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In response to the shelter-in-place order, this project has shifted towards designing a framework for future testing when facilities and labs become accessible again. A solid model was designed on Solidworks to provide an illustration of the intended construction of the testing apparatus. Standard operating procedures (SOP) were created to explain how each step of the testing would have been run. Similar literature data were collected to provide references on wear rate data and expected life spans for sliding shoes when comparing the test data conducted in the Superway facility. To achieve the optimal operating parameters and determine the lifespan of the sliding shoes, a physical lab testing will be the next step for future work because unique conditions in Superway's facility such as dust build-up on the rail and joule heating both influence changes in wear rate.

Best regards,

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

This project focused on the development of a third rail power system as part of the Spartan Superway elevated podcar network, in collaboration with the SJSU Mechanical Engineering Department. While the prototyping and construction is under the purview of fellow students in the Mechanical Engineering Wayside Power Team, the materials used are an equally important aspect to the performance of the final design.

The ultimate goal of presenting a materials selection is dependent on the ability to measure wear and conductivity properties for the chosen materials. In addition, another goal is to determine the proper balance of normal force on the shoe and amperage to minimize wear rate and extend the lifespan of the sliding shoe used for the project. For the former, the use of a pin-on-disk device is standard tribological practice.

There are a multitude of variables that affect the rate of wear for a conducting carbon-on-steel system in addition to the normal pressure and linear sliding speed that are standard: the voltage difference and current interact with the sliding speed to cause additional wear not present for a non-conducting system

This project was initially projected to measure the effects of typical operating parameters on the sliding electrographite shoe regarding their max lifespan. The experiment must have been observed in a physical lab setting, so a wear-testing apparatus was designed for the graphite current shoe collector based on a pin-on-disc. The testing apparatus is a jig that fits onto an existing Buehler metal sample polishing grinder on loan from the Materials Engineering department as a measure to fit within the limited Spartan Superway budget, as well as to keep the design flexible for future use by Mechanical Engineering students for other Superway needs once the base grinder was returned. This resulted in a design as flexible as possible to accomodate any sort of horizontal spinning plate as a driver. Amperage, normal force on the shoe, speed and distance will be the operating parameters to adjust and to measure how aspects of the shoe such as friction coefficient, wear volume loss, and conductivity will be affecting the expected lifespan of the shoe.

Design constraints for this project are relatively few, aside from constraints that all projects face such as time, funding, and access to equipment. Specifically for this project, the electrical testing conditions for the pin-on-disk machine should be congruent with the specifications laid out by the Power Module team at the Superway. These requirements will affect the operating conditions under which the tests will be performed and are vital to getting a complete understanding of how the unique conditions of this application will affect the material choice.

1.2 Broader Considerations

As with any major project, there are more considerations to be made for the 3rd rail than just the technical feasibility and basic design of the system.To fully meet the needs of the Mechanical Engineering Wayside Power team, the Power Module team, and the Superway project as a whole, there were many considerations made in addition to the simple technical challenges encountered during the design process. Of these considerations, one of the most important was that of ensuring that the work done this year would be easily usable by future Spartan Superway students, due to the limitations on in-person fabrication and testing imposed by the COVID-19 crisis. One of the main components of the designed machine, the Buhler sample grinder, is a piece that is on loan from the Materials Engineering Department, and thus its eventual return to the Department must be considered. If the apparatus were to be designed solely around the sample grinder, then the rest of the assembly would become obsolete and useless as soon as the grinder is returned. Instead, considerations were made in order to keep the design as flexible as possible: the design includes modular t-slot aluminum rails that allow the main assembly to be easily modified to fit any sort of spinning disk mechanism, as well as use existing parts and stock that is already in use at the Spartan Superway for other projects. By providing future Superway students with the resources needed to efficiently conduct their own wear testing, the total impact of this project may end up extending beyond the initial scope.

CHAPTER TWO
BACKGROUND

2.1 Technical Background

The design process for this project is centered around taking well-established principles and applying them to a novel problem. The use of carbon collector shoes for electric trains of all sizes is not new, and therefore the unique challenges this project faces are best understood with s prerequisite knowledge of the principles that underlie the design problems.

2.1.1 Tribology

The main goal of this project was to quantitatively determine what materials and conditions would be optimal for the 3rd rail system used by the Spartan Superway. In order to generate a set of data that provides suitable information to make that decision, some sort of wear-testing machine must be used. The study of friction, wear, lubrication, and the design of bearings or the science of interacting surfaces in relative motion is known as *tribology* [1], and it is these tribological practices that guide what the design of the wear testing machine should look like.

2.1.2 Standard Pin-on-disk Apparatus

To measure the properties of the sliding shoe collector under various conditions, a testing apparatus that simulates and measures the necessary parameters was needed. It is common practice to use a *pin-on-disk* machine to measure the wear rate for a sliding system, a variation of which is shown in Figure 1. The mechanism for a standard pin-on-disk machine is given by the *ASTM G99-17: Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus*, the basics of which are summarized as follows:

> The two materials that are to be tested in contact are the *pin* and the *disk* materials. The pin consists of a 10mm diameter ball, which is stationary and provided with a consistent downward force. The disk is below the pin, and spins to provide lateral movement with

respect to the pin. The wear on the pin is given by loss of volume, calculated either directly from the wear scar on the spherical head of the pin or extrapolated from a loss in mass given a known density.

2.1.3 Necessary Modifications

While the standard pin-on-disk apparatus is designed only to measure friction wear (which itself has a number of variables), for the intended purpose of a sliding electrical contact, additions to the procedure must be made. In addition to mechanical wear caused by the sliding of the contacts over the rail material, there is electrical wear on the contacts as a result of the high voltage current flowing through the conductive shoe. As a result, there were a total of three important factors to consider for this test: the type of graphite used for the conductor shoe, the force that holds the shoe onto the rail, and the electrical parameters used for the testing. Each of these factors would be varied in order to build an accurate picture of what the optimal material to use would be, and under what conditions it would have the most optimal performance.

When used for sliding contacts, there are a variety of different graphite compositions that each come with their own benefits and drawbacks. The oldest of these compositions is pure — or at least mostly pure — carbon graphite, which is still often used in industrial applications. This composition has the advantage of being simple to produce and relatively robust, as well as providing a variety of favorable properties such as self-lubrication: the carbon dust produced as the graphite wears is a dry lubricant that can help to mitigate further wearing. Graphite is also mixed with metal dust in a process known as metallization, and combining graphite with copper or silver can vastly decrease the resistance and increase the current carrying capability of a standard carbon graphite. Of course, these metallized graphites come with tradeoffs, notably cost and hardness, the latter of which may significantly affect physical wearing.

The second parameter to be explored was the amount of normal force needed to adequately maintain even and constant contact between the third rail and the shoe to minimize the wear rate. If the normal force is too high, friction will cause undue physical wear, however low force causes sparking and arcing from the high voltage, resulting in electrical wear. In addition, for the purposes of repeatable testing, the downward force on the pink to the disk should be precisely normal. When the current collector is in use, it will not be to such tight tolerances, however, for the purposes of data collection, the force vector must be adjustable to allow for tuning of the system.

The next parameter that was needed to be accounted for was the electrical current that runs through the carbon shoe and rail material. The current that passes through the shoe causes a significant amount of wear if the normal force is insufficient to prevent arcing. To add this functionality to the testing apparatus, a power supply was connected in a circuit with the shoe and rail system, with current flowing in through one of the shoe samples, through the rail material that is spinning on the disk, and out through a second carbon shoe.

In addition to these three physical parameters that must be optimized, there was another challenge to consider: the material loss in each sample must be measured precisely to comply with ASTM G99 standards, where the resolution of the measurement must be at the nearest 2.5 μm if the wear is to be measured by volume or the nearest 0.1 mg if the wear is to be measured by mass. Given the limited time frame of a single school semester, the volume of material that would be lost during the testing process would be very small, and therefore having precise measurement techniques was essential.

2.2 Literature Review

Tribology as a field of study is broad and spans multiple disciplines. While it is most often associated with the material sciences, the domains of mechanical engineering, electrical engineering, and chemical engineering are all closely related to how a part will wear under specific circumstances. For this design project for the Spartan Superway, there is an abundance of literature relating to the wear of collector shoes and rails when integrated into a power distribution system. The use of carbon graphite as a conducting material for a rotating commutator is not new, as the technology itself dates back to the late 1800s when carbon brushes began to replace copper wire brushes for use in DC motors. Beyond their initial rudimentary application, as early as the 1940s and 1950s research into the wear rates and wear patterns of carbon graphite brushes for use in brushed motors began being conducted and published [2] [3].

2.2.1 "Wear mechanism of aluminum–stainless steel composite conductor rail"

For the purposes of the Spartan Superway, however, more specificity in testing is required. This comes in the form of the key paper for this design project, "Wear mechanism of aluminum–stainless steel composite conductor rail sliding against collector shoe with electric current" published in 2007 in *Wear* by authors Dong, L., Chen, G. X., Zhu, M. H., & Zhou, Z. R. [4], where the researchers from the Tribology Research Institute at Southwest Jiaotong University developed a system to run a constant current through a pin-on-disk testing machine in order to measure wear on a copper-impregnated carbon brush with varying levels of normal force and current. This setup has a number of differences from the case of motor brushes, specifically in the geometry of the testing apparatus, volume of current, and applied normal force. This paper is instrumental in providing guidance in the form of a set of known parameters for a similar experimental setup to the one outlined in this design project.

Before finding this paper, the proposed testing values for the normal force were estimated to be 4 or 5 times higher than the 50 N normal force that was found to be optimal for Dong et. al.'s experimental setup; while the optimal parameters for the running of the 3rd rail power system cannot yet be known before the testing is complete, this key paper provides context as to what results should be expected. The relationship between current, normal force, and wear rate are shown in Figure 1, and illustrates the idea that poor surface contact causes more wear than physical friction.

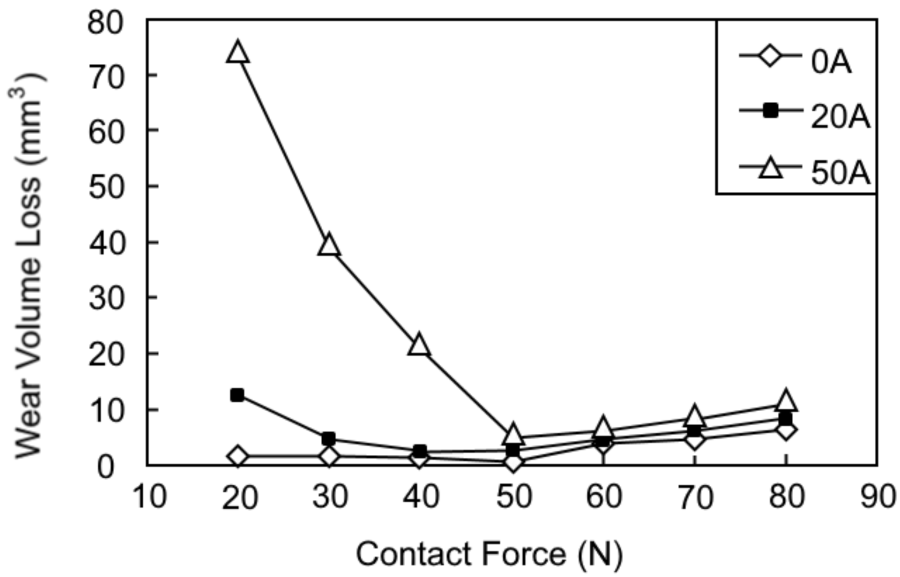

Figure 1. Wear volume loss /mm^3 versus normal force for graphite-on-aluminum wear [4]

As Figure 1 implies, if only the reduction of wear on the carbon brushes is taken into account, an excess of normal force is preferable to too little pressure on the rail. Specific testing for this application will be required to determine the necessary normal force for the geometry of the Wayside Power Team's carbon collector shoe.

2.2.2 "Study on Third Rail Current Collector Shoes Wear of Metro Trains"

The second main research paper that was considered for this project, "Study on Third Rail Current Collector Shoes Wear of Metro Trains", published for the 2016 International Conference on Logistics, Informatics and Service Sciences by authors Yang, C., Cai, G., Li, X., & Bo, J. [5], provides a real-world look into how the actual operating conditions of a 3rd rail power system cause wear on a carbon collector shoe. For the research, a total of 8 brand new carbon collector shoes installed on two different operational trains on the Beijing Subway Line 9 were measured at roughly equivalent distance intervals, and the thickness of the shoes was measured to determine wear on the part.

The findings of Yang et. al., shown in Figure 2, demonstrate that the wear rate of 3rd rail power system collector shoes is not constant, rather the wear rate changes as the shoe is used. This knowledge is important, as it serves as an example that every relevant variable is often not thought of at first. Before reading this paper, it was assumed that the wear rate of the carbon shoe would remain constant, given that there is a mechanism in place to maintain force on the collector shoe. With the insight from this paper, however, that assumption will not be made and the possibility of the wear rate being variable with total distance will be considered.

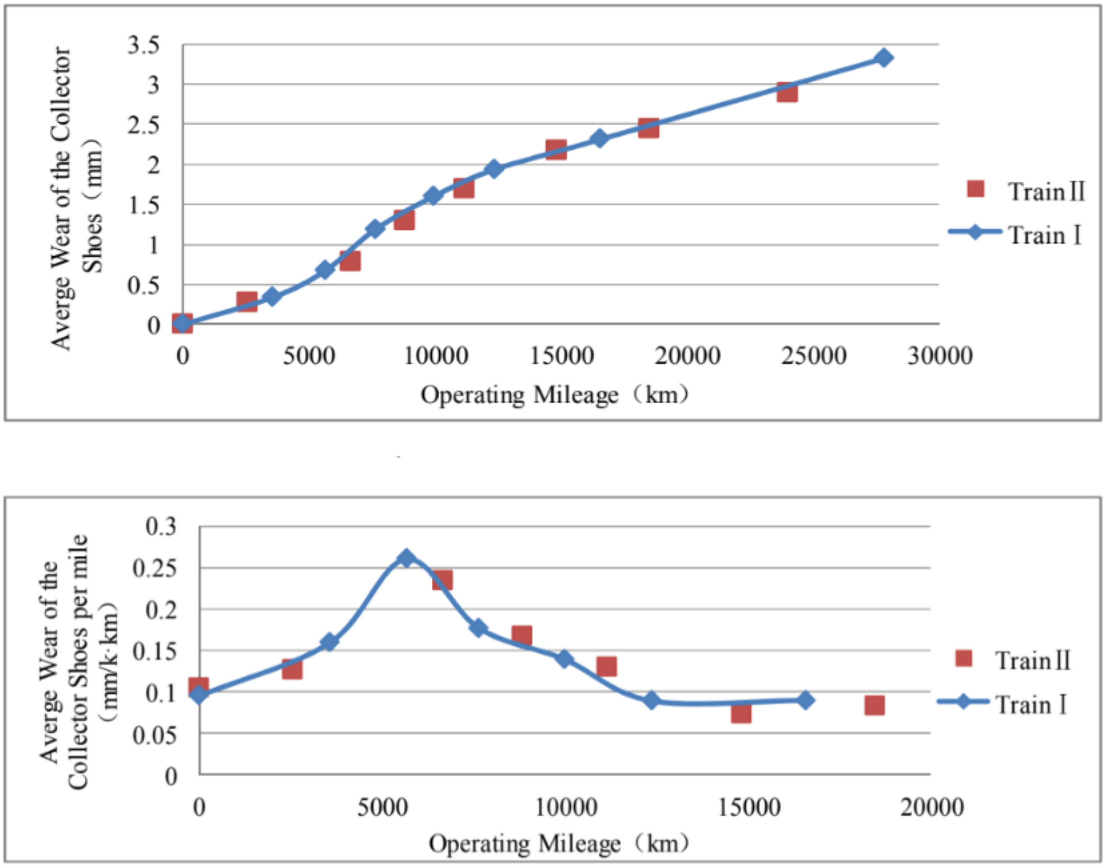

Figure 2. Average collector shoe wear and wear per mileage [5]

2.2.3 “Tribological Behavior of Copper–Graphite Powder”

The third main paper, “Tribological Behavior of Copper–Graphite Powder Third Body on Copper-Based Friction Materials” was published in tribological letters in 2015 and was conducted by Su, L., Gao, F., Han, X., Fu, R., & Zhang, E. [6], investigating the tribological effects of varying compositions of carbon-metalized graphite shoes at different speeds. This paper suggests that the friction coefficient of a 90% graphite to 10% copper shoe is nearly identical to a pure graphite shoe, yet can resist crack growth more than the pure carbon sample. The similarity in the friction coefficient is valuable knowledge that can be considered to narrow down the possible types of samples used for testing.

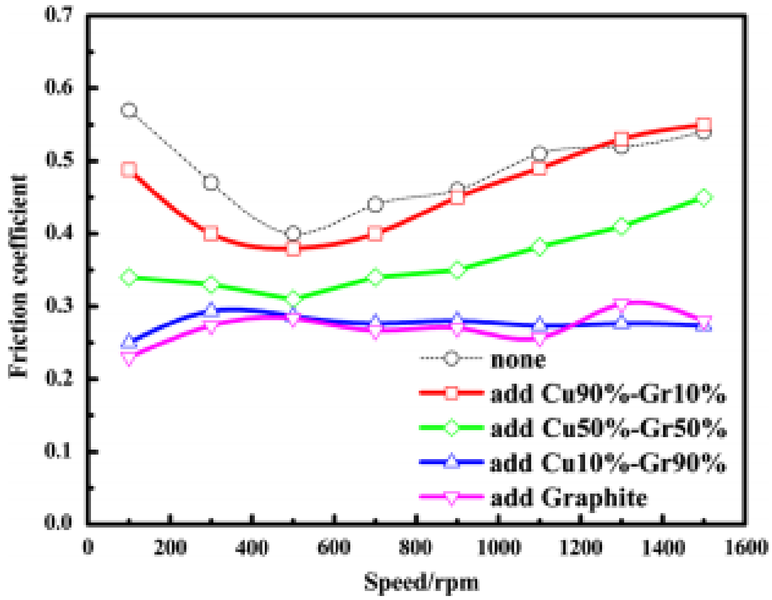

Figure 3. Various friction coefficients of copper-based shoes under different speeds [6]

This paper does not, however, investigate current as a cause for a change in friction coefficient or wear loss. This does raise the question of whether a 90% graphite to 10% copper mix or a pure graphite shoe will perform similarly in terms of conductance, friction coefficient, and wear loss when current is applied. As such, future work on this project will hope to answer these questions by following the same parameters as this paper while applying different loads of current.

CHAPTER THREE
PROCEDURES AND COMPLETED WORK

3.1 Experimental Procedures

The approach for the design and procedure follows the ASTM G99-17 standards consisting of three main components, the frame, pin-alignment linear bearing, and pin holders [7]. These designs were built on Solidworks. The frame is designed to be mainly dependent on single t-slotted aluminum extrusions since a majority of designs at Superway also rely on the same part. This allows for more off-the-shelf parts to be used and lower the cost of manufacturing new custom parts. The device in the middle is the Beuhler sample grinder where the frame will be retrofitted onto the grinder.

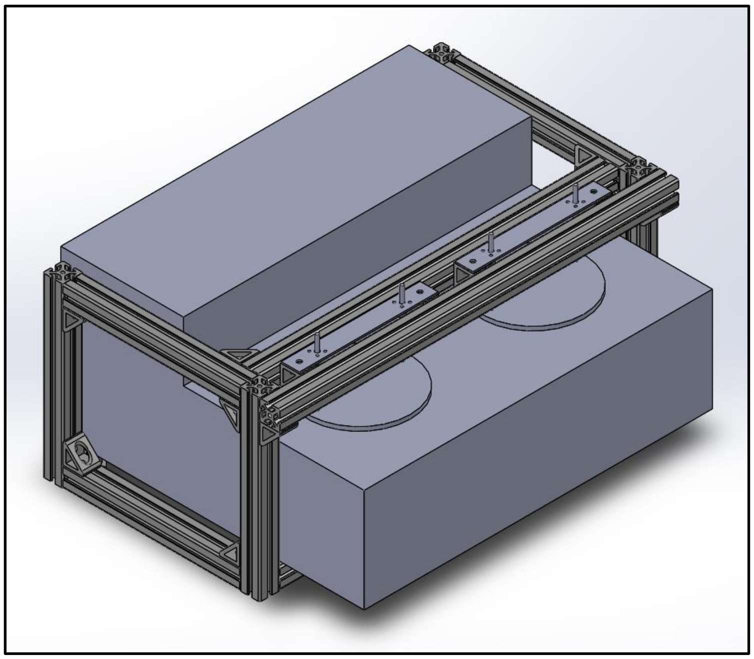

Figure 4. The frame to secure the pin is built with single t-slotted aluminum rails.

Next, the pin alignment linear bearing is secured by fine-threaded adjustment screws. Figure 5 illustrates how this is accomplished.

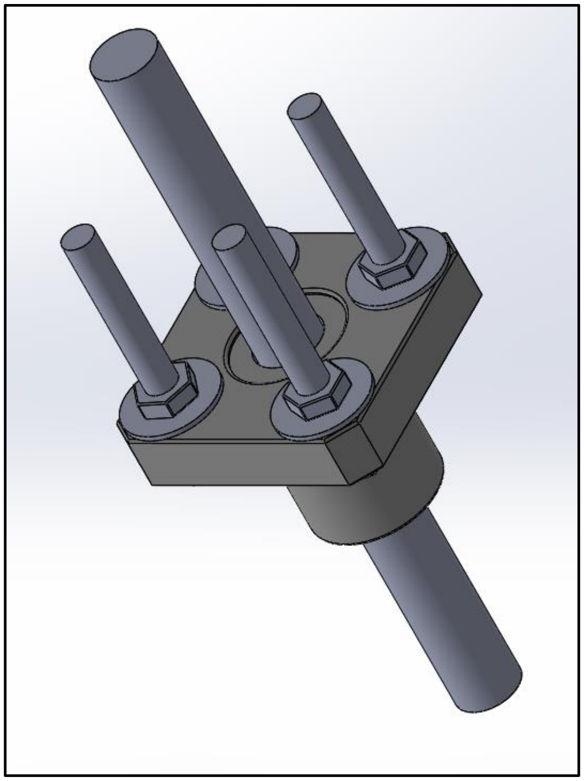

Figure 5. Flanged linear bearing holding the shaft

The reason for using adjustment screws to fasten the bearing is to allow the linear bearing to adjust its angle to be perpendicular with the sliding surface within 1 degree. Designs of the pin holder were made by the mechanical engineering Wayside Power team, shown in Figure 6. Power is conducted through these pins to charge the supercapacitors and batteries that run the podcars while they are between stations. A shunt is connected at the top end of the pin and exits out the rectangular opening to connect onto the main lead.

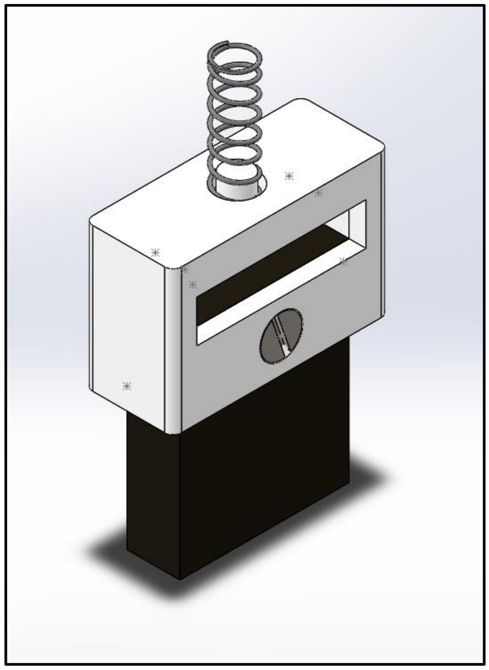

Figure 6. The prototype shoe holding mechanism for testing

The full brush mechanism consists of three thinner brushes that work together to handle the current needed for the charging of the supercapacitors. The dimension of the brush is 0.625 inches thick, 2 inches wide, and 2.5 inches long, with this specific form factor designed to accommodate for the geometry of samples provided by Helwig Carbon.

The first step of the procedure is to have the samples and track cleaned off of any dirt and film. Measurements of the initial size for the samples are taken with a dial gauge to the nearest 2.5 μm. The sample is inserted into the pin holder and fastened with the countersunk screw. Alignment is corrected using the adjustment screws so that the shaft is pointed perpendicular to the sliding surface within one degree. Weighted rings are loaded to sit on top of the shaft collar to the specified amount of force, a measurement is made from the distance of the sample's center point away from the center of the disc to determine the sliding speed. The power supply is turned on as well as the rotation counter, and the sample is to start its run under load. Once the run is complete, everything is powered off and the samples are cleaned again to remove any debris.

3.2 Results

The design choice allows for a modular approach where the fit of frame can adjust to other devices powering the rotation of the disc in the event the sample grinder cannot be used. An order of operation and key steps, from the SOP, will ensure the collected data is precise and repeatable so that the experiment satisfies the ASTM G99-17 standards.

Because of the shelter-in-place, the results for data analysis would not be possible to conduct. However, literature research of data similar to that which would have been conducted in Superway, reports that there is a specific balance of amperage and normal pressure where the wear rate is at a minimum [4]. In their research, they found that their graphite pin with a contact surface of 78.5mm^2, 50 N force, and amperage ranging from 0-50A, had the least amount of wear rate of mm^3 volume loss. This is their threshold value for normal pressure which equates to 0.64 MPa [4]. This information is not enough to make definitive statements about the optimal parameters for the Superway Wayside Power collector shoe design, however it does provide a baseline for future work to compare with.

In regards to testing for impact resistance of the brush or pin, applications analyst Admir Karabegovic, mentioned that physical lab testing would be the most reliable way to measure the sample's ability to absorb impact energy. Grades of electrographite have different material properties where parameters such as hardness and flexural strength are tailored to different applications [8]. Figure 7 lists different grades of this material and their properties.

Grade	Resistivity OHM-IN	Resistivity µOHM-M	Shore Hard	Strength PSI	Strength N/mm²	VD	CF	Film #	Rated Current Amp/in²	Rated Current Amp/cm²
H45	0.0025	62	55	3300	22.8	H	VL	3	80	12.4
H46	0.0010	25	25	1500	10.3	M	L	2	80	12.4
H47	0.0025	62	40	1500	10.3	H	L	2	80	12.4
H49	0.0025	62	45	2000	13.8	H	L	2	100	15.5
H50	0.0021	52	60	2900	20.0	M	L	2	90	14.0
H51	0.0022	55	60	3200	22.1	M	VL	2	80	12.4

Figure 7. Different grades of electrographites from Helwig Carbon; grade H51 is the grade Wayside Power team had chosen to use for prototyping

The H51 grade is used in railroad applications because of its medium level of hardness and stiffness, which in Helwig's experience, reduces the probability of major fractures. A middle degree of hardness is also able to deform more, allowing the material to handle faster strain rates.

CHAPTER FOUR
CONCLUSION

4.1 Summary and Conclusion

Once the shelter-in-place order started, the original direction and deliverables of the project had to shift. The deliverables that could not be completed were addressed first: construction of the testing apparatus, measure wear rate, measure material properties. As a response to this constraint, the solution was to focus on providing the next team with a framework and resources they can reference for when future work is done. The main accomplishments come from learning to design the testing apparatus using the CAD program Solidworks, establishing a standard operating procedure to follow, and collecting data from literature to estimate frequency of maintenance. Results from literature search provided data that is similar to the information this project aimed to collect. Dong et. al.'s experiment states that too much or too little normal pressure and current load dramatically shortens the mileage of the shoes due to mechanical and electrical wear.

For future work, there are factors that were not considered in the design that could impact on how the testing is conducted. The mechanical engineering team, in their prototype for the current collection system, uses a triple shoe system to handle the high current. This allows for smaller individual shoes to be used, however an issue may arise where, as a result of uneven contact force, one shoe is taking more current than intended, reducing its life. This is an additional parameter that could be considered in future testing.

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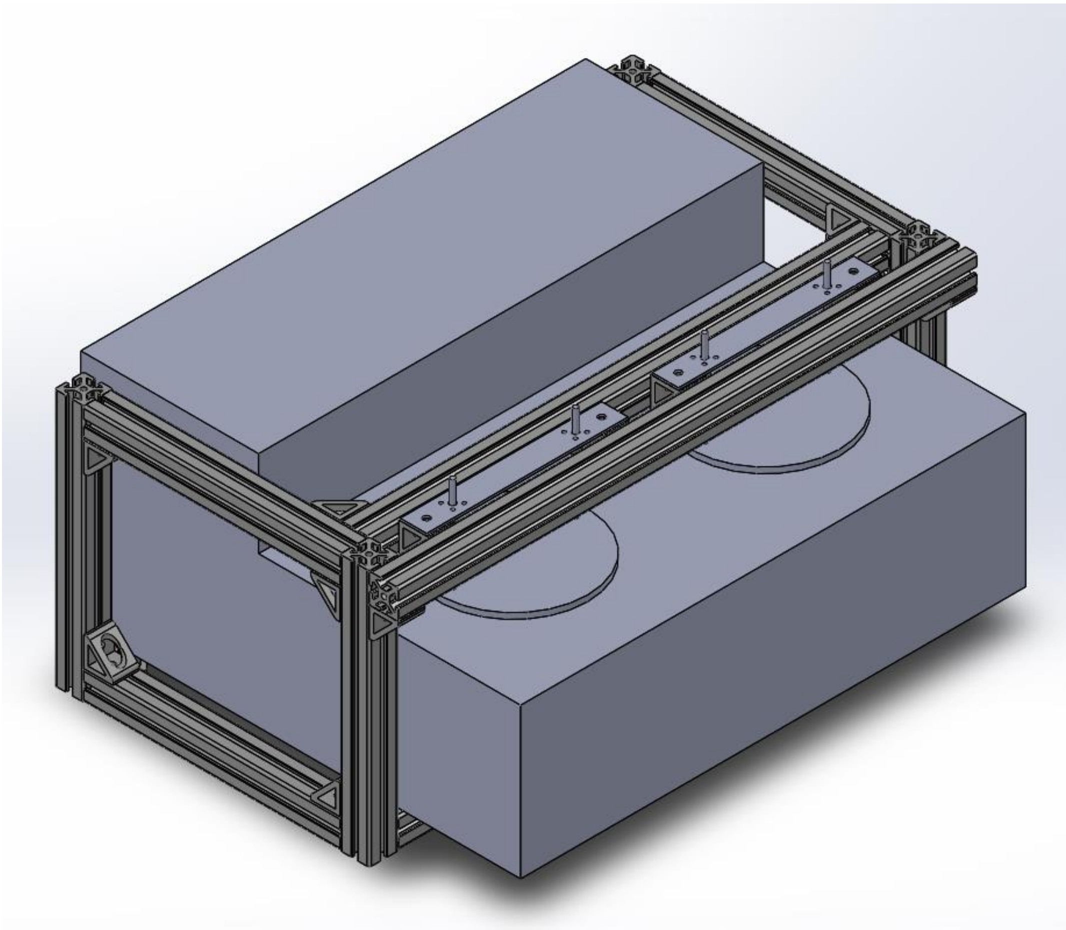
Appendix

Standard Operating Procedure:

Pin-On-Disk Testing Apparatus

By Chuong Nguyen & Ryan Tong Rev. 4 May 2020



SPARTAN SUPERWAY

Purpose	Scope
This SOP is intended to provide users with a structure on how to operate this testing apparatus from start to finish. The guide will outline the preparations and cautions that are needed to be factored in to ensure the collected data is precise and repeatable.	The procedure will cover the procedure in the usage of the apparatus and a set of operating parameters. Changes in or additional operating parameters such as speed and temperature of the sliding contact are outside of the range this SOP will cover. If the user wishes to change parts of the design such as the spinning disk, the crucial parameters to keep in mind are the normal force, amperage, speed, and the distance.

1. Sample Preparation

A. Clean and dry the pin and disk with isopropyl alcohol from any dirt and film
B. Measure the dimensions of the pin sample to the nearest 2.5 μm. This can be accomplished with a dial gauge or any other measurement device with sufficient precision

2. Loading the Sample

A. Lift the pin shaft to insert the pin sample into the pin holder
B. Ensure that the pin is fastened securely using the set screw

3. Leveling the shaft

A. Adjust the set bolts on each shaft until the sample is perpendicular to the sliding surface
B. Using a gauge block or other perpendicular measurement device as a reference, check the alignment of the shaft at three times: two measurements at 90° offset, and an additional measurement at 45° between the previous two measurements

4. Preparing the Apparatus

A. Add weighted rings on top of the shaft clamp to create the desired amount of pressure
B. Turn on the rotation counter device and set the targeted amount of rotations
C. Measure the distance of the sample's center point away from the center of the disc
D. Check the settings on the power supply: either projected current or voltage depending on the testing parameters
E. Start the test with the sample under load

5. Measuring the wear

A. Turn off the apparatus and disconnect the power supply
B. Lift the shaft and remove the sample from the holder
C. Clean off debris from the face and rear of the pin, ensuring there is no physical contact with the wear face
D. Measure the sample dimensions again using the same method as the initial measurement

6. End-of-Test Maintenance

A. Ensure that parts of the machine such as the spinning plate have adequately cooled down from operation
B. Wipe down the exterior of the machine of any debris

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[1] Dong, L., Chen, G. X., Zhu, M. H., & Zhou, Z. R. (2007). Wear mechanism of aluminum–stainless steel composite conductor rail sliding against collector shoe with electric current. Wear, 263(1-6), 598-603.

[2] ASTM International. (2017). G99-17 Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. Retrieved from https://doi.org/10.1520/G0099-17

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- **Francisco Alolong, Jr -** VTA Junior Transportation Engineer
- **Admir Karabegovic -** Helwig Carbon Applications Analyst