days?**	**Wed 1/20/10**	**Fri 1/22/10**
10	▦	Detrmine what PDS Template is	2 days?	Wed 1/20/10	Thu 1/21/10
11	▦	Form PDS Template	2 days?	Thu 1/21/10	Fri 1/22/10
12	▦	Define metric for relevant criteria	6 days?	Sun 1/17/10	Fri 1/22/10
13	▦	Select target values for metrics	2 days?	Fri 1/22/10	Sat 1/23/10
14	▦	Format PDS into HOQ	1 day?	Sun 1/24/10	Sun 1/24/10
15	▦	Write PDS Report	12 days?	Mon 1/25/10	Sun 2/7/10
16	▦	Present PDS	0 days	Mon 2/8/10	Mon 2/8/10
17		**External/Internal Search**	**84 days?**	**Thu 12/3/09**	**Wed 3/10/10**
18		**Portland Aerial Tram Tour**	**11 days?**	**Thu 1/7/10**	**Wed 1/20/10**
19	▦	Arrange group visit to tram	5 days?	Thu 1/7/10	Wed 1/13/10
20	▦	participate in group visit to tram	0 days	Sat 1/16/10	Sat 1/16/10
21	▦	discuss findings from tram visit	0 days	Wed 1/20/10	Wed 1/20/10
22	▦	Search for local codes	41 days?	Sat 1/23/10	Wed 3/10/10
23	▦	Research funicularf trams	32 days?	Wed 2/3/10	Wed 3/10/10
24	▦	Obtain copy of ANSI B77.2-2004	13 days?	Wed 1/20/10	Wed 2/3/10
25	▦	Speak to project sponsor	23 days?	Thu 12/3/09	Wed 12/30/09
26		**Concept Generation & Selection**	**50 days?**	**Mon 12/28/09**	**Mon 2/22/10**
27		**Concept generation**	**36 days?**	**Mon 12/28/09**	**Sat 2/6/10**
28	▦	discuss concepts with project sponsor	11 days?	Mon 12/28/09	Fri 1/8/10
29	▦	Brainstorm for ideas	13 days?	Wed 1/20/10	Wed 2/3/10
30	▦	verify generated concepts meet any standards	2 days?	Fri 2/5/10	Sat 2/6/10
31		**Concept Selection**	**11 days?**	**Sat 2/6/10**	**Wed 2/17/10**
32	▦	Prepare decision matrix	3 days	Sat 2/6/10	Mon 2/8/10
33	▦	evaluate results of decision matrix	2 days	Tue 2/9/10	Wed 2/10/10
34	▦	Design review with sponsor	3 days?	Thu 2/11/10	Sat 2/13/10
35	▦	Re-iterate decision matrix with new information	3 days?	Mon 2/15/10	Wed 2/17/10
36	▦	Ext/Int/Concept Eval. Presentation	0 days	Mon 2/22/10	Mon 2/22/10
37		**End of term Report**	**16 days?**	**Wed 2/17/10**	**Mon 3/8/10**
38	▦	Discuss progress	8 days?	Wed 2/17/10	Wed 2/24/10
39	▦	write report	12 days?	Sun 2/21/10	Sat 3/6/10
40	▦	Create powerpoint presentation	3 days?	Thu 3/4/10	Sun 3/7/10
41	▦	make End of Term Presentation	0 days	Mon 3/8/10	Mon 3/8/10
42		**Detail Design**	**48 days?**	**Tue 2/23/10**	**Sun 4/18/10**
43		**verify concept**	**29 days?**	**Tue 2/23/10**	**Sun 3/28/10**
44	▦	design concept test experiment	10 days?	Tue 2/23/10	Sat 3/6/10
45	▦	build fixture to test concept	10 days?	Wed 3/10/10	Sat 3/20/10
46	▦	obtain instrumentation for test	9 days?	Thu 3/4/10	Sun 3/14/10
47	▦	perform concept test experiment	5 days?	Mon 3/22/10	Fri 3/26/10
48	▦	document concept test results	2 days?	Thu 3/25/10	Fri 3/26/10
49	▦	design review with project sponsor	1 day?	Sun 3/28/10	Sun 3/28/10
50		**create detailed design**	**35 days?**	**Thu 3/11/10**	**Sun 4/18/10**
51	▦	brainstorm required system components	19 days?	Thu 3/11/10	Wed 3/31/10
52	▦	design review with project sponsor	3 days?	Thu 4/1/10	Sat 4/3/10
53	▦	determine attachment points of system to tram	5 days?	Sat 3/27/10	Wed 3/31/10
54	▦	create solid model of design	19 days?	Thu 3/11/10	Wed 3/31/10
55	▦	perform egineering analysis on components	20 days?	Wed 3/17/10	Wed 4/7/10
56	▦	update solid model with engineered components	16 days?	Thu 3/25/10	Sat 4/10/10
57	▦	create bill of materials for system	26 days?	Wed 3/17/10	Wed 4/14/10
58	▦	create drawings	28 days?	Thu 3/18/10	Sat 4/17/10
59	▦	design review with project sponsor	1 day?	Sun 4/18/10	Sun 4/18/10
60		**Prototyping**	**59 days?**	**Thu 3/11/10**	**Wed 5/19/10**
61		**obtain required system components**	**44 days?**	**Thu 3/11/10**	**Wed 4/28/10**
62	▦	order purchased parts	44 days?	Thu 3/11/10	Wed 4/28/10
63	▦	machine non-purchasable parts	38 days?	Thu 3/18/10	Wed 4/28/10
64		**assemble braking system**	**16 days?**	**Wed 4/28/10**	**Wed 5/19/10**
65	▦	perform brake system assembly	11 days?	Wed 4/28/10	Wed 5/12/10
66	▦	install brake system on tram system	6 days?	Wed 5/12/10	Wed 5/19/10
67		**Prototype testing**	**9 days?**	**Wed 5/19/10**	**Sat 5/29/10**
68	▦	perform actual tests on braking system	6 days?	Wed 5/19/10	Wed 5/26/10
69	▦	document results of prototype testing	3 days?	Thu 5/27/10	Sat 5/29/10
70		**Documentation**	**70 days?**	**Thu 3/11/10**	**Wed 6/2/10**
71		**prepare engineering analysis documentation**	**37 days?**	**Sat 4/17/10**	**Wed 6/2/10**
72	▦	tasks to be outlined as detail design requires	37 days?	Sat 4/17/10	Wed 6/2/10
73		**prepare braking system Bill of Materials**	**37 days?**	**Sat 4/17/10**	**Wed 6/2/10**
74	▦	tasks to be outlined as detail design requires	37 days?	Sat 4/17/10	Wed 6/2/10
75		**Compile assembly drawings**	**49 days?**	**Thu 3/11/10**	**Wed 5/5/10**
76	▦	obtain component drawings from detail design	6 days?	Mon 4/19/10	Sat 4/24/10
77	▦	create or obtain drawings for purchased items	49 days?	Thu 3/11/10	Wed 5/5/10
78		**Compile maintenace instructions**	**34 days?**	**Wed 4/14/10**	**Wed 5/26/10**
79	▦	determine appropriate maintenance intervals	6 days?	Wed 5/12/10	Wed 5/19/10
80	▦	determine maintenance requirements	29 days?	Wed 4/14/10	Wed 5/19/10
81	▦	write maintenance instructions	6 days?	Wed 5/19/10	Wed 5/26/10
82	▦	Final Presentation (timline to be determined during ME493)	0 days	Wed 6/2/10	Wed 6/2/10

Appendix G: Product Design Specification

The most important PDS elements for this project are:

- Providing a means to arrest the motion of the cart in the event of a pull cable or winch malfunction. This design element is the primary reason for this entire project. The safety of passengers and cargo depend on the operation of a braking system in the event of a winch or cable malfunction.
- Reliability is of paramount concern with this project because the safety of people is in question.
- The system must be designed to stop a total cart weight of 600 – 800 lbs.
- The braking system must be completely mechanical.
- Capturing the tram cart to the tram structure.
- Documentation including a regular inspection and maintenance schedule, Bill of Materials, component drawings, and operating instructions need to be provided to the project sponsor.

The complete PDS can be found on the following pages.

Performance Priority: High: 🟥 Medium: 🟨 Low: 🟩

🟥 Auto stop or Auto descend on loss of mechanical control of tram cart	ft / sec	0 – 2 ft/sec	Zdenek	set distance traveled over time taken to travel set distance
🟨 Stopping acceleration not to exceed startup acceleration	ft / sec^2	TBD	Zdenek	moving velocity to zero velocity difference over time taken to change velocity
🟥 Required cart load capacity	pounds	150-180 lb cart plus 400-600 lb cargo	Zdenek	Testing system with known weight on cart after assembly of prototype
🟥 Braking mechanism is mechanically operated (non-electrical)	yes / no	yes	Zdenek	Prototype

Environment

Project Requirement	**Engineering Metric**	**Target Value**	**Target Basis**	**Verification Method**
🟨 Life in Service	years	20 years	typical lifetime of mechanical assembly	Protoype
🟥 Operation in all weather conditions	anti friction components protected from elements	Zero water contamination of bearings and other anti friction elements	Zdenek	Prototype

Installation

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
Braking mechanism captures tram cart to tram support assembly	yes / no	yes	Zdenek	Prototype
Provision to remove tram cart from track assembly	yes / no	yes	Zdenek	Prototype

Quality & Reliability

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
All brake system components have minimum factor of safety	Factor of Safety	≥ 2	Zdenek	Analysis of mechanism components
System designed to minimize component wear	yes / no	yes	Zdenek	Prototype

Materials

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
Materials of construction to be corrosion resistant where possible	yes / no	yes	Zdenek	Prototype
All hardware to be Zn or Cd plated, or SS	yes / no	yes	Zdenek	Prototype
Exposed steel surfaces to be painted	yes / no	yes	Zdenek	Prototype
Where possible, off the shelf parts to be used	yes / no	yes	Zdenek	Prototype

Maintenance

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
All lubrication points easily accessible	yes / no	yes	self	Prototype
Attachment points for any guards should be easily accessible	yes / no	yes	self	Prototype

Ergonomics

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
If braking system is designed to stop cart on tram way during an event, a conveniently placed, controlled manual release is provided	yes / no	yes	Zdenek	Prototype

Applicable Codes & Standards

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
Where possible comply with ANSI B77.2-2004 (yet to be obtained)	yes / no	yes	Zdenek	Prototype

Size and Shape

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
Braking system fits under deck of tram cart	yes or no	yes	Zdenek	visual
unsealed components remain above waterline of lower well.	yes or no	yes	Zdenek	visual

Documentation

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
PDS report	Deadline	Feb 8, 2010	ME 492	Instructor Receipt
End of term progress Rpt.	Deadline	March 8, 2010	ME 492	Instructor Receipt
Presentation of all structural analysis to project sponsor	yes / no	yes	Zdenek	Zdenek Receipt
Provide O&M manual complete with assembly drawings, BOM, and operation & maintenance instruction to Zdenek	yes / no	yes	Zdenek	Zdenek Receipt

Timelines

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
PDS report & Presentation	Deadline	Feb 8, 2010	ME 492	Instructor Receipt
Ext/Int/Concept Evaluation Presentation	Deadline	Feb 22, 2010	ME 492	Instructor Receipt
End of Term Report & Presentation	Deadline	March 8, 2010	ME 492	Instructor Receipt
Detail Design	Deadline	April 20, 2010	arbitrary	Ready to build prototype
Prototype	Deadline	May 15, 2010	arbitrary	Zdenek Receipt
Documentation	Deadline	June 5, 2010	arbitrary	Zdenek Receipt
Final Presentation	Deadline	June 5, 2010	ME 493	Instructor Receipt

Miscellaneous

Project Requirement	Engineering Metric	Target Value	Target Basis	Verification Method
Quantity	Integer value	1	Zdenek	Prototype
Cost of production	U.S. Dollars	< $1,000	Zdenek	Prototype

Appendix H: Suggested bolt tightening torque

			SAE Grade 2 Bolts					SAE Grde 5 Bolts					SAE Grade 7			SAE Grade 8		
Size	Bolt Diam. D(in.)	Stress Area A(in^2)	Tensile Strength min psi	Proof Load psi	Clamp Load P (lb)	T Dry	Torque Lub.	Tensile Strength	Proof Load	Clamp Load	T Dry	Torque Lub.	Clamp Load	Tight Dry	Torque Lub.	Clamp Load	T Dry	Torque Lub.
1/4-20	0.2500	0.0318			1320	66	49			2020	96	75	2500	120	96	2860	144	108
1/4-28	0.2500	0.0364			1500	76	56			2320	120	86	2880	144	108	3280	168	120
5/16-18	0.3125	0.0524			2160	11	8			3340	17	13	4120	21	16	4720	25	18
5/16-24	0.3125	0.0580			2400	12	9			3700	19	14	4580	24	18	5220	25	20
3/8-16	0.3750	0.0775			3200	20	15			4940	30	23	6100	40	30	7000	45	35
3/8-24	0.3750	0.0878			3620	23	17			5600	35	25	6900	41	30	7900	50	35
7/16-14	0.4375	0.1063			4380	30	24			6800	50	35	8400	60	45	9550	70	55
7/16-20	0.4375	0.1187			4900	35	25			7550	55	40	9350	70	50	10700	80	60
1/2-13	0.5000	0.1419			5840	50	35			9050	75	55	11200	95	70	12750	110	80
1/2-13	0.5000	0.1599			6600	55	40			10700	90	65	12600	100	80	14400	120	90
9/16-12	0.5625	0.1820			7500	70	55			11600	110	80	14350	135	100	16400	150	110
9/16-18	0.5625	0.2030			8400	80	60			12950	120	90	16000	150	110	18250	170	130
5/8-11	0.6250	0.2260			9300	100	75			14400	150	110	17800	190	140	20350	220	170
5/8-18	0.6250	0.2560			10600	110	85			16300	170	130	20150	210	160	23000	240	180
3/4-10	0.7500	0.3340			13800	175	130			21300	260	200	26300	320	240	30100	380	280
3/4-16	0.7500	0.3730			15400	195	145			23800	300	220	29400	360	280	33600	420	320
7/8-9	0.8750	0.4620	60,000	33,000	11400	165	125			29400	430	320	36400	520	400	41600	600	460
7/8-14	0.8750	0.5090			12600	185	140			32400	470	350	40100	580	440	45800	660	500
1-8	1.0000	0.6060			15000	250	190			38600	640	480	47700	800	600	54500	900	680
1-12	1.0000	0.6630			16400	270	200			42200	700	530	52200	860	660	597	1100	740
1-1/4 7	1.1250	0.7630			18900	350	270	105,000	74,000	42300	800	600	60100	1120	840	68700	1280	960
1-1/4 12	1.1250	0.8560			21200	400	300			47500	880	660	67400	1260	940	77000	1440	1080
1-1/4 7	1.2500	0.9690			24000	500	380			53800	1120	840	76300	1580	1100	87200	1820	1361
1-1/4 12	1.2500	1.0730			26600	550	420			59600	1240	920	84500	1760	1320	116600	2000	1500
1-3/8 6	1.3750	1.1550			28600	660	490			64100	1460	1100	91000	2080	1560	104000	2380	1780
1-3/812	1.3750	1.3150			32500	740	560			73000	1680	1260	104000	2380	1780	118400	2720	2040
1-3/8 6	1.5000	1.4050			34800	870	650			78000	1940	1460	111000	2780	2080	126500	3160	2360
1-1/2 12	1.5000	1.5800			39100	980	730			87700	2200	1640	124005	3100	2320	142200	3560	2660

Source: http://www.fandisc.com/tti.htm

Appendix I: Expense Report

Expense Report

June 6, 2010

Tram Brake Capstone Project

Date	Description	Qty.	Unit Cost (USD)	Shipping (USD)	TOTAL (USD)
3/1/10	Parking Brake caliper 5206-AP-10024	*1*	*89.00*	*13.23*	*102.23*
4/12/10	200 lb spring scale part # HOM-7820-000-000	*1*	*39.15*	*9.31*	*48.46*
5/14/10	Spring MMC#96485K131	*1*	*8.40*	*2.50*	*10.90*
5/14/10	Self-Lube Bronze Race Ball Joint Rod end	*2*	*7.03*	*2.50*	*9.53*
5/19/10	3/8” – 24 x 6” threaded rod	*1*	*2.46*	*N/A*	*2.46*
5/26/10	Gift certificate to material donor	*1*	*60.00*	*N/A*	*60.00*
5/26/10	Gift certificate to outside fabricator	*1*	*60.00*	*N/A*	*60.00*
				Total	*293.58*

All-Pro Off Road, Inc.
541 N. Palm Ave.
Hemet, CA 92543

Voice: 951-658-7077
Fax: 951-658-2375

Invoice

Invoice Number: 63247

Invoice Date: Mar 1, 2010

Page: 1

Sold To:

Timothy Lagasse
16653 S. Beckman Rd.
Oregon City, OR 97045

Ship to:

Timothy Lagasse
EMI
2441 SE Stubb St.
Milwaukie, OR 97222

Customer ID	Customer Phone #	Payment Terms	
97045 Timothy	503-314-7712	Prepaid	
Sales Rep ID	**Shipping Method**	**Ship Date**	**Customer PO**
	UPS Ground		

Quantity	Item	Description	Backorder Qty	Unit Price	Extension
1.00	5206-AP-10024	1ZA2R1770365716498 Parking Brake Caliper		89.00	89.00

Vehicle Info:

Subtotal	89.00
Sales Tax	
Freight	13.23
Total Invoice Amount	102.23
Payment/Credit Applied	102.23
TOTAL	0.00

Check/Receipt Ref No: 47549
UPS Tracking #:

All parts sold by All-Pro Off Road are for off road racing use only and are not intended for use on the street. Please do not order parts that you do not intend to keep. All-Pro charges a 20% Restocking Fee for all returned orders that were correctly shipped by us. No cash refunds, store credit only. Exchanges or credits will not be allowed later than 30 days after purchase. No refunds for shipping costs. Pricing and availability are subject to change without notice.

McMASTER-CARR®

Purchase Order
0514ASKIDMORE

Page 1 of 1

9630 Norwalk Blvd
Santa Fe Springs CA 90670-2932
562-692-5911
la.sales@mcmaster.com

Andrew Skidmore
1912 Sw 6TH Ave #1024
Portland OR 97201

Order Placed By
Andrew Skidmore

05/14/2010

McMaster-Carr Number
2148378-01

Line		Description	Ordered	Shipped
2	**96485K131**	Spring-Tempered Steel Jumbo Compression Spring, 3" Length, 1.937" OD, .192" Wire Diameter Unit Price: $8.40 Extended Price: $8.40	**1 Each**	**1**
1	**6072K33**	Self-Lube Bronze Race Ball Joint Rod End, 3/8"-24 Right-Hand Thread Female Shank with Right-Hand Thread Stud Unit Price: $7.03 Extended Price: $14.06	**2 Each**	**2**

3	213	03	07 - 75	K131	1 EA	2
3	216	01	08 - 30	K33	2 EA	1

Charges for this shipment

Merchandise Amount:	$22.46
Shipping Charge:	$5.00
Total:	**$27.46**

Subj: **Order Confirmation (#619011)**
Date: 4/12/2010 11:29:27 A.M. Pacific Daylight Time
From: orders-owks@oldwillknottscales.com
To: octol@aol.com

Order Confirmation

Thank you for your order, Timothy Lagasse.
Your order number is: 619011
Date of order: 4/12/2010 12:29 PM

Shipping Method: UPS Ground
Payment Method: Credit card payment

Ship To

Timothy Lagasse
EMI
2441 SE Stubb Street
Milwaukie, OR 97222
United States
Phone:503-314-7712

Bill To

Timothy Lagasse
16653 S. Beckman Rd
Oregon City, OR 97045
United States
Phone:503-314-7712

Product Information

Product Name	Part No.	Quantity	Item Price	Total Price
Health o meter 7820-000-000	HOM-7820-000-000	1	$39.15	$39.15

Subtotal:	$39.15
Shipping & Handling:	$9.31
Tax:	$0.00

Order Total:	$48.46

SALES DRAFT

CLACKAMS AUTO PRTS INC
1009 MAIN STREET
OREGON CITY, OR 97045
TERMINAL 0495989

376201789991
05/19/2010 15:54:33
VS XXXXXXXXXXXX0476
AUTH. TRANS. ID. 000139853699868
INVOICE 13019 H@2
AUTH. CODE 026098

SALE TOTAL $2.46

CUSTOMER COPY

'34
Since 1934

MACHINE SHOP SERVICE

CLACKAMAS AUTO PARTS INC

503-656-4244

1009 Main St. • Oregon City, OR 97045

THIS INVOICE MUST ACCOMPANY ALL RETURNS.

TERMS: ALL ACCOUNTS DUE AND PAYABLE ON OR BEFORE 10TH OF FOLLOWING MONTH. A **SERVICE CHARGE** OF 1½% PER MONTH IS CHARGED ON ALL PAST DUE ACCOUNTS. THIS IS AN **ANNUAL PERCENTAGE RATE OF 18%.**

ANY WARRANTIES ON THE PARTS AND OR ACCESSORIES SOLD HEREBY ARE THOSE MADE BY THE MANUFACTURER.
WE THE SELLER HEREBY EXPRESSLY DISCLAIM ALL WARRANTIES EITHER EXPRESS OR IMPLIED, INCLUDING ALL IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR THE PARTICULAR PURPOSE AND WE NEITHER ASSUME NOR AUTHORIZE ANY OTHER PERSON TO ASSUME FOR US ANY LIABILITY IN CONNECTION WITH SALE OF THE PARTS AND OR ACCESSORIES.

BILL TO
CASH CUSTOMER

THANK YOU

SHIP TO
CASH CUSTOMER
1

INVOICE NO.	CUSTOMER NO.	DATE	CUST. P.O. NO.	SALES NO.	CNTR. NO.	SHIP VIA	TERMS
123803	CASH	05-19-10		J		03:20P	BC:V0476

	MFG.-PART NUMBER	ORDERED	SHIPPED	BKO	LIST PRICE	NET	NET CORE	EXT. AMOUNT
1	DOR 672-012 SAE THRD ROD		1		3.67	2.46	0.00	2.46
2								
3								
4								
5								

MACHINE SHOP SERVICE

FREIGHT	LABOR	SHOP	TOTAL CORE	TAXABLE AMT.	SALES TAX		SUB TOTAL
0.00	0.00		0.00	0.00	0.00		2.46

RECEIVED BY X

LIST TOTAL ▶

PAY THIS AMOUNT ▶ 2.46

Appendix J: Approval & Project Handover Letter

Customer:
Zdenek Zumr
1024 SW Troy St.
Portland, OR 97219
zzumr@aol.com
503 515 3351

The Trambreak team:
Tim Lagasse
Andrew Skidmore
Binh Nguyen

Project Advisor:
Dr. Yi

Portland, June 6 2010

Trambreak Project Handover

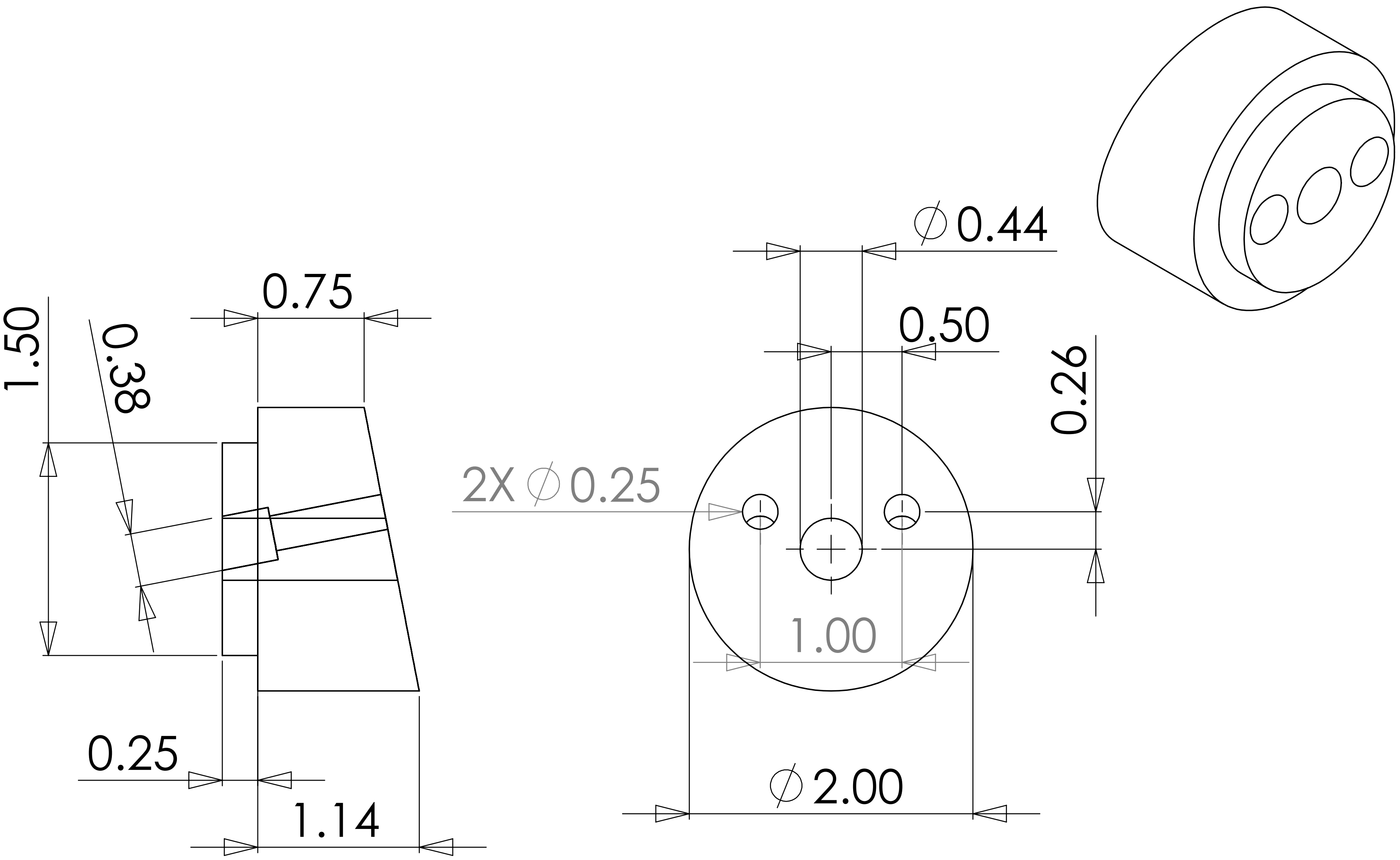
As the customer in the 2010 Tram Brake Capstone Project by above team, I would like to express my gratitude for the professional execution of the project. All design specifications have been met and the relevant safety features successfully tested in my presence.
The project was executed on schedule with final delivery on 06/02/2010.
At this time here on out I assume responsibility for all aspects of operation of the equipment including but not limited to, installation, maintenance, calibration and verification of operation as needed.
The Trambreak team, Dr. Yi, and PSU are free of liability in any form in connection with this project.

Sincerely

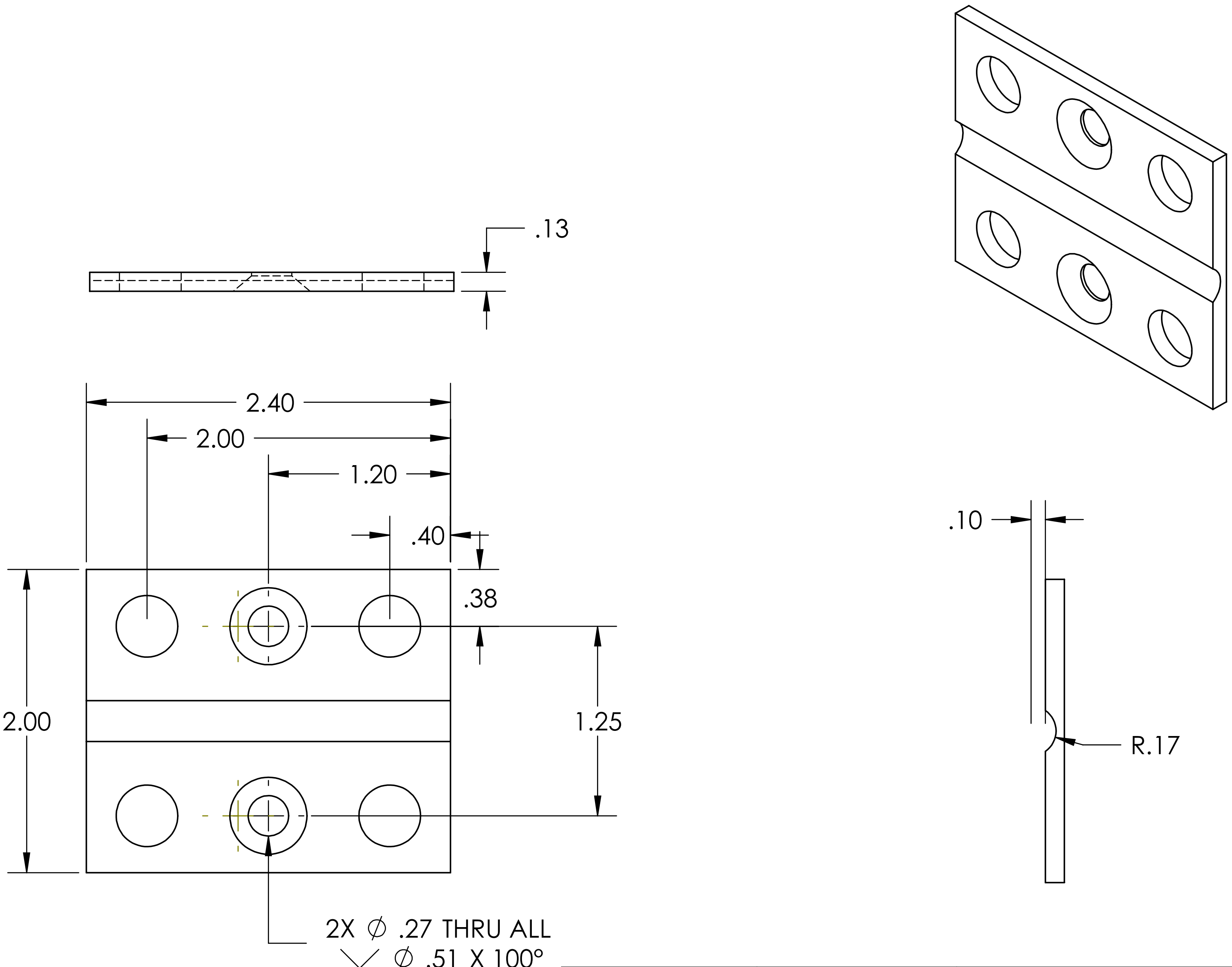
Zdenek Zumr
Signed
Portland, OR
June 6 2010

Appendix K: Production Drawings

Drawings for all components made by the design team are in this appendix. The page numbers are specified by the appropriate drawing number, and the drawings are in numerical order.



ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.01 TWO PLACE DECIMAL ±.001 THREE PLACE DECIMAL ±.0001	MATERIAL SS	Portland State Tram Brake Team			
	FINISH --	DRAWN BY AS	SIZE A	DWG. NO. 1	REV. --
	DO NOT SCALE DRAWING	DATE 5/6/2010	SCALE 1:1	SHEET NO. 1 of 1	



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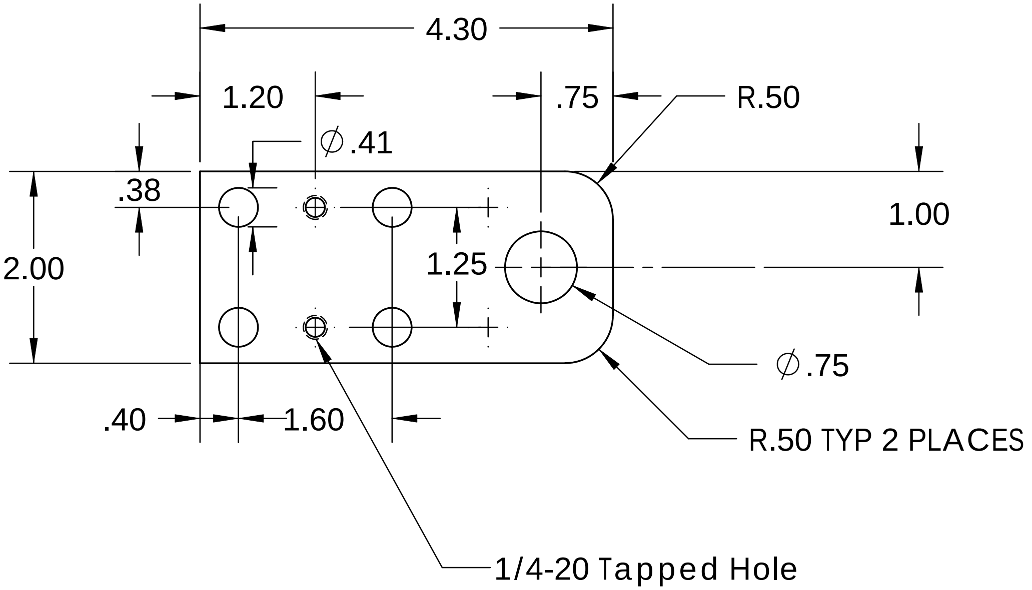

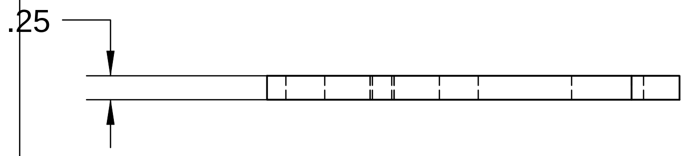

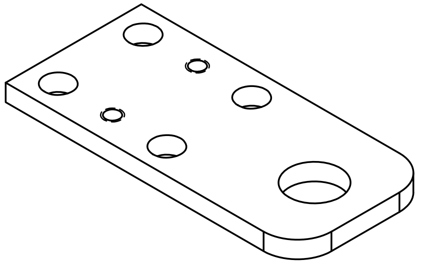

ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL SS	Portland State Tram Brake Team			
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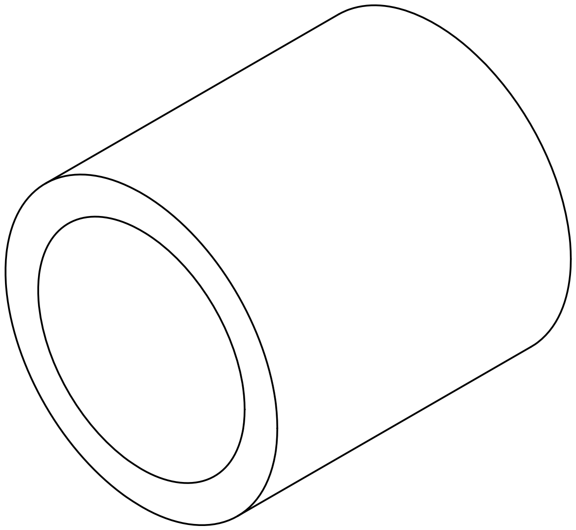
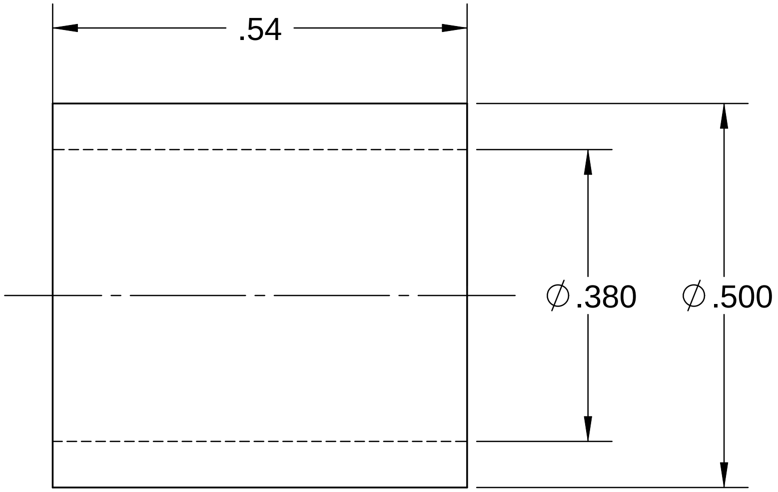
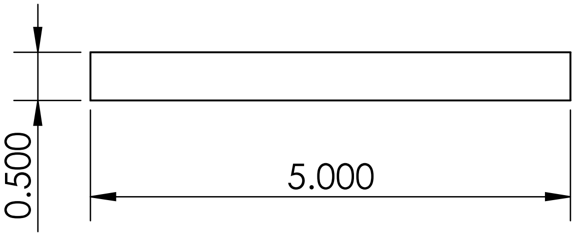
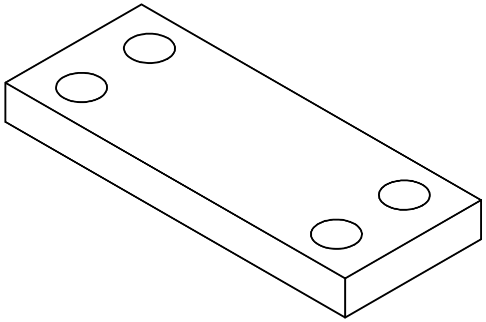
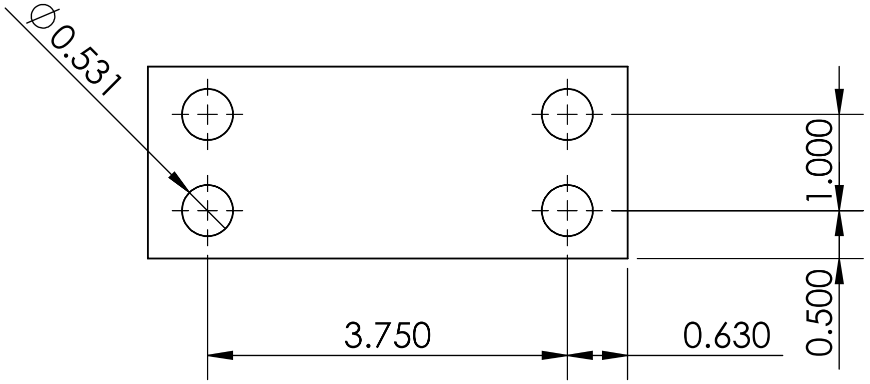




ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL carbon steel	Portland State Tram Brake Team			
	FINISH 32	DRAWN BY TL	SIZE A	DWG. NO. 7	REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 4:1	SHEET NO. 1 of 1	





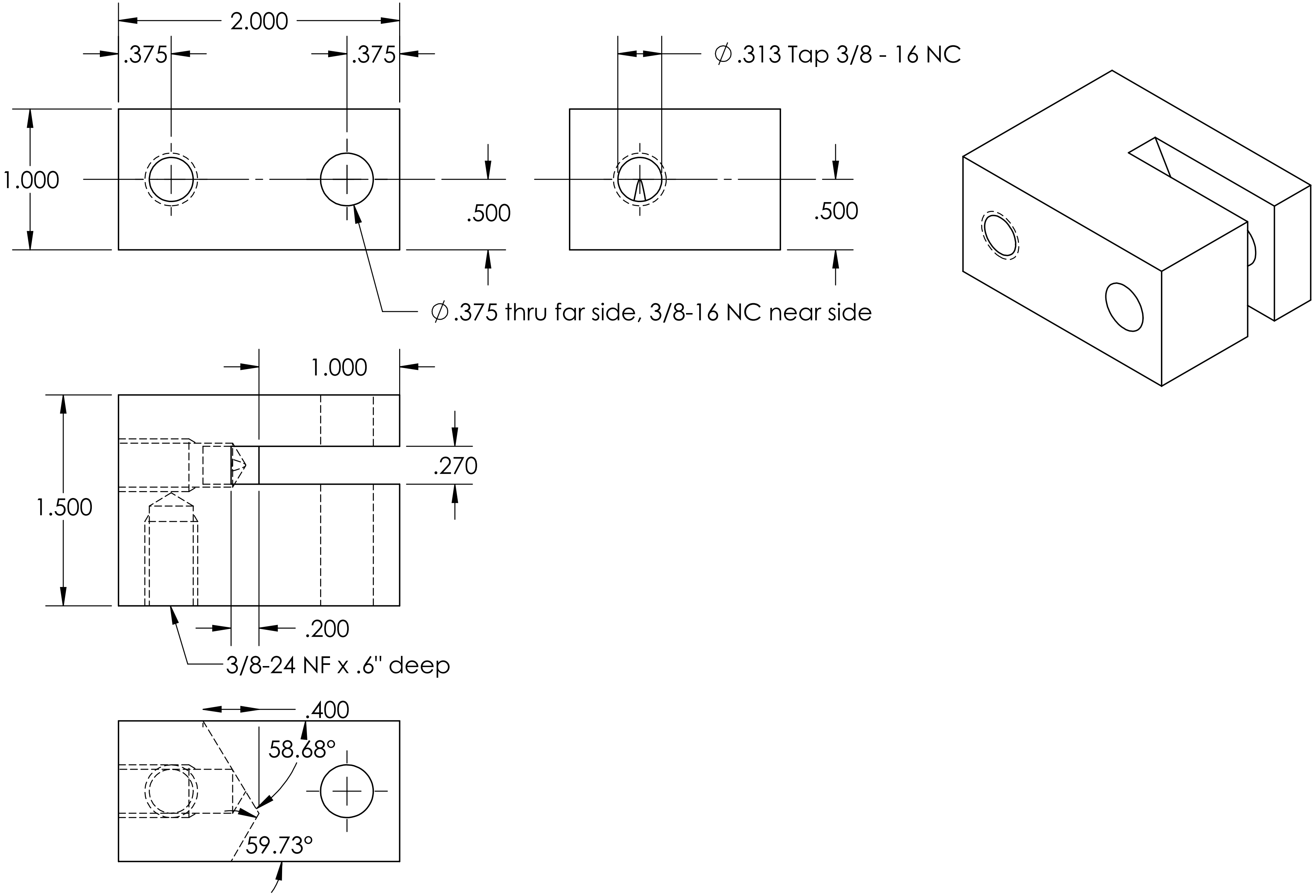


ALL DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED
TOLERANCES:
FRACTIONAL± 1/16
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

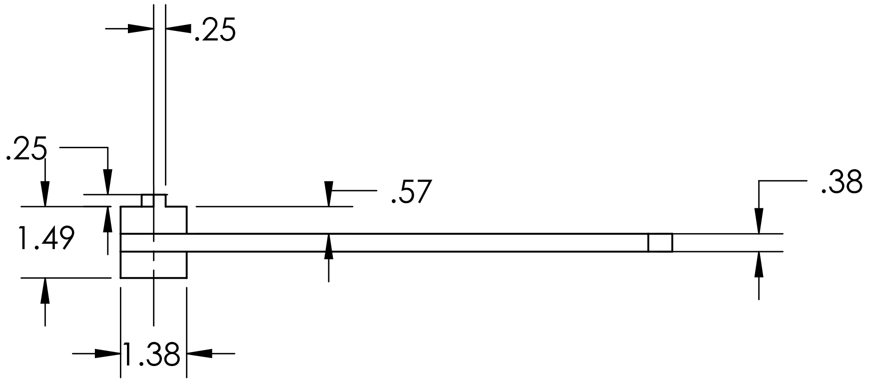
MATERIAL Steel
FINISH --
DO NOT SCALE DRAWING

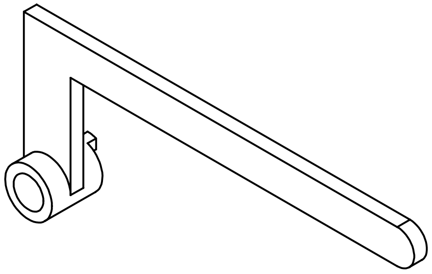
Portland State Tram Brake Team

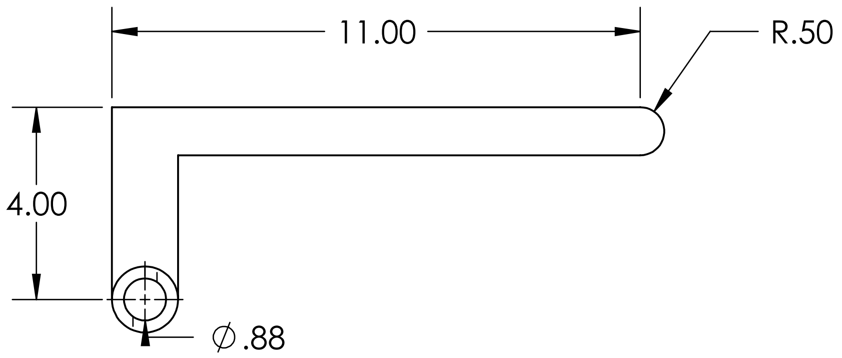
DRAWN BY TL	SIZE A	DWG. NO. 8		REV. --
DATE 6/2/2010	SCALE 1:2	SHEET NO. 1 of 1		



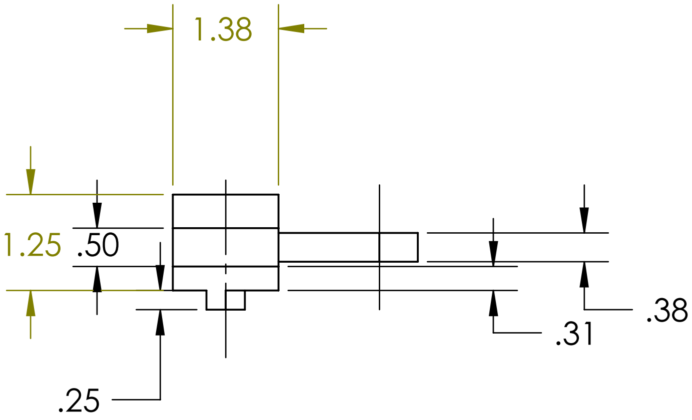
ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Steel	Portland State Tram Brake Team			
	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 10	REV. --
	DO NOT SCALE DRAWING	DATE 5/24/2010	SCALE 1:1	SHEET NO. 1 of 1	

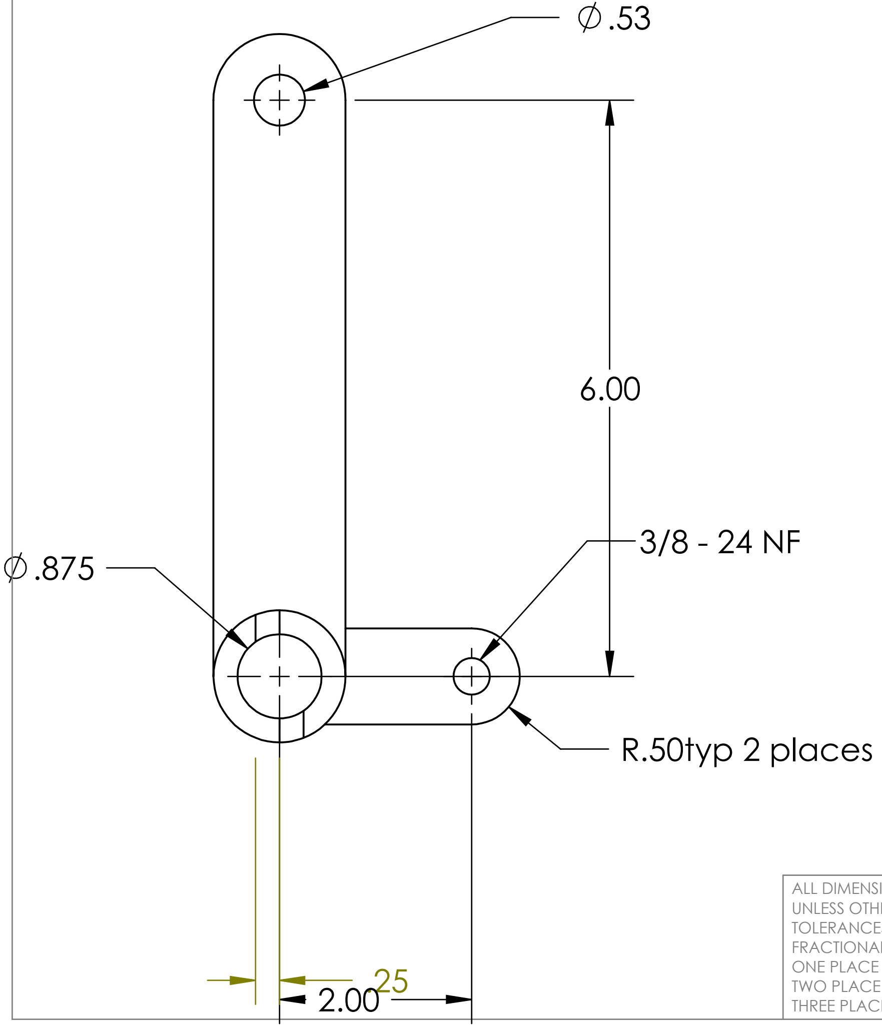


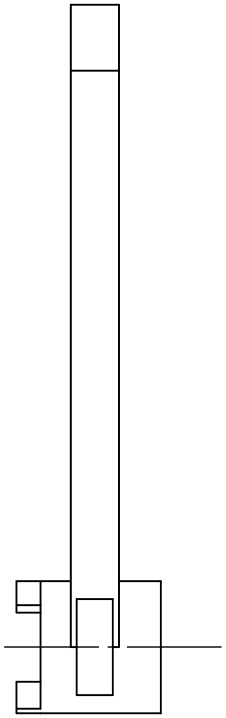


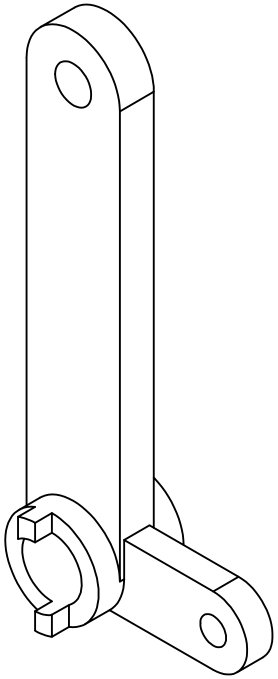


ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED	MATERIAL Steel	Portland State Tram Brake Team			
TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 11	REV. --
TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:4	SHEET NO. 1 of 1	

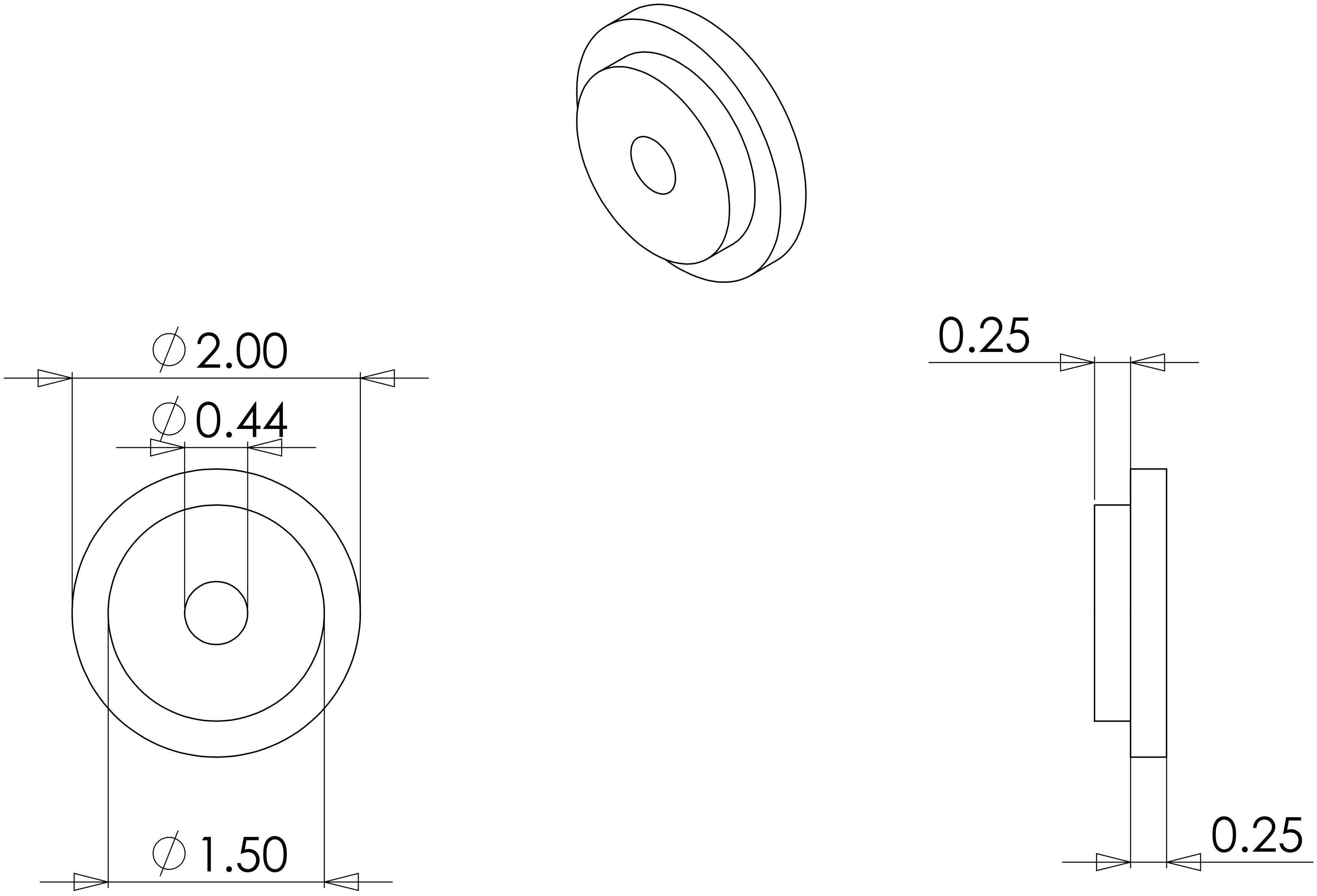




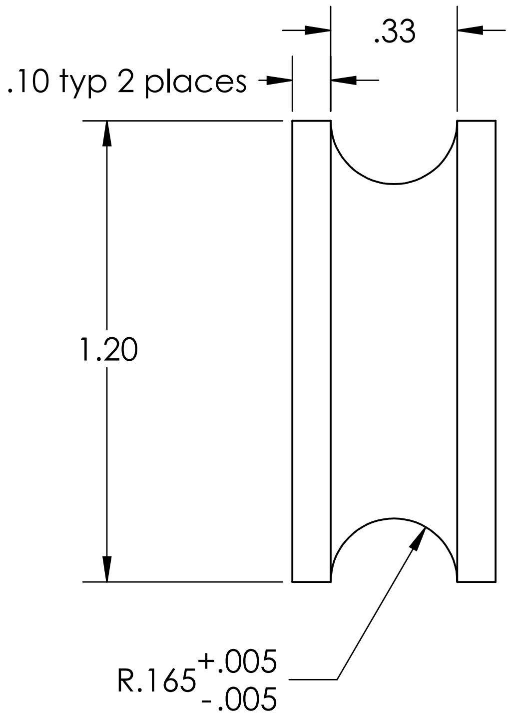


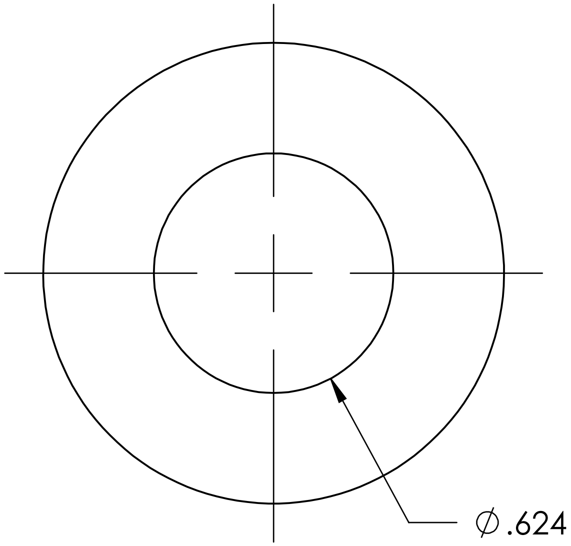


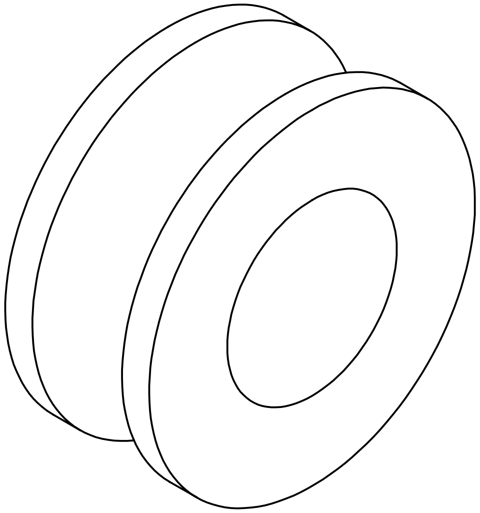
ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Steel	Portland State Tram Brake Team			
	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 12	REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:2	SHEET NO. 1 of 1	



ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.01 TWO PLACE DECIMAL ±.001 THREE PLACE DECIMAL ±.0001	MATERIAL SS	Portland State Tram Brake Team			
	FINISH --	DRAWN BY AS	SIZE A	DWG. NO. 14	REV. --
	DO NOT SCALE DRAWING	DATE 5/6/2010	SCALE 1:1	SHEET NO. 1 of 1	





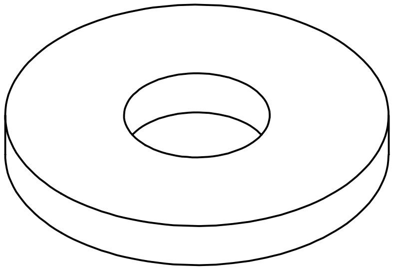


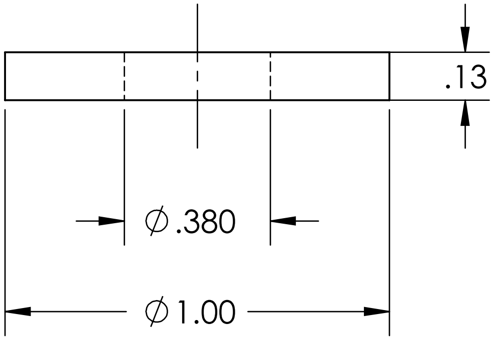
ALL DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED
TOLERANCES:
FRACTIONAL± 1/16
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL SS
FINISH --
DO NOT SCALE DRAWING

Portland State Tram Brake Team

DRAWN BY TL
SIZE A
DWG. NO. 15
REV. --
DATE 5/1/2010
SCALE 2:1
SHEET NO. 1 of 1





ALL DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED
TOLERANCES:
FRACTIONAL ± 1/16
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL Steel

FINISH 32

DO NOT SCALE DRAWING

Portland State Tram Brake Team

DRAWN BY TL

DATE 5/1/2010

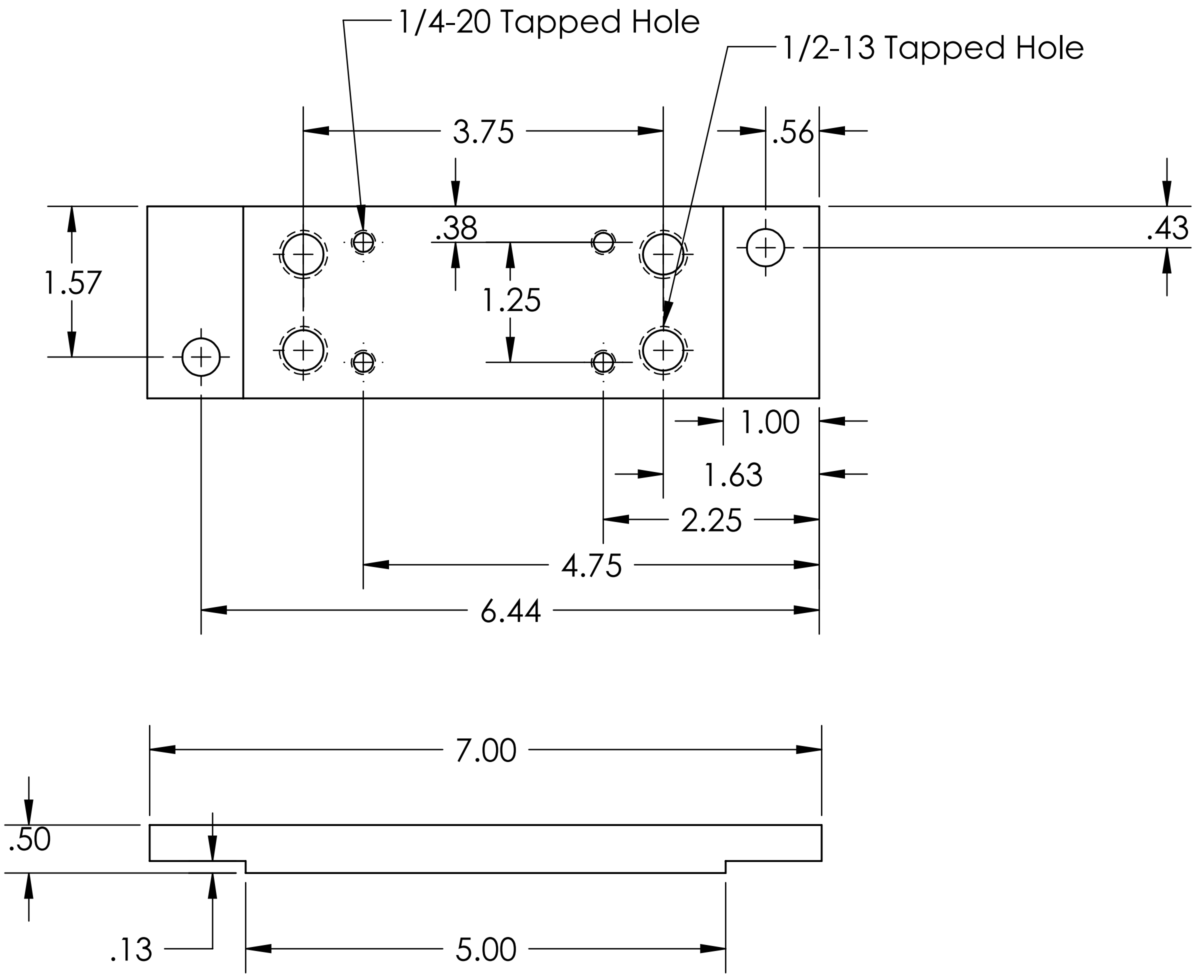
SIZE **A**

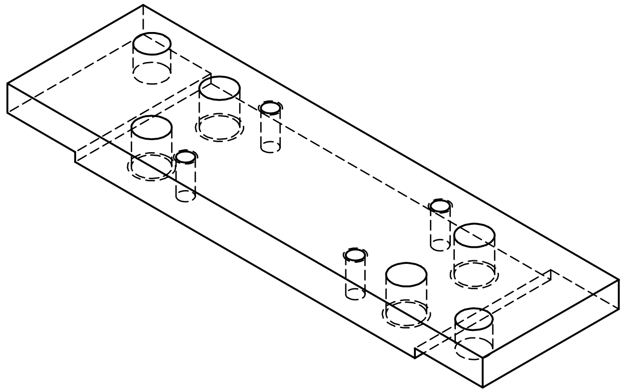
DWG. NO. 16

REV. --

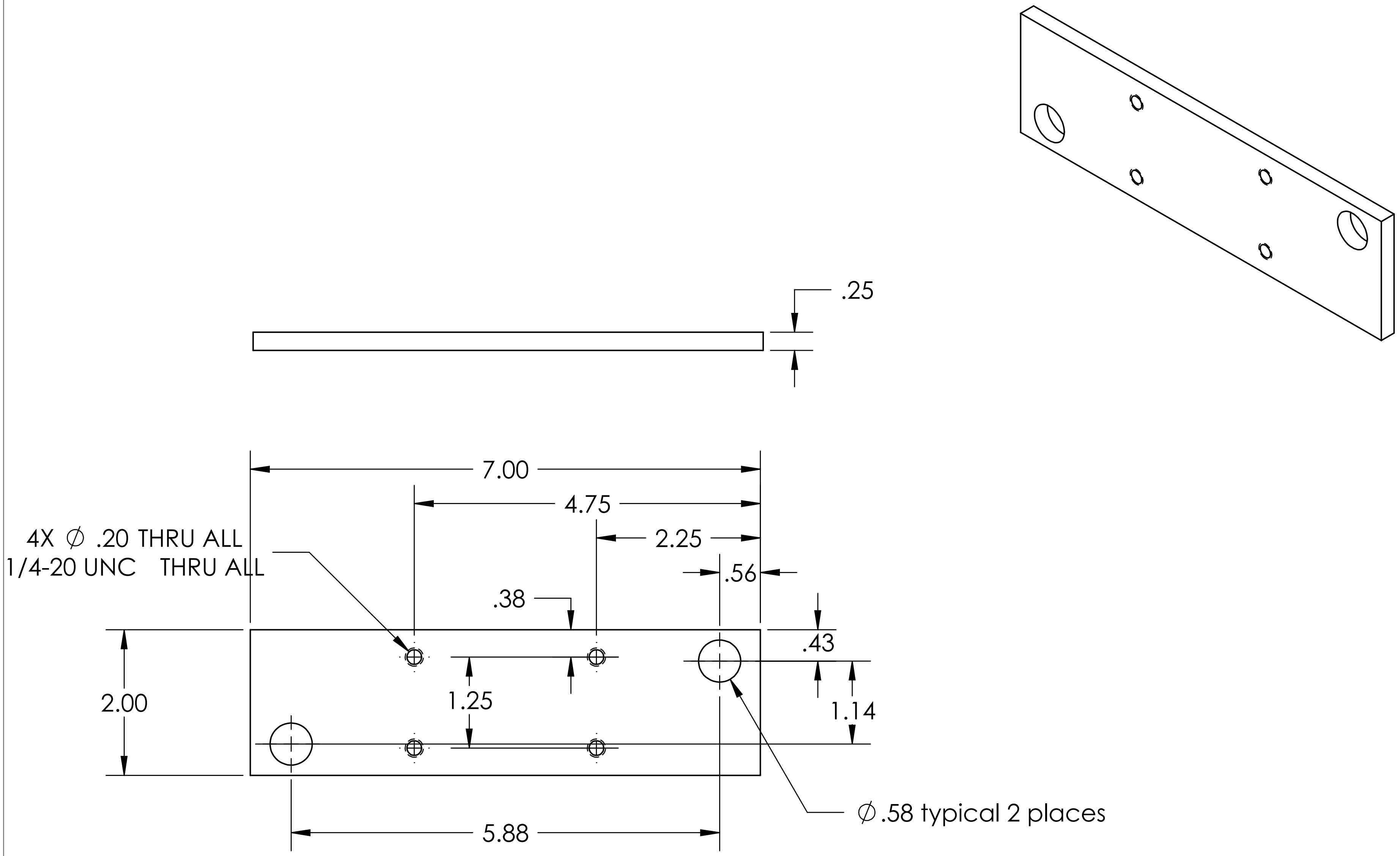
SCALE **2:1**

SHEET NO. 1 of 1

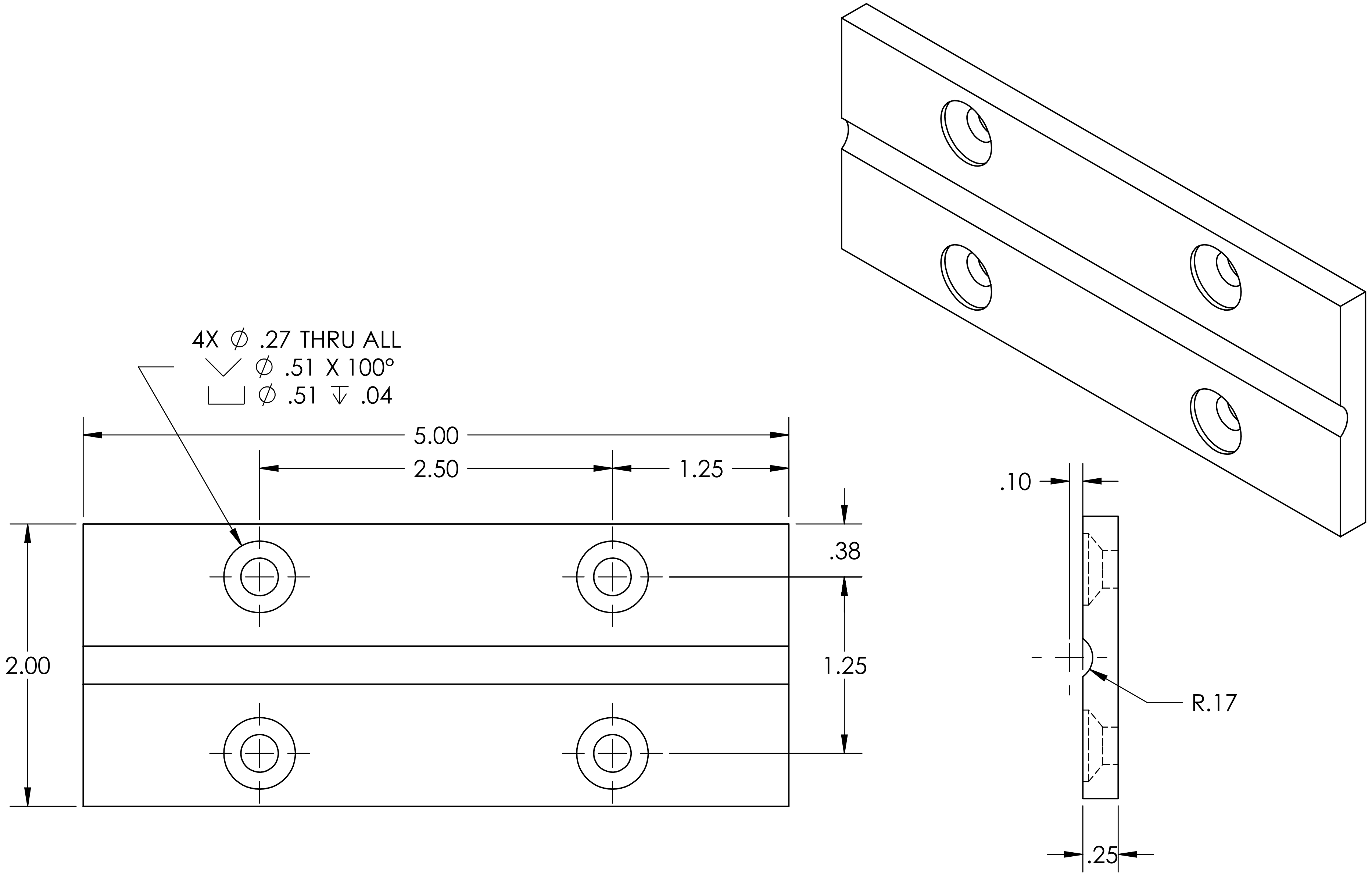




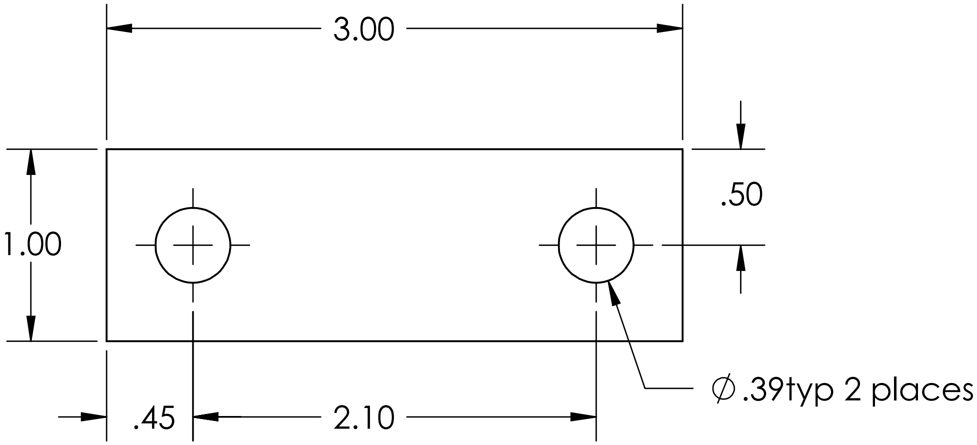
ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Steel	Portland State Tram Brake Team		
	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 17 — REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:2	SHEET NO. 1 of 1

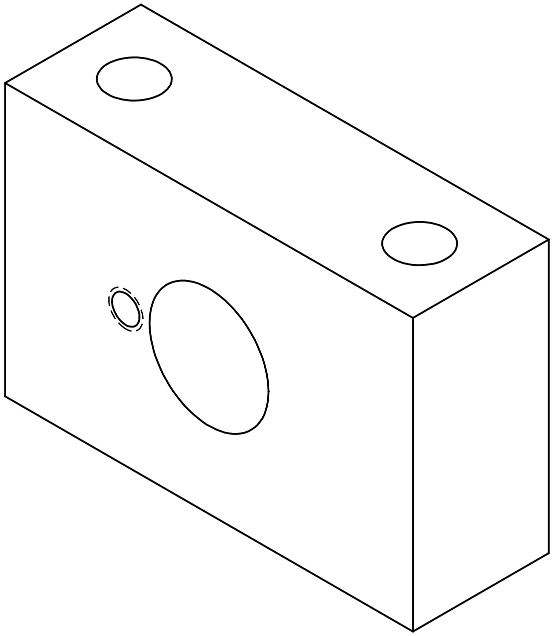


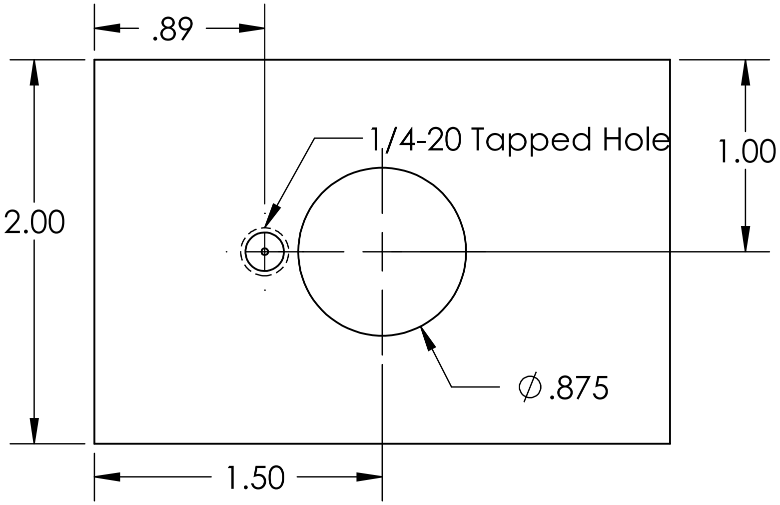
ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Steel	Portland State Tram Brake Team			
	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 18	REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:2	SHEET NO. 1 of 1	



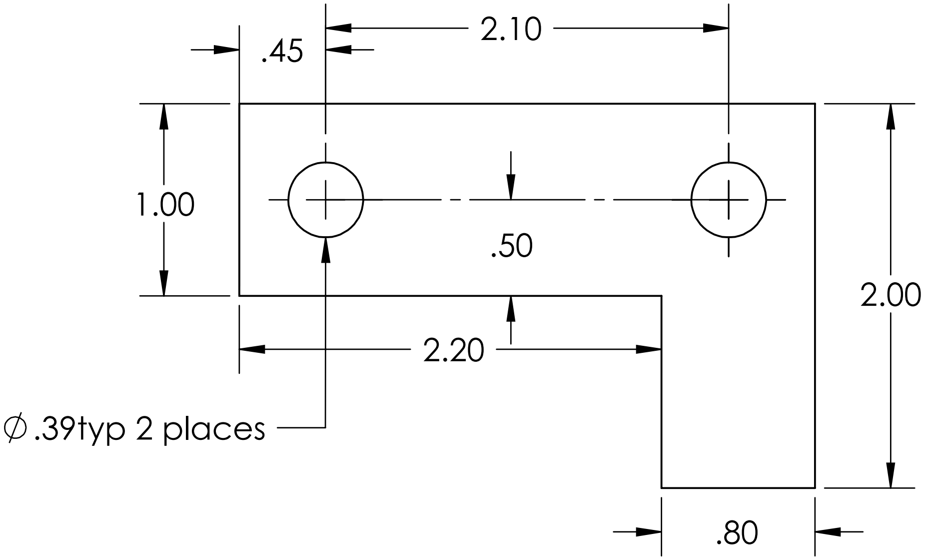
ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL ± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Aluminum	Portland State Tram Brake Team			
	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 19	REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:1	SHEET NO. 1 of 1	

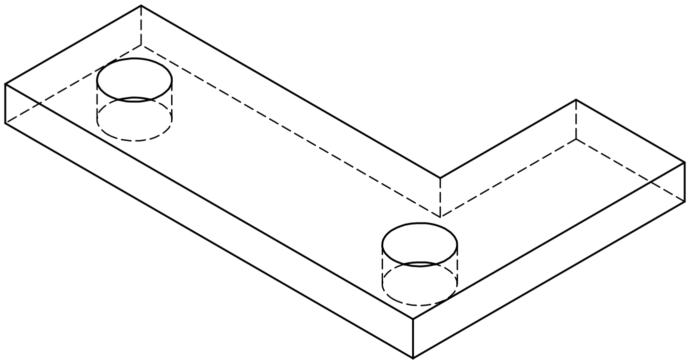


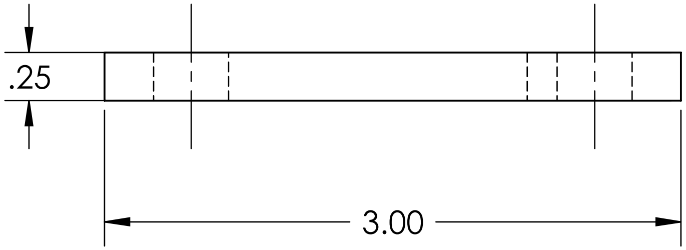




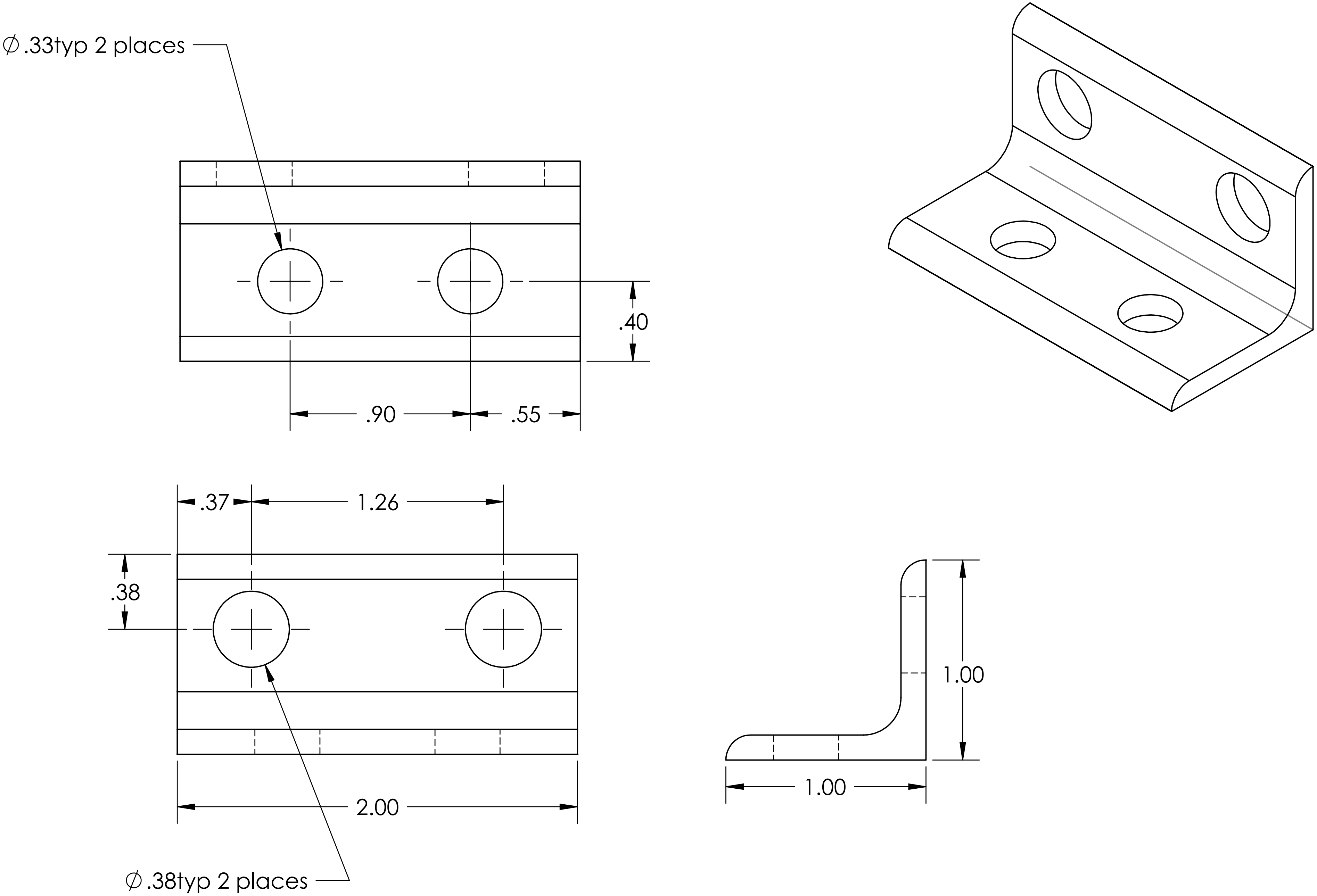
ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Steel	Portland State Tram Brake Team			
	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 20	REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:1	SHEET NO. 1 of 1	







ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL ± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL SS	Portland State Tram Brake Team			
	FINISH --	DRAWN BY TL	SIZE A	DWG. NO. 21	REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:2	SHEET NO. 1 of 1	

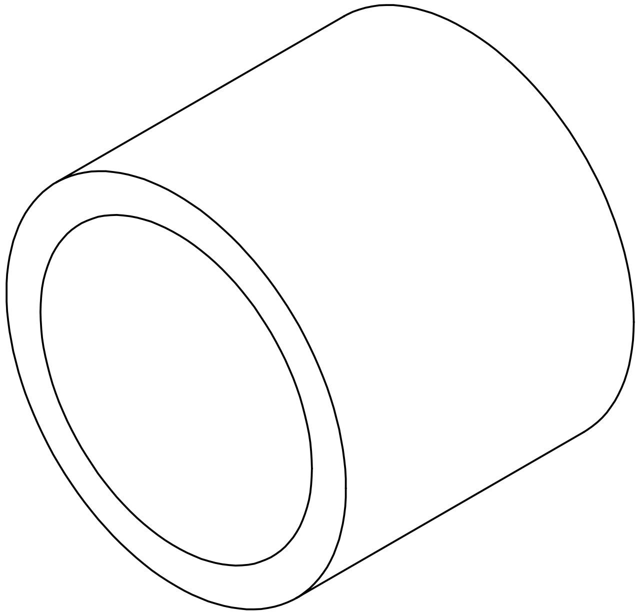


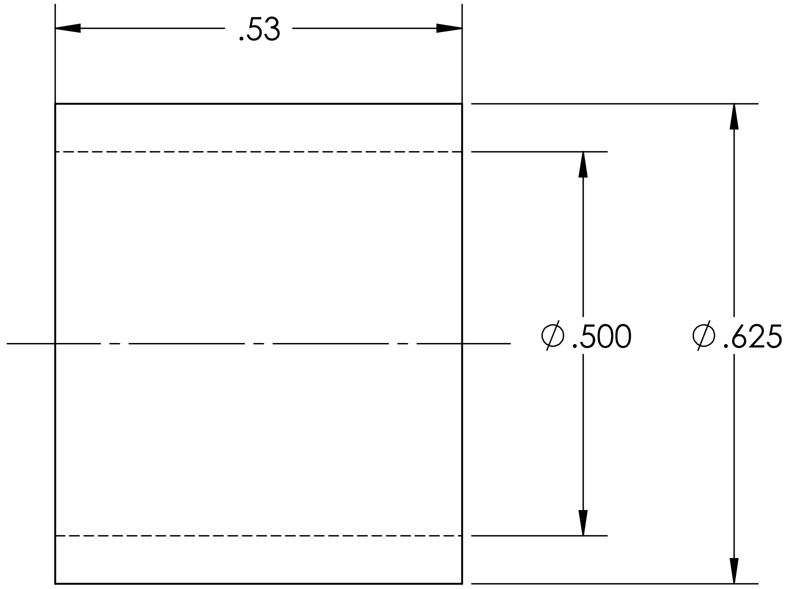
ALL DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED
TOLERANCES:
FRACTIONAL± 1/16
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

MATERIAL Steel
FINISH --
DO NOT SCALE DRAWING

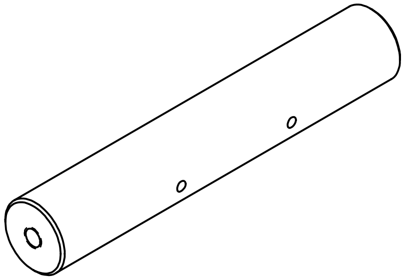
Portland State Tram Brake Team

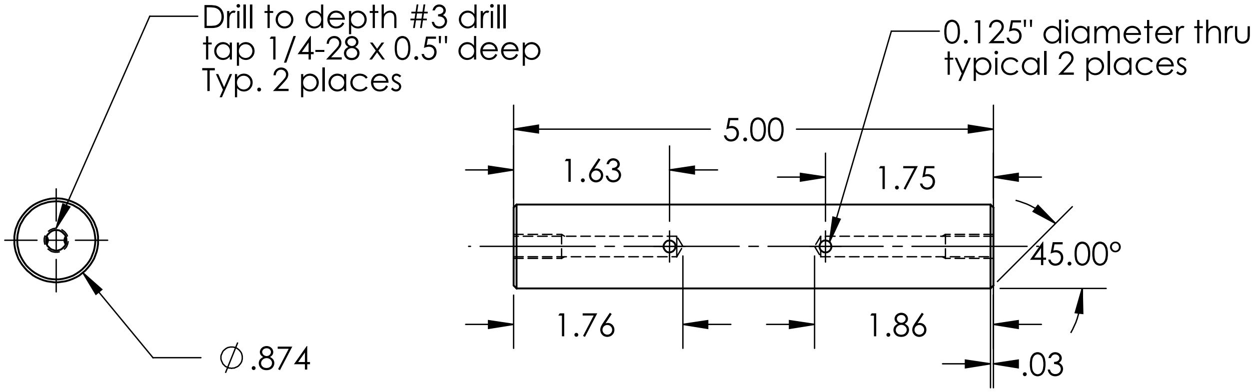
DRAWN BY TL
SIZE A
DWG. NO. 22
REV. --
DATE 5/1/2010
SCALE 3:2
SHEET NO. 1 of 1





ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Brass	Portland State Tram Brake Team				
	FINISH 32	DRAWN BY TL	SIZE A	DWG. NO. 23		REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 4:1	SHEET NO. 1 of 1		





ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED TOLERANCES: FRACTIONAL± 1/16 ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.001	MATERIAL Steel	Portland State Tram Brake Team			
	FINISH 32	DRAWN BY TL	SIZE A	DWG. NO. 24	REV. --
	DO NOT SCALE DRAWING	DATE 5/1/2010	SCALE 1:2	SHEET NO. 1 of 1	