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Innovative Hybrid Braking System

Engineering Report

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Abstract

The presence of Copper in water in high concentration can be a risk to plant and crop growth as well as for human health. A lot of the copper found today in water streams originates from worn out components of braking systems on cars and other vehicles. This is why our team has come up with a braking system that reduces friction braking, and thus elongates the longevity of the brake before it wears out. This is achieved through the use of a contactless magnetic brake, coupled with a regular brake, as the former is only effective at high speeds.

Acknowledgements

Our team would like to thank our mentor, Dr. Kyle Mulligan and our clients at McGill's Tractor Pulling Team for their support and interest in our cause; Prof. Chandra Madramootoo for his perpetual guidance; Mr. Scott Manktelow for his relentless assistance; and our reviewer, Prof. Viacheslav Adamchuk for his patience and advice.

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Introduction

From routine drives to and from the workplace to long-distance hauling services, automotive vehicles are ever-present in our daily lives. And while their pollution, efficiency and fuel consumption are often addressed within the context of innovative ideas and initiatives, there are still quite a few challenges to surmount in order to turn automobiles, trucks, or trains into completely sustainable means of transportation. Amongst those challenges is the friction braking mechanism used to stop or slow down a typical vehicle. In fact, conventional braking systems, partly composed of brake pads clamping down on a wheel's rotor when engaged, contain considerable quantities of copper. Once activated, the friction between the pads and rotor can cause the brake to wear out, and thus leading to copper falling off the components and onto the terrain. Once loose, the copper can be carried through runoff water and eventually settle in fields, potentially damaging the environment.

The ingestion of copper in high enough concentrations has been shown to be detrimental to human health. Morris et al., (2006) conducted a large study on the intake of dietary ingredients coupled with the measurement of cognition over time and concluded that the people with the highest quintile of inorganic copper intake who also ate high-fat diets, lost cognition at six times the rate of other groups. Hence, not only would copper affect the physiology of humans but could also affect the brain with drastic results.

Beyond human consumption, however, plant contamination with large amounts of copper, as stated by Graves et al., (2004); Schuler et al., (2008); Jančula and Maršálek, (2011), is extremely damaging. As it turns out, copper has a concentration-dependent phytotoxicity to algae, phytoplankton, and plants. In fact, it is often used as an aquatic herbicide due to its ability to modify or limit plant development in the aforementioned range of organisms. In contrast to this problem arises another possible issue stated by Calabrese and Baldwin, (2003), where copper is an essential micronutrient for plant growth but can also be limiting in some aquatic systems, meaning that although copper is phytotoxic to some organisms, it might promote plant growth in other unwanted or invasive organisms. An example of this is the species of aquatic fern *Salvinia molesta* which is an invasive exotic in the United states and other countries that spreads very quickly via vegetative propagation. Rai, (2009) states that species of *Salvinia* can be found in contaminated waters and are known to sorb soluble particles. Shupert et al., (2013) found that the growth of this invasive plant was enhanced in the presence of copper and iron from brake pad wear debris, and that this is also true for other types of invasive macrophytes.

Vision Statement

Based on the problem analysis, the vision statement for our endeavor has been formulated and is as follows:

“At the crossroads of cutting edge technology and green-thinking stands our design: the hybrid braking system is a product designed by innovators, for innovators. By combining traditional and cutting-edge technologies, we aim to improve transportation and push for sustainable agriculture, and safe water.”

Design Procedure

To address this issue, a design process was launched and followed from the specific problem identification to finding a viable solution and eventually unveiling the results to the interested parties. The procedure was kicked off with a close analysis of the problem as previously explained. This problem served as a justification for the design’s need.

Once the specifications and details were obtained, the brainstorming process was started: in order to eliminate the problem, we could either bypass it by introducing copper-free pads. However, this would have left the possibility of other hazardous materials damaging the living environment, like, for instance, asbestos. Further, as Aranganathan and Bijwe (2016) discovered, alternative-composition brake pads tend to perform below standard efficiency, which, in a context as serious as driving, is unacceptable as sub-par results can endanger the user’s life. Thus, the bold path was opted for; the initial concept was to remove friction braking from the equation altogether. And while this idea seemed ideal, and, initially, conceivable, literature reviews and simple physics review revealed the speed-dependence of magnetic brakes, and their inefficiency at low velocities. Hribar (2008) states that braking force is directly proportional to speed, which means that an electromagnetic eddy current system alone can never completely stop a vehicle running under a certain velocity threshold. In other words, as the speed of rotation of a wheel approaches zero, eddy currents become almost obsolete and the braking force that they produce becomes too small to slow down the vehicle and hold it in place in a static position. This key piece of information is the basis through which the best solution to this complex issue was spawned.

Following that, the work was devoted to obtaining the ideal solution. This long and challenging process spanned 4 months, which were spent on literature and data gathering, theoretical analyses, modelling, and calculations. Eventually, a satisfactory design, which is detailed subsequently, was determined. In short, the mechanism selected to mitigate the copper problem was a middle ground between a purely electromagnetic and an exclusively hydraulic braking system: the hybrid braking system incorporates the two technologies to combine efficiency and sustainability in order to improve transportation. The four-month process that led up to finding this concept was also a catalyst to finding a mentor as well as a client who turned out to be interested in the initiative.

Together, they provided tools, both material and intellectual, as well as guidance to carry forth the successful implementation of the idea.

Context of the Project

Mentor

Dr. Kyle Mulligan is currently the Assistant Chief Mechanical Engineer at Canadian Pacific Railway and has also previously worked as an engineer for Bombardier Aerospace. Dr. Mulligan graduated in 2007 with a Bachelor of Engineering (B.Eng.) in Systems and Computer Engineering. He then completed his Master of Science (M.Sc.) in the field of Biomedical/Medical Engineering in 2009, before finishing his Doctor of Philosophy (Ph.D.) in Mechanical Engineering at the University of Sherbrooke in 2013. With his astonishing academic credentials, as well as his current position at Canadian Pacific Railway, Dr. Mulligan seemed like a great choice for a mentor. Additionally, his knowledge in equipment monitoring, which includes braking systems, has been a valuable asset in designing and conceptualizing our prototype. Dr. Mulligan has been an important resource since the start of the project by actively participating and supervising our progress. He has been providing valuable inputs for research criteria and idea generation which lead to interesting conclusions.

Client

Through a chance encounter and subsequent discussion, the executives of the McGill University Tractor Pulling Team, also known as MuTrac, came to know about the idea for a hybrid braking system. MuTrac is a student-run tractor design team consisting of Bioresource Engineering students which is based on the Macdonald Campus of McGill University, Canada. The main target for this team is to design and build a quarter-scale tractor to compete in the annual Quarter-Scale Tractor Pulling Competition which is hosted by the American Society of Agricultural and Biological Engineers (ASABE). While the hybrid brake isn't necessarily specific to tractor use, and by no means exclusive to agricultural vehicle use, MuTrac representatives approached the design team, expressing their interest in the project. In fact, they were primarily attracted to the design in the hope that the concept of hybrid braking system could be used in the report submitted to the Quarter-Scale Tractor Pulling Competition jury, as it could serve as an innovative edge over their rivals. Appreciating the collaboration as a decent platform for research and development for, eventually, moving on to larger markets, perhaps for which the hybrid braking system would be even more adapted, such as electric vehicles, lumber trucks using eddy retarders, roller coaster or trains, the offer from McGill's Tractor Pulling Team seemed to be a valuable opportunity as they would provide tools (tachometer), licenses (SolidWorks, etc.) and support in exchange for the right of using the concept in their own written report. This collaboration, although allowing much liberty with regards to testing and creativity, was not a free-for-all. In fact, the conception of the design was made considering the constraints of agricultural vehicles like tractors; this however didn't not lead the design group to forego the focus of ultimately marketing the product to vehicle companies. Hence, while the link between hybrid braking and competitive tractors may seem weak, the collaboration between the two teams was strong, productive, exciting, and mutually beneficial.

Product Design Specification, Quality of Function Deployment and TRIZ

The design of the hybrid braking system, although leaning towards overall versatility and adaptability to any type of common vehicle, was tailored to fit the specifications of our client. Hence, multiple tools were used to transform restrictions and constraints into guidelines and opportunities.

First off, the team based the product design specifications on requests made directly by the client as well as a large-scope vision and common sense. While this may sound quite abstract, translating those concepts into conceivable technologies was possible, and achieved through the use of Quality Function Deployment to narrow down the possibilities and potential models for the prototype.

In fact, QFD matrices were used to determine, in order, the design requirements, engineering concepts, product characteristics, the building and acquiring operations processes and the quality control of the model. This effective method was used in a loop every time possible improvements could be made on the product, following testing and feedback.

Moreover, in an effort to answer complex questions such as "why hasn't this been done before?" and "why would our design succeed where other people's designs have failed?", TRIZ (*теория решения изобретательских задач*), or theory of inventive problem solving, as it is known in English, was referred to.

To maximize the efficiency of the tractor and minimize the amount of power drained from the battery, the client specified that this hybrid braking system needs to be designed to use as little energy from the battery as possible. In other words, the braking system must consume very little power to allow for it to be diverted to other parts of the tractor.

Additionally, the ¼ scale tractor is subject to multiple stresses and strains throughout the competition. The boundaries of what machines are cable of doing and resisting without failing are pushed to the extreme. Thus, the second product specification defined by the client was that the braking system had to be strong enough and be able to sustain the stress exerted on it without failing, just as all the rest of the components of the tractor are subject to this criterion. To do so, the quality of the material for this braking system is crucial. The chosen materials must be sturdy and be able to perform under stress and heat.

Furthermore, in this competition every gram counts, and for each extra pound added to the tractor, a heavy price in power consumption is paid. This year, the tractor is already over the desired weight by around 45 kg, and MuTrac will be shaving every gram they can. For example, this year they have gone from using lead-acid batteries to lithium batteries to save on weight among other things, even if the cost is significantly higher. Thus, the client specified that this hybrid braking system had to be as lightweight as possible.

Finally, this is a student run organization and as in any organization money is always an important limiting factor. In order for this braking system to be implemented, it has to be adaptable. The client specified that ideally, the system must not be more expensive than the conventional system already in place. If it does cost more, it must be inside a very reasonable range.

These four criteria were the main concern for our client in order to gain a leading edge over their competitors in the competition. However, this design has the capacity of being very global and diverse in its possible applications. Depending on different criteria and objectives, the final product has the possibility of looking different from one project to the next in order to fit that project's specific needs.

Literature Review

Issues with conventional hydraulic braking

Hydraulic or friction braking has been around for a very long time mainly due to its advantages in compactness and effectiveness, but it does suffer from severe limitations. Gay and Ehsani (2006) list many of these limitations which include loss of braking force with increasing temperature (fading phenomenon), warping of discs and wear of pads and rotors, complexity and fuel consumption of power assistance, slow response time due to power assistance, complexity of controlling each wheel's braking independently, necessity of complex and costly anti-lock controls, risk of hydraulic fluid leak and risk of brake fluid contamination by water and subsequent loss of braking power, as well as challenging integration with anti-lock, traction, and dynamic stability controls. Another big issue with friction brakes is the cost of replacement parts such as pads and rotors once they wear down, and this will be examined more in depth further on in this report.

Advantages of a hybrid braking system

To remediate the issues with conventional friction braking systems listed previously, a hybrid braking system is proposed which would combine a contactless magnetic brake with a regular friction braking system. Gay and Ehsani (2006) maintain that a system of the sort would have many advantages over a purely friction based braking system. Some of these advantages include reduced wear, reduced sensitivity to fading, reduced fuel consumption of power assistance, faster control dynamics, easier integration with anti-lock, traction, and dynamic stability controls, easy individual wheel braking control, as well as mostly electric actuation. One key issue brought up here by Gay and Ehsani (2006) is the issue of using electromagnets versus using permanent magnets to induce the eddy currents. Permanent magnets seem to be the preferred choice because they don't need to be powered by an external source to induce a magnetic field, contrarily to electromagnets. The shortcomings of electromagnets include heavy weight, excessive power consumption, as well as vulnerability to power failure. Permanent magnets overcome all these shortcomings, and are advantageous due to their ease of control through electrical or mechanical means.

Inspiration from German ICE 3 trains

As stated in our approach, we plan on using a re-engineering technique to adapt ICE 3 train braking systems for use in agricultural vehicles. In order to re-engineer the existing system, we must first understand how it works. (Hribar, 2008) states that these trains are equipped with electromagnets placed very close to the rails which create eddy currents as the train moves forward and the electromagnets move over the rails. The eddy currents produced allow for quick, efficient slowing of the train. As previously mentioned however, this type of braking system can only slow down the train since the braking force is directly proportional to the speed of the vehicle, meaning that it becomes obsolete under a certain speed. On these types of trains, the electromagnetic braking system is complemented by a friction braking system to allow the train to come to a complete halt, usually using fin brakes to safely park the train once arrived at destination.

Adapting the model to agricultural vehicles

The most important piece of literature that we have found is a paper written by Sebastien Emmanuel Gay on the theory behind a contactless magnetic brake for automotive purposes (Gay, 2005). This paper includes an introduction to friction braking, a theory of eddy current braking, analytical and numerical models of the eddy-current brake, its excitation and power generation, a record of experimental validation, and an investigation and simulation of the integration of the brake in conventional and hybrid vehicles. This paper is very complete and provided us with many comparison points and interesting design concepts that have been useful in the design procedure. Also, this piece of literature gave us a starting point, and confirmed that a hybrid braking system was a feasible and worthwhile solution.

Electric machinery analysis

A variety of papers were also found and used as a basis for electric machinery-related calculations and theory. In this regard, Anwar and Stevenson's work on "Torque characteristics analysis for optimal design of a copper-layered eddy current brake system" (2011) was a cornerstone of our reasoning, as it offered not only accurate step-by-step procedure to solve torque-speed problems related to electric machinery in general, but more specifically gave profound insight about eddy current brakes, their vast range of advantages, and their inconveniences. Finally, "Effective Eddy Current Braking at Low and High Vehicular Speeds – A Simulation Study" (2017), a paper by Olisaeloka, Andrew and Chinagorom, describes adequately the performance of eddy currents at low and high rotation speeds, as well as an adapted and comprehensive method of determining critical speed for eddy current brakes functioning; a method we, of course, used to define our own transition speed between eddy current and hydraulic braking systems.

Heat transfer analysis

Gay's "Contactless Magnetic Brake For Automotive Applications" (2005) paper provides valuable information regarding the inherent properties of magnetic brakes as well as their behaviour in different situations. Coupled with an arduous study of Evtushenko, Gorbacheva and Ivanik's paper on "Thermomechanical Processes In The Friction Heating Of Disk Brakes" (1994), it is possible to develop a good sense of how a hybrid brake must be designed to be reliable under different conditions. More particularly, it provides extensive information and description of the state ofthe disc's surface, locus of most thermal reactions, throughout the braking process. On the other hand, Talati and Jalalifar's "Analysis of heat conduction in a disk brake system" (2009) provide the basis of heat transfer calculations, and the concept behind analytical solution methods, as well a guidance as to which formulae to use. Concerning heat conduction and generation in eddy current brakes, resources adapted to our case were hard to find, as our product is highly innovative and studies on electromagnetic brakes in automotive vehicles seem to be extremely hard to come by. However, since our design is profoundly inspired by Europe's ICE 3 trains, we based our analysis on "Rail temperature rise characteristics caused by linear eddy current brake of high speed train" (2014) Lu, Li et al., as it analyzed situations that could be adapted to fit our model.

Specific Considerations regarding tractors

While the hybrid braking system aims to be as versatile as possible in order to be eventually used in other vehicles than tractors, considerations based on our client's request had to be taken into account. The most obvious constraints, since we are talking about a small- scale tractor, is space use. Our prototype must be as compact as possible. This would also decrease its weight, as lightness is an important criterion, especially in the perspective of the ASABE competition. While hybrid braking systems are often thought of as bulky and expensive, we seek used components and parts to reduce manufacturing costs all while encouraging a circular economy. One last consideration, quite particular to our client's situation, was the type of magnets we would be using. While electromagnets enable a better control and enhanced consumption efficiency through regenerative braking, we decided to go for permanent rare earth magnets instead. This choice was motivated and justified by three critical reasons. First, building our own solenoid magnet could be a source of error and a risk, in a situation where risks and errors cannot be afforded, as the consequences could be quite grave. Then, permanent magnets are less costly, lighter, and immensely space efficient. Finally, the ASABE competition is a pulling competition. This implies that all the energy that the tractor can produce should be used for pulling; and a solenoid magnet would require power to function; whereas permanent magnets are always functional and regulated by the airgap (the distance between the magnets and the disc).

Proposed Solution

Based on the literature review, a definitive solution and design goal can be formulated. It consists of a hybrid braking system, composed of a magnetic eddy current brake coupled with a conventional friction mechanism. The functioning of eddy currents is governed by Lenz's law, which itself is based on Faraday's law of induction. It dictates that the direction of current induced in a conductor by a changing magnetic field due will be such that it will create a magnetic field that opposes the change that produced it. Mathematically, it is represented by:

$$\varepsilon = -\frac{\partial \Phi_{\mathbb{B}}}{\partial t} \qquad (1)$$

Where ε is the electromagnetic force, $\partial\Phi_{\mathbb{B}}$ the change in magnetic flux, and ∂t the change in time.

This solution was decided upon for several reasons, the main one being that as previously mentioned, eddy currents are only effective at slowing down a vehicle above a certain speed. This means that to have a complete braking system, we need an auxiliary system to complement the magnetic braking system under some critical speed. The system is fully automated so that when the vehicle slows down to the critical speed, the braking system switches from magnetic to hydraulic without any input from the operator of the vehicle. This critical or transition speed is low, meaning that the brake pads used in the hydraulic braking system get used much less than they regularly do and at much lower average speeds than usual. This reduces maintenance costs for worn out brake pads and rotors as well as reduce copper leaching to watersheds from brake pad wear, which is why this is the best solution to pursue.

Preliminary Results and Assessments

To ensure a decent functioning of our design and avoid risks and technical complications that could harm the manufacturer, tester, or even the consumer, a few technical analyses and prevention studies must be conducted. Closely related to risk prevention initiatives, the following analyses and calculations outline the main challenges faced and the results obtained by our team. The yielded data points towards measures that can and should be taken to respond properly to the challenges, and allow us to assess the solidity, integrity and limitations of our product.

Electric machinery

The main purpose of an electric machinery analysis is to determine the transition point between the hydraulic and eddy current brakes. This transition is determined by two factors: maximum reduction of friction braking and proper functioning of the eddy current brake. In fact, the main reason why hybrid braking is necessary (as opposed to simply having an eddy current brake) is that electromagnetic braking is rotation speed-dependent. Since the concept of eddy currents are governed by Lenz's and Faraday's laws, the magnitude of the eddy currents produced by the magnets' activities increases with rotational speed of the disc. Inversely, it decreases as the disc's rotation is slowed down, as does the efficiency of those eddy currents tostop the disc completely. Hence, below a certain point, eddy currents become ineffective and another type of braking must take over; in our case, hydraulic braking. In this section, we therefore determine the speed at which eddy currents become ineffective.

Functioning through the movement of a rotor (the disc) and a stator (the permanent magnets), the eddy current brake can be considered as a miniature induction machine, and thus, the principles valid to the latter can be applied to evaluate the behavior of an eddy current brake.

More specifically, we are interested in assessing the torque-speed relationship of an eddy current brake. This torque speed curve allows to verify the effectiveness of the eddy current brake when compared to the torque speed curve of the vehicle's engine.

To obtain the parameters necessary to conduct a legitimate assessment, the braking torque needed to stop the vehicle must be calculated. We will thus consider a standard case that will be used throughout all calculations in this section of the report. This case is an extreme braking situation, where values are overestimated so as to be conservative. In fact, if the braking system is functional in such a situation, it should be able to withstand practical situations with milder conditions.

With basic physics calculations, specified in Appendix 1, we find that the entire vehicle requires a braking torque of 980 N•m to be stopped. Thus, each brake must be able to reach a torque of 245 N•m at any given time, to prevent failure in case of emergency braking.

Based on the work of Anwar and Stevenson, the torque speed curve for a Neodymium eddy current brake was graphed (Appendix 1).

Using this data, one can notice that as the angular speed surpasses 800 rpm, the torque value plateaus. Peak torque thus either occurs at 900 rpm, or outside the scope of the measured points. However, it is possible to determine at what point the desired torque can no longer be provided by the braking system. In fact, below 280 rpm, the torque produced by the eddy currents is below 245 N•m.

By using this value, we can determine, through simple calculations (detailed in Appendix 1), the linear speed below which the eddy current brake on its own becomes insufficient. This critical speed is thus 14.78 km/h, which we can round up to 15 km/h.

Therefore, between speeds of 15 and 0 km/h, the hydraulic system must take over to ensure a safe braking process. Nevertheless, it is capital to note that any failure can be injury-inducing or even fatal to the conductor of the vehicle our system will be installed on. Thus, it is important to have a safety factor. In fact, although we aim to reduce friction braking, it seems evident that safety should be a priority in this case; which is why we decided to use a 1 km/h safety margin. Increasing the determined critical speed thus yields a new transition speed between the two systems of 16 km/h. In addition to the safety factor, the design includes an overlap speed r222ange, in which both systems are applied simultaneously to ensure maximum efficiency and security. Further, for ergonomic purposes, the code for the overlap period will be made such that linear braking is still possible, despite both systems being applied. This is explained in further details in the Programming section of this report.

Fluid mechanics

A common misconception associated with friction braking systems is that when the brake pads squeeze against the rotor, the *pressure* of the squeezing action is what slows the vehicle down. As it turns out, this is only part of the equation since brakes are essentially a mechanism used to change energy types. When a vehicle is travelling at a certain speed, it generates *kinetic energy* so that when the brakes are applied, the pads that squeeze against the rotor convert this energy into *thermal energy* via friction. The cooling of the brake then dissipates this thermal energy which slows the vehicle down. This whole process follows the First Law of Thermodynamics which is sometimes known as the law of conservation of energy. This law states that energy cannot be created nor destroyed, it can only be converted from one form to another. As previously stated, in the case of friction brakes, the conversion is made from kinetic to thermal energy.

In terms of fluid mechanics, friction or hydraulic braking systems work based on Pascal's law. The law states that pressure exerted anywhere in a contained incompressible fluid is distributed equally in all directions throughout the fluid. If we reduce the hydraulic brake model to a simplified two-piston system, the pressure exerted on the pedal side piston follows the relation $P1 = F1/A1$ and the pressure exerted on the wheel side piston follows the relation $P2 = F2/A2$ where P stands for pressure, F for force, and A for area. According to Pascal's law, pressures on both pistons are equal, giving us P1 = P2 and therefore $F1/A1 = F2/A2$. Finally, the force applied to the piston on the wheel side will equal F2 = $(A2/A1)$ * F1 which means that a small force applied to the pedal side piston will give a greater force applied to the wheel side piston assuming the area of the wheel side piston is greater than that of the pedal side piston.

Based on Pascal's law, we can set an area for the master cylinder at the end of the fluid line. Through calculations detailed in Appendix 1, we find that the required cylinder area, to ensure safety and maximum comfort for the user, is 0.0607 m^2.

Another interesting phenomenon associated with the thermodynamics of friction braking systems is the phenomenon of brake fade. Brake fade occurs when brakes are applied at relatively high velocities for extended periods of time. This causes the rotor to heat up to a point where it can no longer absorb any more heat, causing the brake pads themselves to start absorbing the excess heat. All brake pads are made of friction materials held together with some sort of resin, and as the brake pads heat up, this resin begins to vaporize and form a gas. This gas then proceeds to form a thin layer between the pad and rotor, causing the pad to lose contact with the rotor which reduces the friction greatly leading to brake fade. This type of brake fade is more common in older vehicles, as newer vehicles tend to have less outgassing from the brake pad compounds. That being said, newer vehicles are still subject to brake fade through another process.

In newer vehicles that utilize newer brake pad compounds, brake fade comes from issues with the hydraulic fluid instead of issues with the brake pad compounds themselves. As the rotor heats up to its maximum, the brake pads transfer heat to the calipers and the brake fluid used inthe system begins to boil and form bubbles. Because air is a compressible fluid and brake fluid is an incompressible fluid, when the brake pedal is activated, the air bubbles compress instead of having the brake fluid transfer the motion to the brake calipers, leading to what is called modern brake fade. Also, it is important to note that for our hydraulic braking system, DOT 4 brake fluid was favored, since it can handle higher temperatures than DOT 3, making it safer for the surrounding components.

Heat transfer

A major consideration in the design of the brake pad and rotor, heat transfer analysis is crucial to assess the potential thermal limitations of our design. Although those limitations are considerably difficult to overcome, since they depend on materials' properties, understanding them is capital. In fact, being aware of potential shortcomings of certain types of materials beforehand is decisive in choosing the right pieces and parts, their composition and physical design. For example, being aware of an element's limitations regarding heat transfer can ensure balance between efficiency and safety. Thus, heat transfer analyses allow us to see what design produces the least and can withstand the most heat. Thermal resistance is imperative in braking systems, as failure due to damage caused by heat dissipation can be harmful, or even fatal, to anyone operating the vehicle on which the system is installed.

Therefore, with the design envisaged based on previous consideration (magnetic conductivity, torque-speed relationship, weight, cost, etc.), heat transfer calculations and analyses were conducted to assess how the design created would fare under high thermal stress conditions. To ensure maximum safety, we adopted a very conservative method, accounting for higher speeds, pressures and conductivity; as well as lower ventilation to evaluate the resistance of the hybrid braking system under overall extreme conditions.

Hence, if the properties of the design configured can withstand those parameters, then adequate function is certain in real-life applications.

Since our design consists of two main sections, a hydraulic and an electromagnetic one, the choice of conducting two different heat transfer analyses was evident, as each section's components have their own properties. Further, it is worth noting that empirical results are often more effective in predicting a design's behavior than theoretical calculations. However, "on-paper" computations are a necessary step of the pre-construction process, as they prevent the waste of resources (often financial and budgetary ones) and allow a decent prediction of practical behavior. Nevertheless, to enhance accuracy and precision, 3D modelling and digital simulations were made to obtain further data regarding our design's response to heat production and dissipation.

During the braking process, pads and discs are subject to multiple types of thermal reactions. The heat produced during braking time, occurring at the surface of both the rotor and stator (the pad, in the case of friction braking, and the magnets, in the case of eddy current braking), is distributed throughout the system, mostly through conduction. The ventilation process and the temperature variation caused by fluid (in our case, wind) movement falls under convective heat transfer. Finally, radiation heat transfer, which happens mostly within the airgap, occurs through electromagnetic waves at a nanoscale, and will hence be considered as negligible for simplicity purposes.

i. Hydraulic Braking System

Hydraulic brakes can be subject to two different types of serious potential risks caused by high temperatures. Naturally, the first one, however unlikely, is the failure of the system due to material damage. When heat accumulates, some materials' structure, rigidity and functioning can be affected by thermal conditions. One can easily picture, for instance, metal melting at extremely high temperatures. This phenomenon depends on both the ventilation of the braking system and the materials' properties. In most cases, although braking systems can reach temperatures of 1273.15 K, the components that make up the system can withstand extreme thermal conditions. Thus, in hydraulic braking systems, the true risk is brake fade. In other words, it is the temporary reduction or complete loss of braking power. It occurs when the brake pad and disc's friction power isn't enough to decelerate the vehicle at a desirable rate. Brake fade is caused by heat accumulation, and usually occurs when temperatures reach 600 K.

The origin of the heat generated while applying a friction brake comes from the kinetic energy being dissipated to stop the vehicle. According to the energy conservation law, since there is no energy input in the system, the total amount of energy doesn't vary during braking. Thus, assuming no other type of energy is involved, the difference of kinetic energy must be equal to the heat generated.

The most convenient way of modelling the heat transfer within the friction braking system is by finite element analysis. This method allows us to evaluate infinitesimal sections of the system and their reaction to stresses, whether they be structural, thermal or other. Using the previously computed coefficients as input data, we can see the evolution of heat transfer throughout a braking process. The modelled results of the finite element analysis can be found in Appendix 1.

Based on this analysis, we obtain a maximum temperature of 92.45ºC during hydraulic braking. Relating that to materials' thermal resistance properties, cast iron, which makes up most of the braking system's structure starts getting minimally damaged at temperatures above 1000ºC. It is thus evident that heat accumulation in the brake cannot possible attain damaging levels, especially with ventilation being ensured by the drillings and slits in the rotor.

ii. Eddy Current Braking System

With the friction component removed from the equation, the eddy current part of our design is primarily subject to convection heat transfer, especially if radiation heat transfer is neglected. However, it is considerably complicated, if even possible to obtain a representative, relevant and accurate of temperature distribution and heat dissipation caused by magnetic braking. This is due to the simple reason that forced air convection cools the rotor's back while the airgap is where the heat is generated, leading to an uneven distribution of temperature in the system. Analytical methods aren't sufficient to determine the brake's response to thermal reactions. Even numerical methods and model simulation prove considerably challenging to achieve such a feat, as input data isn't limited to single values, and the number of iterations of the procedure would be excessively large.

The accurate determination of temperature distribution and magnitude has thus been done empirically, upon prototype assembling, and is discussed further in following sections. Nevertheless, based on the works of Gay and Evtushenko et al., it is possible to affirm that eddy current brakes, as they are contactless, are less susceptible to thermal reactions than hydraulic brakes, as a strong correlation exists between temperature and friction coefficients.

Therefore, with a full friction braking process (from 50 km/h to 0 km/h) having been modelled and assessed in the previous section, it is safe to state that the maximum possible temperature that could occur in our design, given the type of vehicles our clients build and operate, has been accounted for.

Moreover, based on the finite element analysis done by Lu, Li et al. on high speed ICE 3 train models, peak temperature during a full stop braking process from 100 km/h doesn't surpass 84.62ºC in the airgap (primary point of heat generation). Of course, the structure, and thus ventilation of ICE 3 trains isn't identical to that of tractor brakes, but since the vehicle our model would be installed on would run at significantly lower speeds, we thus assume that maximum temperature increase caused by the eddy current brake cannot not yield overall levels above 84.62ºC.

However, maximum temperature evaluation isn't the only aim of this section, and heat distribution within the disc of the eddy current brake, much like in the hydraulic case, is of interest. Thus, setting an upper temperature boundary of 84.62ºC (since we know our model cannot possibly exceed ICE 3 trains braking temperatures), we modelled the heat transfer process using the ANSYS software (Appendix 1).

Finally, regarding the resistance parameters of the eddy braking system's components, the magnets are the limiting factor, as they are simultaneously the most crucial, as well as the most fragile element when it comes to heat accumulation. However, with a Curie temperature (point at which magnetic properties are degraded) of 300ºC, withstanding a maximum heat of 84.62º is guaranteed. We thus deem the hybrid system rigid enough to provide maximum performance at all times.

Product Architecture

Basic Construction of the Prototype

Relying on the results of our preliminary analyses, the conceptual and computational models of the hybrid braking systems could be decided upon. The materials, measurements and components were figured out by opting for the scenarios according to which the safety and reliability of the system would not be compromised.

The prototype that we constructed was based on the notion that it had to be functional and adaptable to a real-life situation. Considering that, for the sake of this prototype, a regular disc brake caliper and rotor were extracted from a 2007 Dodge Caravan and used as the basis for the hydraulic braking system. This rotor was coupled with a used hub taken off a piece of agricultural machinery, which allowed for a relatively good representation of what the model would look like in a real system. To get this to rotate, a ¼ HP, AC motor was added using a belt and a system of pulleys. These pulleys were sized in relation to how fast the rotor should be rotating, and some ingenuity was required when it came time to connect the pulley to the rotor itself. A system of coupling nuts and bolts was designed to do so, with a connecting plate providing the structural strength needed for the relatively high torque produced. This led to having a fully functional rotating wheel system that could be used as the basis for the hybrid braking system.

Designs Considered

During the design process, we went through several iterations of what the final product should look like. Two main components needed to be designed for the prototype to be functional, the magnetic braking system and the hydraulic braking system. Seeing as our system is designed to be implemented on an agricultural vehicle, the hydraulic braking system will already be in place, meaning that the main concern was designing the magnetic braking system.

For the magnetic braking system, a certain degree of innovation was required to design something that could be presented as functional. Much thought was put into determining what type of design would be best suited for our prototype, leading to several different ideas. Originally, we had decided that incorporating both the hydraulic and magnetic systems into one unit would be the most efficient way to go, but it was later determined that this type of system would bring about a slew of issues that could easily be avoided by having two separate systems, without compromising too much wheel well space. This led to preliminary designs of what the individual stator for the magnetic braking system should look like. This process began with two separate stator pieces seen in figure 1, a left stator and right stator, that would be connected in a fashion where they could be activated in unison. This would have allowed for a variable airgap between the rotor and the magnets, which would have been useful for braking power regulation, at the expense of valuable compactness. The dual stator concept would also have made for a more costly and complex automation process, and since this was a preliminary prototype, this idea was dismissed for the sake of feasibility.

The previous realizations led to the first working model of the stator which can be seen in figure 2 below. This stator was designed as one solid piece as opposed to two separate stators as previously discussed. The stator was originally designed in an experimental fashion, where it was understood that a few iterations might be required to get it working efficiently. This led to the first design having too large of an airgap between the magnets and the rotor, as well as lacking a few slots so that more magnets could be used to gain more braking power. One feature of the first prototype that was carried over to the final one was the large back plate of the stator, since this provided structural stability as the magnetic force had the potential of pushing the sides of the stator inwards. As this was an iterative process, the first design was still 3D printed and tested to be able to assess what needed to be improved for the second version of the model. The first design was too clunky, too weak in terms of power output, and not well adapted to the space constraints of our system. These issues were addressed in the second iteration of the stator, which eventually became the working model used as part of the final prototype.

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This final prototype was tested rigorously and deemed to be efficient enough to be used as part of the final design. For the purpose of the prototype, 3D printing the piece was a simple and cost-effective option, so this is the one that was used. As the stator slows down the rotor through the use of eddy currents, heat is generated which is why a heat transfer analysis was conducted before designing this stator. The results of this analysis led us to conclude that the polymers used in the 3D prints could withstand the heat produced, and this is why this avenue was chosen in terms of producing the actual piece. For a real-life application, other materials might be considered as the heat produced could exceed what was simulated in our model. Aluminium is one material that was considered during the design process, as it is lightweight, relatively strong, and a great heat conductor. As previously stated, making the stator out of aluminium would have complicated the process and made it costlier, but when dealing with heavy agricultural machinery, aluminium would most likely be a better choice. The current prototype shown in drawing TP-1 (Appendix 2) could easily be adapted to be produced out of aluminium, which was a design consideration from the start.

Electronics

The main purpose of having a programming component to our design is to allow smooth and efficient transition between the two braking systems. One may consider a mechanical alternative to this matter, but as space and weight are primary concerns, and since we aim to eliminate any type of maintenance requirement from the user, the computerized option seems most favorable. In fact, the programming aspect of our project may well be its most innovative feature. The concept of the code would detect speed variation and execute the shift between the two systems once critical speed is reached. During the braking process, as the eddy current brake is applied, the vehicle's velocity decreases. Variation in speed is detected by an optical tachometer, which tracks the disc's rotation and sends the information, as an electric signal, to the computing unit. Hence, as it is coupled with a mechanical component, the computing unit is able to process the rotational speed of the rotor. Once the critical speed, set at 16 km/h in the previous section, is reached, the computing unit outputs a digital signal to activate the hydraulic brake. This signal is converted to an electric current, which then reaches the brake itself. Inversely, when the vehicle accelerates, and the critical speed is surpassed, a similar process takes place, disabling the friction brake and enabling the activation of the eddy current system. It is worth noting, however, that due to safety concerns, an overlap speed range is envisaged. In other words, both systems are enabled between 15 and 16 km/h so as to ensure a safe and smooth transition as speed decreases below critical level.

Briefly, the code itself was programmed using Arduino, following thorough research, apprenticeship, and eventually debugging and troubleshooting. In short, it consists of a "for" loop regarding the transition trigger, and a "while" loop to regulate the overlap range. A sample of the code has been transcribed in Appendix 1, however, due to multiple conditions, including the binding under a Non-Disclosure Agreement with our client, the entirety of the program cannot be disclosed. However, it can be, of course, provided upon request after July 31st i.e. the end of the team's contract with the client.

Tools and Materials

While laid out in an initial report issued 4 months prior to this one, the tools and materials are detailed and specified in greater detail in this section, drafted *a posteriori* of the building process.

First, the hydraulic braking system, is composed of a pair of brake pads, a rotor, a caliper and a hub. The brake pads are made of a metal brake shoe and a brake lining. The lining used is free of asbestos and made of ceramic due to health and safety concerns (ceramic brake pads are quieter, can withstand higher temperatures and have an overall longer lifespan than semi-metallic pads) as reported in The Pros & Cons of Ceramic Brakes (2017). The rotor used is made of cast iron, as is the caliper which is a single piston floating caliper. The piston in the caliper is activated by a hydraulic system, which then squeezes the brake pads against the rotor to apply braking force.

To engage the brake, a hydraulic system is necessary. This system is made of brake lines, and brake fluid, with a pedal recycled from an old ATV at the very end. The master cylinder, incorporated in the ATV pedal is responsible for transmitting the force applied to the pedal directly to the brake pads. The brake fluid travels from the master cylinder to the caliper through reinforced rubber tubes for maximum flexibility. The fluid used was a DOT 4 braking fluid, since it can withstand cold temperatures without thickening and resists boiling in warmer temperatures. The US Government Publishing Office (2011) states that DOT 4 has a dry equilibrium reflux boiling point (ERBP) of 230 °C and DOT 3 has a dry ERBP of 205 °C, while DOT 4 has a wet ERBP of 155 °C and DOT 3 has a wet ERBP of 140°C.

The components for the eddy current braking system include neodymium-iron-boron (NdFeB) rare earth magnets, a caliper and a linear actuator. Neodymium-iron-boron magnets produce more energy as well as a greater magnetic flux than other rare earth magnets such as ferrite or samarium-cobalt magnets. They are also less expensive, lighter and more compact than other rare earth magnets as mentioned by Gay (2005). The magnets are placed within the holes of a 3D printed polymer stator.

Since the prototype serves primarily as a testing component, it was built with a support platform made of plywood and steel as a tabletop. A DC motor is used to rotate the disc through the intermediary of two pulleys and a rubber belt. Of course, to support all this structure, a pulley shaft, a metal plate, coupling nuts and bolts are fixed in place on the surface of the hub, maintaining the rotor in place. An optical tachometer connected to an Arduino Uno unit serves as speed sensor and is connected to the system through a breadboard and electrical wiring. A servo motor and switch ensure the transition between the two braking systems. A complete table of materials specifications with full breakdown of costs is available in Appendix 1.

Environmental, Social and Economic considerations

The hybrid braking system was specifically imagined to impose minimal environmental, social or economic strain on its users and their environment. However, every design comes at a cost, and considerations cannot be ignored. In fact, although our product's main purpose is to reduce copper concentration in runoff water, the use of rare earth magnets implies a considerable environmental impact due to extraction methods. Neodymium magnets are often used in technological products due to their efficiency and useful properties; but obtaining them proves costly in terms of environmental resources, as they are often extracted by acid injection, which can be harmful to the ecosystem surrounding the extraction site. While safe extraction methods are being developed, including *ex situ* techniques, they aren't widespread, and often require additional costs, making them, for the moment, not viable.

Social factors have also been considered in the design process; namely, the fact that tractor buyers are often known to operate on their own vehicles, whether to fix a component or modify it. With a new technology such as ours, however, a certain adaptation is required from the operator (whether it be the consumer or a mechanic), and a new set of understandings can be essential. Naturally, the hydraulic part of our system requires no adaptation, but the electromagnetic aspect of it might require knowledge that an electrician or even a computer scientist might have, if the code used is subject to necessary modifications.

After much brainstorming and arduous reflections, the hybrid braking system seems to have no considerable cultural impact, especially since it is made to be inclusive.

Life Cycle Analyses

Life cycle assessment of rare earth magnets

Neodymium-Iron-Boron rare earth Magnets are becoming more and more present in our society as the increase of sustainable technologies such as electric or hybrid vehicles and wind turbines are being produced on a global scale. According to Sprecher et al. (2014), China is the main producer of rare earth elements with “50% of worldwide mineral reserves and 86% market shares”. Therefore, the life cycle analysis is focused on China's conventional method of extraction of the rare earth elements, to the processing into a rare earth magnet and finally recycling of the elements. Bayan-Obo open pit mine accounts for ⅔ of the extraction of rare earth oxides by conventional extraction techniques. It is estimated that the mine contains 750 million tons of ore at a 4.1% purity as report Sprecher et al. (2014). The raw ore is then transported 150 km to the city Baotou where it undergoes several refining processes until it reaches a purity of up to 99.99%. LCA Results for 1kg of REO from the same research, the eutrophication potential in a low-tech scenario is 0.18 kg NOx-Eq, freshwater aquatic ecotoxicity is 3.5 kg 1,4-DCB-Eq, and the human toxicity is at 320 kg 1,4-DCB-Eq. After the ore is refined, it then goes through nine industrial processes until the final product is the NdFeB permanent magnet. From Table 2. LCA Results for NdFeB Production in Sprecher et. al (2014), the eutrophication potential in a low-tech scenario is 1.9-E01 kg NOx-Eq, freshwater aquatic ecotoxicity is 14 kg 1,4-DCB-Eq, and the human toxicity is at 150 kg 1,4-DCB-Eq. There are currently two methods of recycling rare earth magnets. The first is a manual recovery of the magnet, and the second is the recovery after shredding and reprocessing. The environmental impacts to produce NdFeB permanent magnet is much less for both, however manual recovery leads to a 36% recovery rate, while shredding recovers less than 10%.

Life cycle assessment of brake pads

Volvo Cars Corporation is one of the first car companies to undertake a full life cycle assessment, which includes an environmental impact assessment and an energy requirement, for one of their braking pads assembly lines. According to Andersson & Dettmann (2013), the environmental footprint was determined to be 15-20 kg CO_2- equivalents per brake disc. The highest eutrophication potential value is 0.0597 [kg NOx-Eq]. The analysis also concluded that the main contributor to the environmental impact is the acquisition of the raw materials. The highest mean value of energy consumption to produce one brake pad is 1.134 kWh, and the standard deviation within the variants is 0.0187 kWh. Additionally, the lifespan of the brake pad depends of a large set of factors some of which includes vehicle type, driving habits, environmental stresses, and the brake pad itself. A typical brake pad last between 48280 km and 112654 km, and the typical north

American driver travels 21 478 km a year. Therefore, the average lifespan for a pair of braking pads is 3.75 years should “Brakes FAQ, How Long Do Brake Pads Last?” (2005) be believed.

Social Considerations

The hybrid braking system does not display any feature impacting society as of yet, since its current status as prototype doesn’t allow it to be widely used. However, were it to be mass-marketed in the future and produced at a large scale, the main societal impact would be the adaptation of the public and the industries to the obsolescence of brake pad replacement. This could be both a positive and a negative impact as it reduces labor and cost for the general public but could be poorly received by brake pad companies and lobbies.

Economic Considerations and Cost Analysis

Throughout the process of the project, our group did not find any funding to subsidize our prototype. This was due to the fact that our design project was not considered for any grants we applied for. On the other hand, private funding was not sought out by the team. Furthermore, Mutrac were not able to relinquish any of their funding due to the fact that they were on a very tight budget and had already spent all their finances on equipment. Taking all this into consideration, the main goal we set for ourselves was to find the cheapest way to produce a prototype that could do a good job at simulating real conditions. In the search of material and equipment, a significant amount of it was donated to us or lent. This significantly cut back the cost of the prototype.

A table available in Appendix 1 provides a full breakdown of the total cost of each component of the hybrid braking system.

The cost of the overall table top came up to 663.50$, which represents a significant amount of money just for a table top design. The reason for the cost of this table top design being so elevated is due to key components of our design. For starters, the most expensive piece of equipment is the AC motor. The decision to spend 199.99$ on this AC motor rather than purchase a 60$ or 80$ DC motor, is due to the importance of this piece in our design. It was crucial to obtain a powerful and resistant motor that could sustain the rigorous testing that we put it through to obtain data for our analysis of the braking system. If the motor would have failed during our testing, it would have been very problematic and a huge setback both financially and in terms of our time constraints. For those reasons, the extra cost for a new, good quality motor payed for itself in the long run. The second main cost in this prototype was the purchase of the actuator. This was another crucial part of our design if we wanted to make our table top prototype fully automated. The price for actuators quickly rises when the force and size requirements increase. We had to purchase an actuator that would be able to sustain the weight of the shaft, the stator, and the clamps holding it in place. The third most important cost in this design were the rare earth permanent magnets. Again, we opted to purchase good quality magnets to make sure that our prototype performed how we expected it to.

As one can observe from the list of materials and the image of the prototype, the reason that the cost was so elevated was because we had to reinvent what would already be in place on an agricultural vehicle. For a real application, items such as a rotor or an AC motor would not need to be purchased. As seen from the pie chart, the true cost of our magnetic breaking system and part of the hybrid brake system is much less than the current cost of the table top prototype. One can see that the magnets are 41% of the total price, where for our table top design it is merely 6.74% of the price. From this data, it is reasonable to think that if this hybrid braking system would be implemented on MuTrac's ¼ scale tractor, the price for the extra magnetic braking system to be added would be very reasonable.

Compensation for Impacts

The hybrid braking system was made to reduce environmental, social and economic stress on its users and their environment. However, every design comes at a cost, and considerations cannot be ignored. In this case, the use of rare earth magnets implies a considerable environmental impact due to extraction methods. Social factors have also been considered in the design process: with a new technology such as ours, a certain adaptation is required, whether it be from the consumer or a mechanic, and a new set of understandings can be essential to fix any damage on the brakes. Further, the economic impact of our product is non-negligible. The presence of a dual system, although reducing replacement costs, cannot be commercialized below a certain value. Finally, regarding occupational health and safety and ergonomic considerations, our design is made in such a way that ensures security for constructors and consumers alike.
Reducing, replacing and compensating the previously stated impacts is paramount to our team. We thus designed a product that offers features balancing or cancelling out any potential negative effect. For instance, environmentally, our team shall invest, as much as possible, in safely extracted or recycled magnets. Further, the system requires little to no maintenance and is designed to outlive the vehicle on which it is installed, eliminating fixing or replacement needs, and thus costs and labor. Moreover, in addition to being safe and reliable, the hybrid braking system is as ergonomic as can be: the technology behind it allows linear braking and smooth transitions between the electromagnetic and hydraulic systems, thus enhancing the safety and comfort aspects of our design.

Estimating copper reduction

According to Weisbaum (2006), “the average life expectancy of new vehicles of these days is around 8 years or 150,000 kilometers”, and well-built vehicles can last 15 years or 300,000 kilometers. According to Brake FAQ (2005), brake pads can last between 48,000 km and 112,000km. From these values, it is suggested that the four brake pads can be replaced at least times to 6.25 times throughout the whole life span of the car. In other words, during the life of a vehicle, it is possible that 12 to 24 brake pads have been worn out. According to Moran (2014) “brake pads contains an estimated average of 8% copper by weight”. With an average weight of 1kg, the amount of copper present is 8g following the data in "How much does a Brembo Performance big brake system weigh vs. O.E. components" (2015). Within a life of a vehicle, between 24g to 192g of copper can be released into the environment. If we take into consideration the average number of vehicles in the United States alone for the last 15 years, which is roughly 247,421,120, as stated in “Number of vehicles registered in the United States from 1990 to 2015 (in 1,000s)” (2017), the total amount of copper released in the environment is roughly 26721.5 tons of copper. One assumption made is that the coupled friction break will only need a pair of friction brake pads per wheel for the total longevity of the car. Therefore, we can expect that a rough estimation of the copper emitted in the environment would be a third to a sixth of the fraction currently being released.

Risk Assessment and Management

Risk Assessment

The assessment of risks associated with the design and operation of the hybrid braking system is inherently included within the manufacturing and testing of the process. In fact, the two risks categories delineated by manufacturing risks and operating risks have all been observed and monitored throughout the assembling process and, for operating hazards, during the testing phase.

Therefore, a decent idea of the principal dangers and problematic exposures have been gathered throughout the design procedure. The conception of the hybrid braking system has allowed a detailed and profound exploration of any and all possibilities that could follow Murphy’s law.

First of all, regarding the manufacturing process hazards, it must be recognized that no matter of the endeavor, workers, constructors and testers are permanently and continuously exposed to high risks due to the manipulation of machinery, as well as the fact that product optimization has often not been performed prior to the professionals’ exposure to the prototype.

Risk occurrence throughout the manufacturing process can thus be considered as a quite elevated probability. For the specific case of the hybrid braking system, the main hazards encountered during the design process were mostly related to machinery use and high-speed rotational mechanisms; whether it be drills, grinders or the motor used to power the wheel's rotation.

Despite security measures already in place and enforced by regulations adopted by McGill University's Technical Services on their grounds, chances of minor injuries aren't entirely eliminated, especially when working with a heavy rotor spinning at around 900 RPM.

Cuts must be expected and prevention against infection through rusty equipment (Tetanus/lockjaw infection) must be considered.

Following the optimization and completion of the prototype, the risks are lowered through risk management and elimination of hazardous components. Further, the use of heavy machinery is no longer necessary, and the testing of the technology as well as use time of the prototype throughout the testing procedure have pushed the product forth along the infamous technology bathtub curve (see Appendix 2).

Hence, failure of the system is reduced and so is the injury of the clients and operators. In fact, given the predominantly failure-related nature of hazards related to the hybrid braking system (and braking systems in general), the risk factor for the post-optimization model of the prototype during operation by the client is deemed to be minimal and near-negligible.

Moreover, throughout the tests conducted, it has been established that the reliability of the hybrid braking system is established, as the results obtained are observable and reproducible and are contained within a reasonable standard deviation and margin of error and can be predicted with a large degree of confidence.

The results also show considerably low maximum temperatures within the braking system, which further reduces any risk associated to overheating, material degradation, brake fade or even direct harm to the user.

Risk management

Notwithstanding the already-low risk levels of the operation of the hybrid brake prototype, a risk management plan must be put in place: throughout the design, production and unveiling of the model, measures have been adopted and respected to ensure a safe use of the product.

To guarantee the in-workshop safety of the producers, preventive measures proved to be more effective: wearing gloves, protective glasses, clamping down the parts to be drilled, cut or modified, and of course being vaccinated against potential infections due to oxidized metals (Tetanus toxoid, TT) and the likes.

Combined with the already-in-place measures, those initiatives were sufficient to conduct all project-related work in total safety and security throughout the span of an academic year (2017-2018) without any disaster occurring to the workers, their environment, the public and even the surrounding facilities and appliances.

Regarding the post-production use of the braking system, safety has been ensured and even increased by maintaining all pieces and parts fixed at maximum tension, using tools and solutions like sealants, and by opting for a motor with an emergency stop button.

Additionally, all blueprints, plans and test results were provided to our clients to facilitate regular checkups on the model, and a telephone line which will be active 24 hours a day has been provided to enquire about suspicious phenomena, complaints, emergency situation management and product assessment services request.

Finally, an ultimate component has been planned to be added to the design (but is, for now, delayed to accommodate the clients' inspection of the prototype) is a Plexiglas casing that would prevent loose particles (rust, oil, asbestos, etc.) or pieces from disturbing the operator during the use of the system. It is planned to be installed and locked within the coming weeks.

Manufacturing Process

All the data, tests and values obtained throughout the various processes explained in the aforementioned sections allowed the team to undertake the physical and material production of the hybrid braking system, keeping in mind the respect of all stated constraints as well as the objective to obtain a functioning, safe and reliable prototype.

The first step we undertook was to acquire a rotor. We then proceeded to remove the rust from the rotor by applying a solvent called Evapo-Rust and giving it a proper grind. It was important to have a smooth and even surface on the rotor to allow for the hydraulic system to perform properly. It was also important for the prototype to resemble a typical rotor on an agricultural vehicle for the purpose of proper simulation. The next step we undertook was to drill holes in the center of the rotor to convert a 5-bolt pattern into a 4-bolt pattern to fit the hub. To prevent shaking and oscillation from occurring, holes had to be centered and aligned with the hub, which was provided to us by McGill University's Technical Services. In order to spin the rotor, a mount was installed on the hub where an extension was created to attach a pulley. This mount was comprised of four, ½-inch diameter zinc coupling nuts, and four, ½-inch diameter zinc finish hex cap bolts that were ordered from Fastenal and (). The mount also comprised a ¼-inch thick steel plate where four holes of ½-inch diameter were drilled. These holes aligned with the four coupling nuts coming out of the hub where the rotor was connected. The next component added was the AC motor, with the proper pulleys, shaft and belt. The motor is an OmniDrive, and the specifications of this motor are ¼ HP, 115V, 4.8A, 60hz, and 1725 rpm. The shaft was machined in such a fashion as to allow for the proper size groove to fit the key so that the shaft and the 8-inch diameter pulley would form a single piece. To connect the shaft to the steel plate, a 1-inch diameter hole was drilled into the center of the plate. The shaft was then welded to this spot so that the pulley could then be attached to it. We then had a smaller pulley with a diameter of 4 inches on the motor side that connected to the larger pulley on the rotor side through a belt. These dimensions were purposely selected to have the proper ratio that would allow us to spin the rotor at 862.5 rpm, giving us a speed of 13.9 m/s or 50 km/h.

The second step of the manufacturing of the table top hybrid braking system was to attach a hydraulic braking system to the rotor. This was accomplished by fixing the brake caliper, which was purchased at the same time as the rotor from a shop that sells used parts, to the back of the shaft of the hub. A ¼ inch thick steel plate was acquired and fitted to the back of the caliper to ensure that the hydraulic braking system was properly secured and mounted. This was accomplished by welding the steel plate to the steel shaft of the hub, so that the caliper could sit comfortably over the rotor.

For the caliper to apply pressure and friction to the rotor, the caliper was connected to a master cylinder, which was obtained from an old ATV. The caliper already had part of a brake line hose, however, it was cut during the recycling of the piece. Therefore, the old brake line had to be retrofitted with a new brake line. This was accomplished by removing the flexible and worn out rubber brake line tube by cutting the old steel brake line a few centimetres before the rubber one started. The second step was to connect the old brake line with a new steel brake line. This was possible by using a compression and connecting fitting kit. The old line and new line were expanded at their ends, and with two connecting brass pieces, it was possible to join both together. After measuring how much steel braking line was needed for the new line, it was cut. Finally, the new brake line was connected to the master cylinder obtained from the ATV. The system was bled properly to allow any air to escape.

The third step in the manufacturing process was to install the magnetic braking system around the rotor. This was accomplished by designing and 3D printing a stator in which permanent magnets were tightly fixed in place. With the help of an Arduino and an actuator, it was possible to have a mechanical arm to simulate automation in a real context. Code was written to run this mechanism which is discussed further on.

The final step was to connect both the hydraulic and magnetic braking systems together. Unfortunately, this part of the design was not able to be finalized due to time constraints and other outside factors.

Challenges

Throughout this design project, a multitude of hardships were faced when designing and most importantly constructing the prototype. The first hardship we had, was getting the rust off the rotor. This took a significant amount of time over the winter break to accomplish. Although a very good job was accomplished with the outer surface of the rotor, the interior was still quite rusted out and showed signs of degradation. After we obtained the hub from the local work shop at McGill university, it came time to mount the rotor to the hub. Unfortunately, the bolt pattern on the rotor did not match the one on the hub. Therefore, new holes had to be machine drilled in order to fit the rotor on the hub. Due to a miss calculation and a lack of experience on our part, the new holes which were drilled did enable the rotor to fit on the hub, but the rotor was not properly aligned with the axis of rotation of the hub which caused a significant wobble in the rotation. After this problem was fixed, the rotor was securely fastened to the hub using ½-inch locking nuts.

The next challenge was figuring out how to spin the rotor. We knew we wanted to accomplish this task using an electric motor. Therefore, we undertook research on what type of motor would be required for our situation and what maximal speed we wanted the rotor to spin at. After some research, we found a store where they sold a multitude of electric motors for ventilation purposes. The OmniDrive AC Electric Motor fit the criteria we needed and fell inside the range of our budget.

After obtaining the motor, we needed to conceptualize a possible mechanism that would enable the motor to be able to spin the rotor. We decided to connect a mount to the 4 bolts coming from the hub, which took some ingenuity as described above. This proved to be complicated because the coupling nuts and bolts needed to fit the hub were not sold in local retail stores. Therefore, these pieces had to be ordered via McGill and privately from overseas. Thus, we were halted on that aspect of the design until the crucial pieces came from abroad.

We did not waste time waiting around however. We started to undertake the brake line issue and the hydraulic braking system itself. This was surprisingly harder than we expected. Even though the instructions looked straight forward, this was not a simple task. The hard part was preventing leaks from occurring at the connection of the old and new hydraulic brake line. This was mostly since the old hydraulic brake line was in a bad state and already connected to the caliper. It was very difficult to flare the old brake line without splitting it and consequently making it obsolete. In the end, after multiple tries, it was possible to flare both brake lines and connect them together.

When the pieces we ordered finally came in, we had a bit of an issue drilling the steel ¼-inch thick plate to allow the hex bolts and coupling nuts to align with each other in order to be securely fastened the plate. Multiple cuts and grinds of the metal plate had to be done to ensure safety of the mount when it would start spinning at a high velocity.

The next challenge we encountered in the design of this system was when we started designing the stator for the magnetic brake system. The first model produced had too large of an airgap to slow down the rotor in an efficient matter. This was easily resolved by changing the width and dimensions of the stator on our second attempt. During the printing of the second stator, the 3D printer ran out of material, so the piece was halted before it could be completed. Thus, printing the proper stator took several iterations, as is usually the case when designing a piece like this. However, during this time, it was still possible to run tests on the first stator that was produced, giving us good baseline data.

Tests and Results

Conducted Experiments

The physical assembling of the prototype throughout the project timeline is certainly not a standalone objective *per se*. Beyond the system's role as a pilot testing model, it is meant to serve, at the very least, as a basis for a fully functional four-wheel hybrid braking mechanism that could eventually be commercialized not only for tractors, but other types of vehicles like electric cars or trains, for which braking often represents a considerable portion of the activity and can even be a limiting factor during work.

To ensure a smooth and successful follow-up process that would adapt the prototype's design to wider scope projects and large-scale production, the hybrid braking system's functioning mustn't only be explained, but also quantified. This quantification is achieved by obtaining, analyzing and post-processing data that is later to be interpreted to allow adjustments, modifications, simplifications and additions to the current pilot model. The relevance of the data has been defined depending on the end-goals and primary impacts of the project. This decision process was determined by a ranking procedure based on the criticality of the matters and laid out in a table (see Appendix 2) in order of importance and feasibility.

Hence, the data of interest has been reduced to two categories: since the rotor's full stop is the primary objective of the design, stoppage time was deemed to be highly critical; further, the main risk during the operation of the prototype (and, eventually, the marketed product) is the overheating of the rotor. Heat transfer processes were thus considered as data of primary interest. It follows that two series of tests were conducted; one for each data category.

Test 1: Braking Efficiency

The braking efficiency as discussed throughout this project relates to the capability of a certain braking system to perform a full stoppage of a rotating body within a certain time frame. Hence, the concept of braking efficiency can be quantified via a measure of braking time. Once the data is gathered, it is analyzed and compared to other reference results from processes having similar parameters. Those reference results, in the case of the hybrid braking system, are those obtained from performance assessment of conventional braking systems. Comparisons and interpretation are further discussed in subsequent sections.

The nature of the braking efficiency test series thus simply consisted of measuring the time between brake activation and rotor stoppage. The first step was to get the rotor spinning at maximum speed (50 km/h), then the magnetic brake was activated (time measurement start), and finally the rotor's speed was brought down to a null point (time measurement end). Since the design procedure consisted in somewhat of trial and error processes, the test series was conducted for the two stator models designed.

Further, since hydraulic braking is a mainstream and established technology whose functionality is known and confirmed, the tests focused heavily on the upper-speed braking mechanism; in other words, the magnetic braking time was prioritized during testing as it is the phase that remains most novel and, therefore, for which data is most lacking. Nevertheless, due to a fundamental of consumer and operator safety, total braking times were also measured and analyzed to affirm the sound functioning of the entire process and all components.

Test 2: Thermal Performance and Heat Transfer

Heat transfer within the braking system is a phenomenon that could represent a considerable portion of the risk and risk management stages of the design, as high temperature level could induce damages or cause a malfunction in the braking process or even in the activation of specific mechanisms (especially given the presence of microcomputer units). To assess the criticality of the risk, it is important to base the analysis on quantifiable data; hence the thermal performance and heat transfer test series.

Thermal performance tests were conducted at the very end of the braking process, at the point at which heat accumulation over time is maximal. Heat accumulation and temperatures were observed through a thermal sensing camera. The first step was to bring the rotor up to full speed (50 km/h), activate the brake, and have the rotor stop completely (thermal performance test start and end).

Much like the braking efficiency tests, heat transfer assessments have been conducted to obtain results that could later be compared to an already acquired database. However, it is critical to note that, given the novel nature of the hybrid braking system's design and the difference in materials between this system and conventional (hydraulic ones), coming across an accurate heat transfer assessment in literature is no easy feat. Further, the case specificity and high variability of conditions render an analytical solution quite difficult to obtain. Hence, the results have been compared with finite element models (FEM) made during the pre-construction phase of the project.

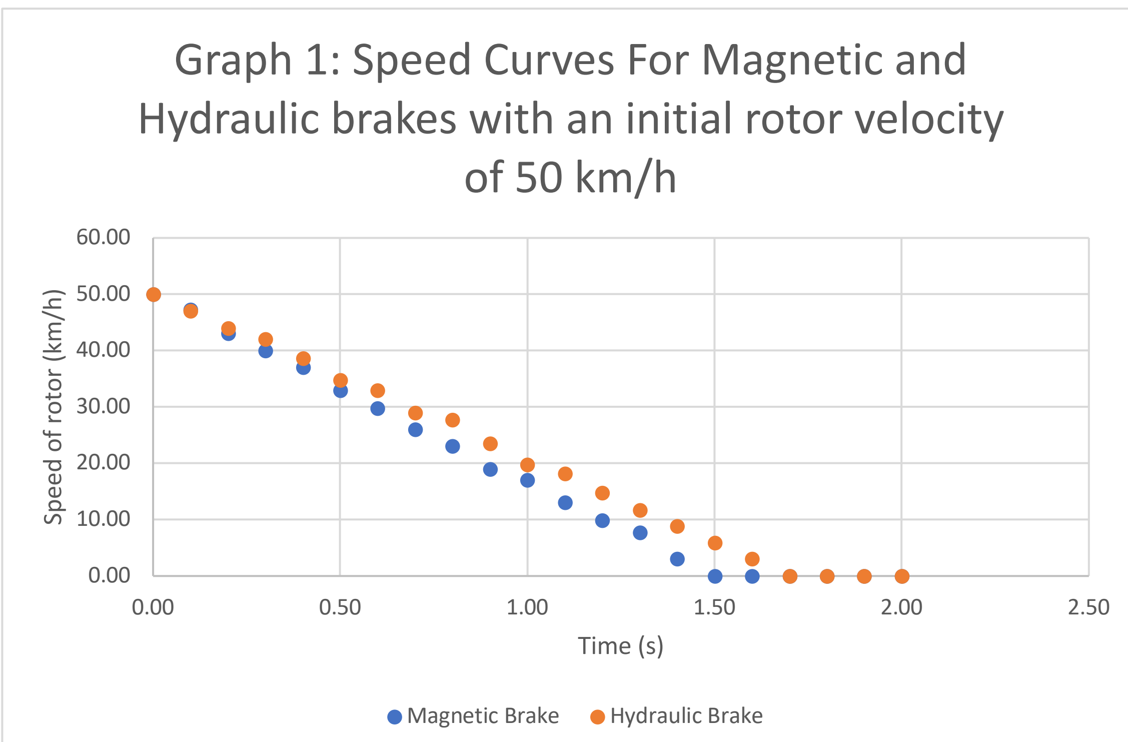
Results

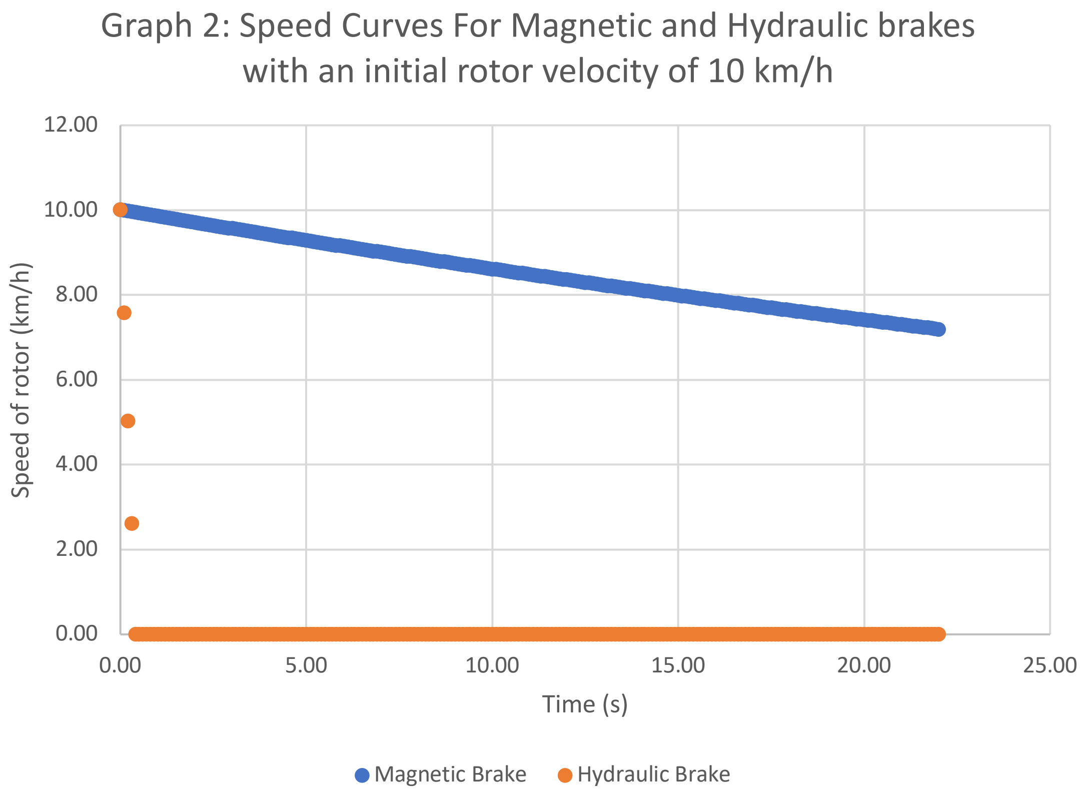
Test 1: Braking Efficiency

i. Magnetic brake speed curve

Using a tachometer, the rotation speed of the disc could be measured. Once the speed value was obtained by the tachometer, it was relayed to the computer through an Arduino Uno microcomputer. This allowed the storage of data and eventually the recall of all speed values to obtain a speed curve for various braking methods.

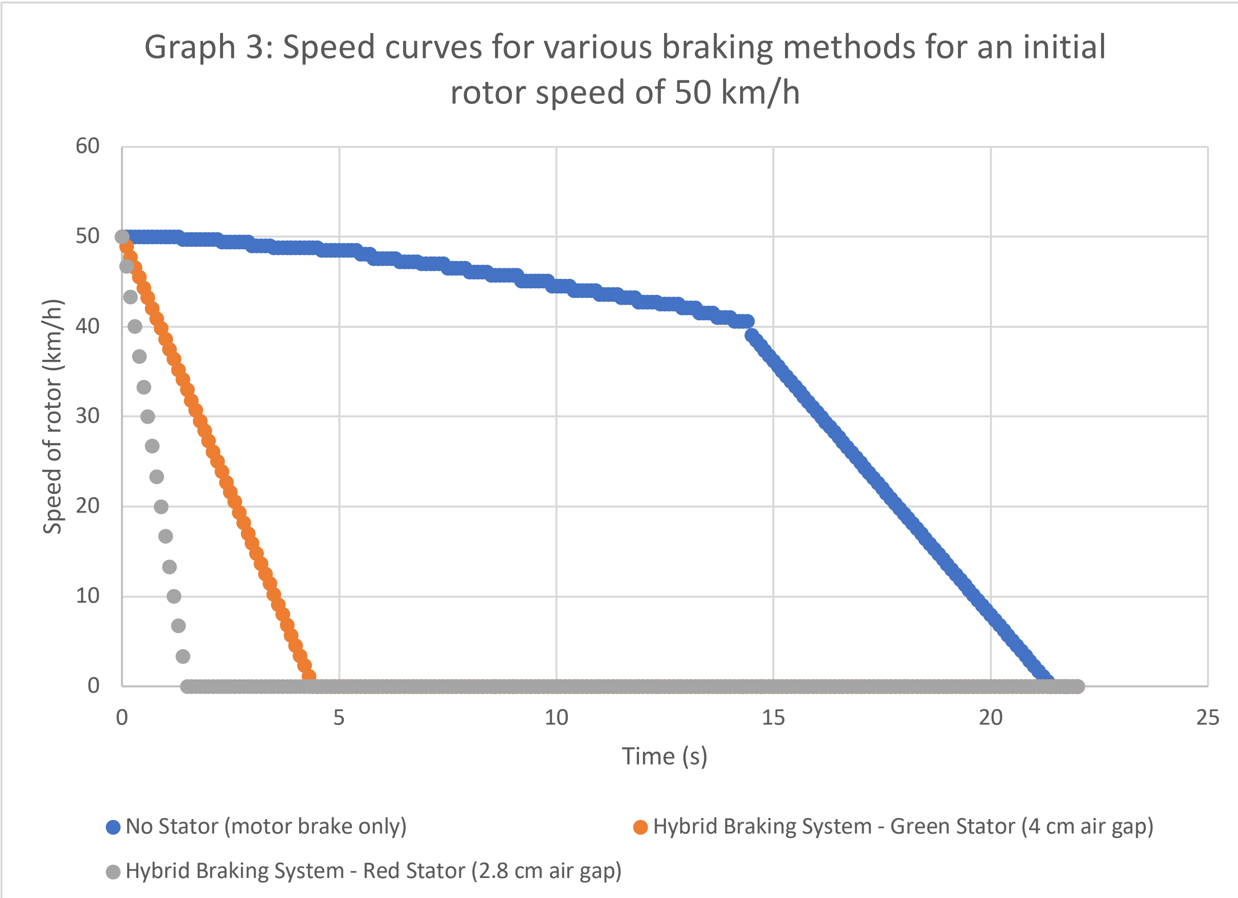
The speed curve is a useful tool to evaluate the smoothness of a braking system: ideally, a linear deceleration is desired to ensure a proper functioning of the system, and more importantly, safety and comfort of the conductor. The following graph shows the speed curves obtained for a standalone magnetic system engaged on a rotor with an initial speed of 50 km/h (14 m/s) and 10 km/h (2.8 m/s), as opposed to a standalone hydraulic braking system under identical conditions.


Graph 1: Speed Curves For Magnetic and Hydraulic brakes with an initial rotor velocity of 50 km/h
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Speed of rotor (km/h)
0.00
0.50
1.00
1.50
2.00
2.50
Time (s)
Magnetic Brake
Hydraulic Brake



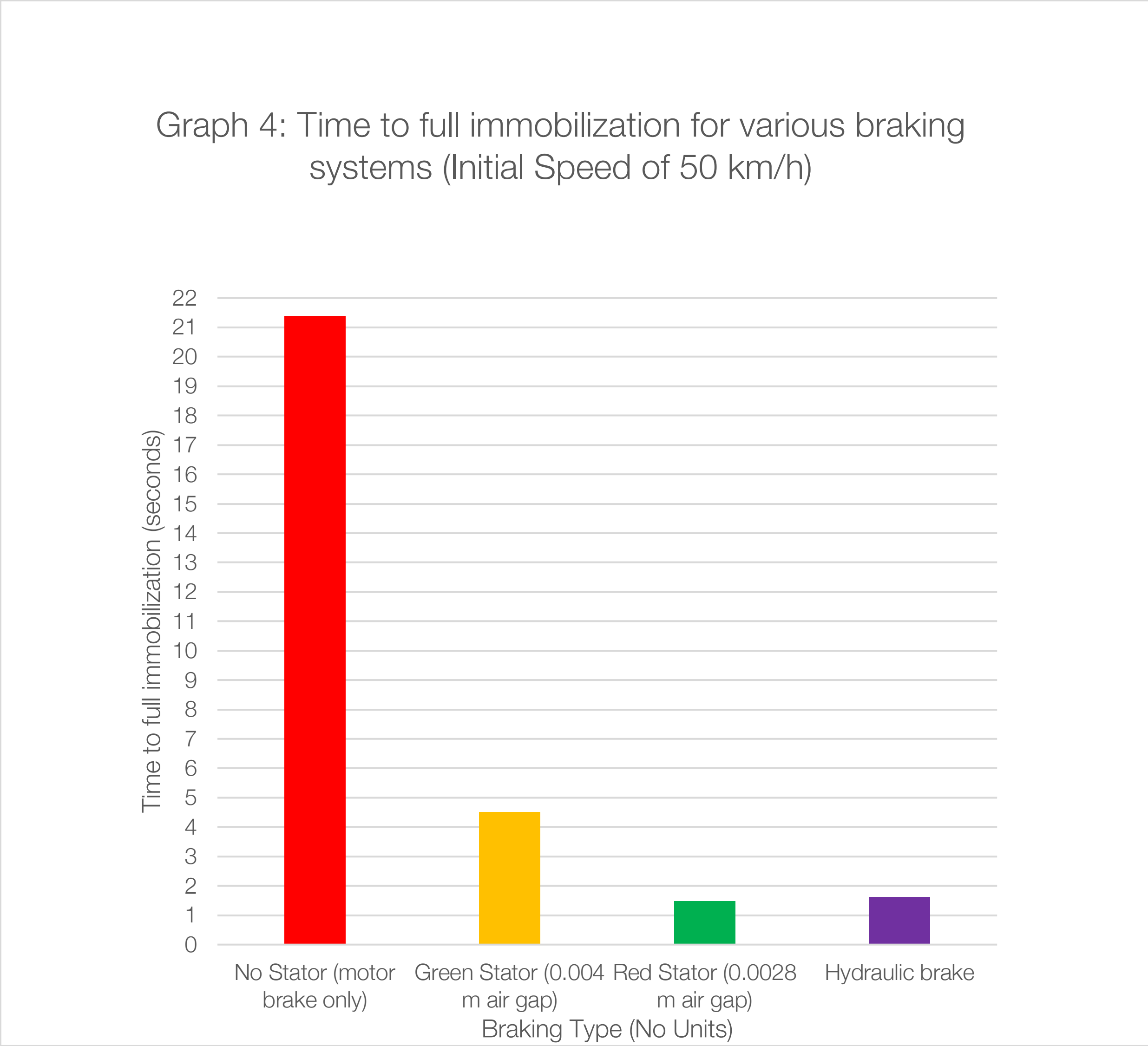
ii. Hybrid braking system speed curve

Beyond simply testing the performances of the two primary braking systems independently, it is interesting to observe the overall performance of the hybrid braking system based on the two designs made. In fact, as many novel products, the hybrid braking system isn't simply the sum of its components, but interactions between a network of mechanisms and parts that complement each other. Further, such a complete analysis provides valuable insight as to the need for an improvement on the initial design (more specifically, the first version of the 3D printed magnetic stator). The following graph shows the speed variation over time depending on the type of braking system applied, in an emergency situation; *id est* brake application lasts from peak velocity set at 50 km/h (14 m/s) until total immobilization.



iii. Braking time

To obtain a clearer view of total braking time based on various braking systems, the average time values were post-processed and laid out in a column graph presented below. This visual support allows the comparison of all tested and researched methods.



As observed, the final design (Red stator) of the hybrid braking system is as efficient if not more than the hydraulic brake standalone. The results are further explained in the discussion.

Test 2: Thermal Performance and Heat Transfer

To conduct the thermal performance and heat transfer test series, an infrared thermal camera was employed.

Displaying an accurate representation of the actual heat map of the targeted object, the thermal camera provides a temperature reading and assists in estimating whether the braking process based on the designed components remains under maximum temperature limits, and thus doesn't damage any component of the overall setup, and eventually the vehicle on which it is mounted.

The images found in Appendix 1 were produced using said camera and can be compared with the finite element models discussed previously in this report, in order to assess the safety of the braking design as it has been executed. The photos were captured immediately after total immobilization was reached from an initial rotating speed of 50 km/h (14 m/s) using the improved design of the hybrid braking system.

Discussion

Test 1: Braking Efficiency

The speed curve of the magnetic brake standalone confirms hypotheses regarding the use of magnets within the context of electrical induction. In fact, following the Maxwell-Faraday equation and Lenz's law, the rotation of a disc within the axis of a magnetic enclosing cause an induction of eddy currents that counter the rotational movement of said disc. With an initial speed of 50 km/h, this concept is uncontested and ensured to function properly; and the quasi-perfect linearity of the slope indicates a smooth and safe braking procedure. However, the speed curve for the magnetic brake as a standalone mechanism under an initial speed of 10 km/h shows an extremely slight effect of the braking system over the rotation of the disc. In fact, one may even say that the deceleration is only due to friction, drag or an imperfection in weight repartition within the rotor.

In fact, as understood and explained previously throughout this paper, the action of magnetic brakes is speed-dependent, and inefficient below certain speeds (see Appendix 1 for critical speed of magnetic brakes). The speed curve for the magnetic system thus does not only provide insight pertaining to the linearity of the brake, but also justifies the addition of a hydraulic braking system to the magnetic one, as the former is constantly reliable and non-speed dependent.

The overall speed curve drawn for two hybrid system designs as well as a no stator situation compares the tested and control cases with a regular hydraulic braking system based on literature data (Road Safety Knowledge Centre & Colas United Kingdom, 2003). The speed curve shows a much more efficient performance achieved with the second hybrid brake design when compared to any other system; confirming the righteousness of the team's decision to modify the initial magnetic stator and reducing the air gap. Braking linearity however, can yet be slightly improved to match that of the conventional hydraulic braking system to provide a smoother and overall better user experience through ergonomics, comfort and maximum safety.

Regarding the total braking times, when presented as rough numbers independent of any other data or scale, the data measured during the testing phase might not mean much, which highlights the importance of comparing said times to standard values and already established numbers. Since the hybrid braking system aims to be at the very least as efficient as conventional hydraulic systems,

In automotive engineering, braking time is rarely discussed, as, commonly, braking efficiency is dealt with in terms of stopping distance, which, in short, is the sum of the distance travelled during the driver's reaction time and the one travelled from the brake activation point until complete vehicle immobilization. Nevertheless, a few investigations, often oriented towards and presented to automobile companies or government organizations rather than the general public, do consider time as a measure of braking performance.

Such is the case of a study jointly conducted by a British research center and a Sussex-based road design company, in which the speed curves and stoppage times have evaluated for vehicles during extreme situations; *id est* emergency braking while neglecting air drag. The conditions for this research match the testing conditions for the hybrid braking system, as neglecting air drag by definition ignores the shape, size and volume of the vehicle employed, thus solely considering wheel speed. The results of the study have hence been deemed appropriate for use a reference values for comparison purposes. The following chart presents the two sets of data and enables the interpretation of results obtained for the hybrid braking system performance tests.

Observing the column graph, it is evident that the improved design of the hybrid braking system is quite efficient. In fact, this graph confirms the results obtained through the speed curve assessments. With an average total time of 1.47 seconds until complete rotor immobilization, it is evident that, in terms of efficiency, the improved hybrid braking system can compete, and even outperform conventional hydraulic brakes, for which the average speed appears to be convergent at 1.62 seconds. This simple showcase of data indicates an enormous potential for the product, from a marketing perspective.

Test 2: Thermal Performance and Heat Transfer

By comparing the results observed through the infrared thermal camera with those previously determined using Finite Element Modelling (FEM) with the ANSYS software, it is possible to assess the safety of the hybrid braking system when it comes to overheating risks and risk management.

In fact, while the FEM indicated a maximum temperature of 92.45ºC (365.6 K), the visual obtained for the rotor heat map immediately when total immobilization was reached read a top temperature of 27.9ºC (301.05). The difference between both results is of 64.55 degrees, which is quite considerable; however, it is critical to note that while the simulation (FEM) was conducted assuming minimal aeration of the rotor, pads and overall system, the empirical test was done with maximum air exposure, which resulted in certain aeration of all components and hence a cooling effect through convection via the colder ambient air.

Overall, a lower maximum temperature makes the hybrid braking system even safer than previously believed when it comes to thermal performance, as it is not prone to overheating, brake fading or component damage through heat conduction, convection or radiation. Nevertheless, further tests must be conducted in order to obtain the maximum temperatures once the system is mounted and installed on a vehicle, where other pieces (wheel, tire, etc.) covering the rotor may be sources of heat containment and reduce dissipation, potentially increasing the chances of overheating.

Prototype Presentation

Following the testing phase, deliverables were unveiled at McGill's Tractor Pulling Team headquarters. A budget review was done in order for our client to have a final assessment of the hybrid braking system's cost. Remarks, comments and requests were all taken into consideration to facilitate the redesigning process.

Feedback

Based on oral comments, the client was satisfied with the presented prototype and understood the restrictions and constraints that affected the final design. Of course, requests have been formulated, including the use of a variable air gap stator, and the design of a single, semi-circular caliper that would integrate both braking system, as well as the computing unit.

Since, the prototype presented was only a pilot test platform, our client will not be able to incorporate the hybrid braking system in their tractor design. However, as agreed in the contract and non-disclosure agreement signed in October 2017, the McGill Tractor Pulling Team will use the hybrid braking technology as part of their report to the jury within the context of their annual competition, as they have deemed it to be of interest to them.

It is important to note that while our client served as generous contributors and collaborators on this project, following a mutual agreement between the McGill Tractor Pulling Team and our team, the redesigning process has started, in the hope of optimizing the system and attract bigger investor eventually allowing the design to be patented with an ultimate aim of incorporating the hybrid braking system of electric vehicles, trains, trucks, roller coasters, or any other type of vehicles for which the braking process can be a limiting factor both in terms of energy and environmental impact.

Optimization

An important part of the design process lies in the re-designing of the prototype based on results, feedback and ideas for improvement. As we progressed with the project, we came to the realization that several things we did were not optimal and could be done in a better way. Although most of our goals were met, there are always improvements to be made on our design. The first major improvement that could be made to our design is implementing it on an agricultural vehicle and seeing how it performs in this context. This was always a goal for our team, but we knew that realistically, we did not have the time nor the man-power nor the funding to attempt such an endeavour. Nevertheless, our prototype has set the groundwork for what would be considered the next step, which would be actually implementing the system. Another huge improvement that could be made to our design is having a dual stator system for the magnetic portion of our design, as this would allow for more control over the use of the magnetic brake. Having a dual stator allows for more freedom to play with the air gap, meaning that one could potentially control how much magnetic power is needed very precisely. Our model does something like this, but since it is one solid piece, only the surface area of the magnets controls the magnetic power, as the air gap is fixed. Having a dual stator design is definitely an improvement, but it is also more cumbersome and complex, so further prototyping would be needed to achieve this.

Another improvement that could be made to our design is using new materials to replicate the prototype that we designed. As previously discussed, we used several recycled materials during the construction of our prototype, including the rotor and the caliper. We have documented the struggles that we had with these materials, since we had to refurbish them, and we could obviously not get them back to their best state, as they were old and worn down. For this project, they performed just fine, but it would have been interesting to see what kind of results we might have obtained had we opted to get brand new parts. The brake pads we used for the caliper were worn down and the rotor surface was not perfect by any means, which are obvious sources of error. In the grand scheme of things, those factors probably didn't affect our results that much, but had we had the funding, it would have been interesting to see if our choices made a difference in the result.

Another significant improvement that could be made to our design is having both systems be activated through one mechanism, which was the original way things were supposed to work. Our prototype has not accomplished this, since both systems are activated separately while still working in unison with each other. The next step in this aspect of our design would be to have one single mechanism, like a pedal, that would activate both systems sequentially. This would be much more user friendly as the operator could activate one pedal and have both systems do their sequential duties through automation. This is the end goal for our project, one that we have not reached, but this could definitely be accomplished if the system was implemented on an agricultural vehicle so that we could actually design this sort of automated system.

We have previously discussed the decision that was made to use permanent magnets in our design instead of electromagnets, but one possible improvement that could have been made to our prototype is to try to use an electromagnetic system in comparison with our current system. The downfalls of electromagnets come from their weight, complexity, and power requirements, but they also provide several advantages. Having an electromagnetic system would allow for braking power regulation, much like the dual stator system. This is very beneficial to the operator who could navigate higher speeds using only the electromagnet as a speed regulator. Our system falters a bit in this case due to the fixed power output from the permanent magnets, although we can regulate it through surface area exposure.

Regarding magnet type, the use of a solenoid magnet is to be considered, as this would allow the possibility of increasing the versatility and use of our design by integrating a regenerative braking component. This would also justify an application of the hybrid braking system to electric vehicles as those are the ones most prone to be equipped with this specific, very promising, and highly eco-friendly technology.

Finally, another improvement that could be made to our design is weight reduction. We have already tampered with this a bit, especially during the design of our magnetic stator, but our prototype has a lot of potential for weight reduction. As previously discussed, our client demanded that the weight be minimized, which we did to a certain extent, but some materials used could be traded for lighter but potentially more expensive ones. One of our design goals was to have an ergonomic design that could be adapted to many different types of agricultural vehicles, and reaching this goal begins with reducing the weight of the hybrid system.

Conclusion

As we undertook this project, we realized that the scope was very large, and our resources were rather limited. Nevertheless, we set goals for ourselves from the start and followed through on most all of them. This project was an immense learning experience for all of us and several breakthroughs were made in terms of physical prototyping and data collection, that can hopefully be used by others who choose to explore this technology. As we have been inspired by several who have come before us in this area of research, we hope to have made a contribution with this detailed report, however small it may be. Much work is left to be done to achieve the ultimate goal of this project, which is for the system to be implemented in an actual vehicle, but this report has laid the groundwork for this become a reality.

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Appendix 1: Results and Calculations

The following parameters have been used as a basis for all the following calculations:

Property	Disc
Disc Material	Cast iron
k of Disc (W/(m•K))	47-80 (avg. 63.5)
Inner Diameter of Disc (m)	0.072
Outer Diameter of Disc (m)	0.28
Thickness of Disc (m)	0.025
Mass of vehicle (kg)	1000
Initial speed v_0 of vehicle (km/h)	50
Final speed v_{final} of Vehicle (km/h)	0
Deceleration rate of Vehicle (m/s^2)	7

Braking torque calculations:

To compute the magnitude of the force that must be applied to stop the vehicle, Newton's second law of motion is used:

$$F = m \cdot a$$

With a mass of 1000 kg and a deceleration rate of 7 m/s^2, we found that 7000 N are required. To transform this into torque, we use the following formula:

$$T = F \cdot r \cdot \sin(\theta)$$

Where r is the rotor's radius and θ the angle at which the force is applied, in this case 90 degrees about the axel of the vehicle. This yields a total torque of 980 N•m. Assuming each wheel exerts the same force, the total torque is divided by the number of wheels on the vehicle, yielding a torque of 245 N•m per brake.

Fluid mechanics and cylinder area calculations:

Based on Pascal's law, we can set an area for the master cylinder at the end of the fluid line. In fact, if the total force needed to fully stop the vehicle is 7000 N, then assuming all four wheels can provide equal braking torque and have the same dimensions, then 1750 N is the braking force necessary for a single brake. Turning to the other end of the fluid line (*id est* the brake pedal inside the vehicle), we look to define the amount of force that must be applied to produce a 1750 N force on the rotor. As ergonomics constitute a paramount criterion in the design of our product, it only seems logical to us that the user's comfort be maximized in all braking situations. Therefore, based on a knee angular position chart as correlated to exerted force published by NASA (see Appendix 2), we believe that 300 N is a reasonable and optimal value. This force would be applied by the operator of the vehicle on a standard braking pedal, with an area (A_1) of approximately 0.0104 m^2 (empirically measured), thus creating a pressure of about 28846.2 Pa.

Now that the two forces are determined, as well as the pedal area, using Pascal's law, we compute the required cylinder area:

$A_2 = (\frac{F_2}{F_1}) * A_1$

yielding 0.0607 m^2.

Heat transfer and maximum temperature calculations:

Neglecting drag and other losses outside the brakes, the brakes' retardation power is given by the negative of the time derivative of the car's kinetic energy:

$$P = \frac{-d}{dt}\left(\frac{mv^2}{2}\right) = -mv\frac{dv}{dt} = -mR^2\omega(t)\alpha$$

Here, m is the car's mass, v denotes its speed, R equals the wheel radius (0.25 m), ω is the angular velocity, and α is the angular acceleration. The acceleration is constant in this case, so $\omega(t) = \omega 0 + \alpha t$.

By definition, the retardation power equals the negative of the work per unit time done by the friction forces on the discs at the interfaces between the pads and the discs for the eight brakes. The friction force per unit area, f_f, is approximately constant over the surface and is directed opposite the disc velocity vector, $\mathbb{v}_d = \upsilon_d e_\phi$, where e_ϕ denotes a unit vector in the angular direction and the magnitude of, $\mathbb{v}_d$ at the distance r from the center equals $\upsilon_d(r, t) = \omega(t)r$. Here, to obtain the maximum heating case, we define r as being the center of the rotor's ring radius. Thus, since $f_d = f_f e_\phi$ we obtain the following result for the retardation power:

$$P = -8\int\int f_f dA \cdot \mathbb{v}_d = 8\, f_f(t)\omega(t)\int\int rdA$$

We can approximate the last integral with the pad's area, A, multiplied by the distance from the center of the disc to the pad's center of mass, r_m.

Combining the two expressions for P gives the following result for the magnitude of the friction force, f_f:

$$f_f = \frac{mR^2\alpha}{8r_m A}$$

Under the previously stated idealization that retardation is due entirely to friction in the brakes, the heat power generated per unit contact area at time t and the distance r from the center becomes

$$q(r,t) = -f_f \cdot \mathbb{v}_d(r,t) = \frac{mR^2\alpha}{8r_m A} r(\omega_0 + \alpha t)$$

$$\mathbb{v}_d = \omega(t)\,(-y, x)$$

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q - \rho C_p \mathbb{u} \cdot \nabla T$$

where k represents the thermal conductivity (W/(m·K)), C_p is the specific heat capacity (J/(kg·K)), and Q is the heating power per unit volume (W/m3), which in this case is set to zero.
We then use to following equation and solve for temperature

$$q = -A_{surface} \cdot h \cdot (T - T_\infty)$$

Where $A_{surface}$ is the area of the rotor, T the temperature on its surface (maximum temperature), and T_∞ temperature of air (or ambient temperature).

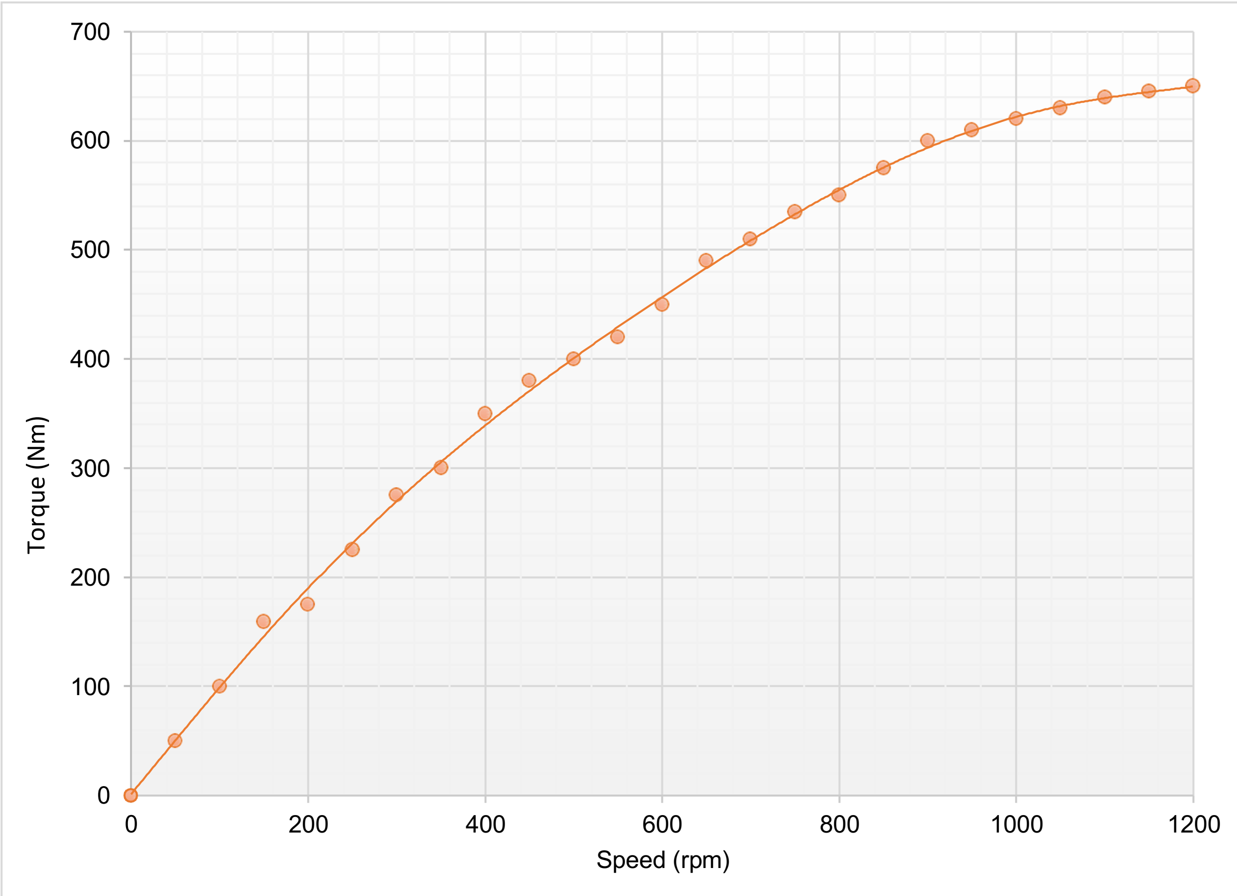
In this case, h is the convective film coefficient, which can be calculated with

$$h = \frac{0.037k}{d} Re^{0.8} Pr^{0.33} = \frac{0.037k}{d} \left(\frac{\rho d v}{\mu}\right)^{0.8} \left(\frac{C_p \mu}{k}\right)^{0.33}$$

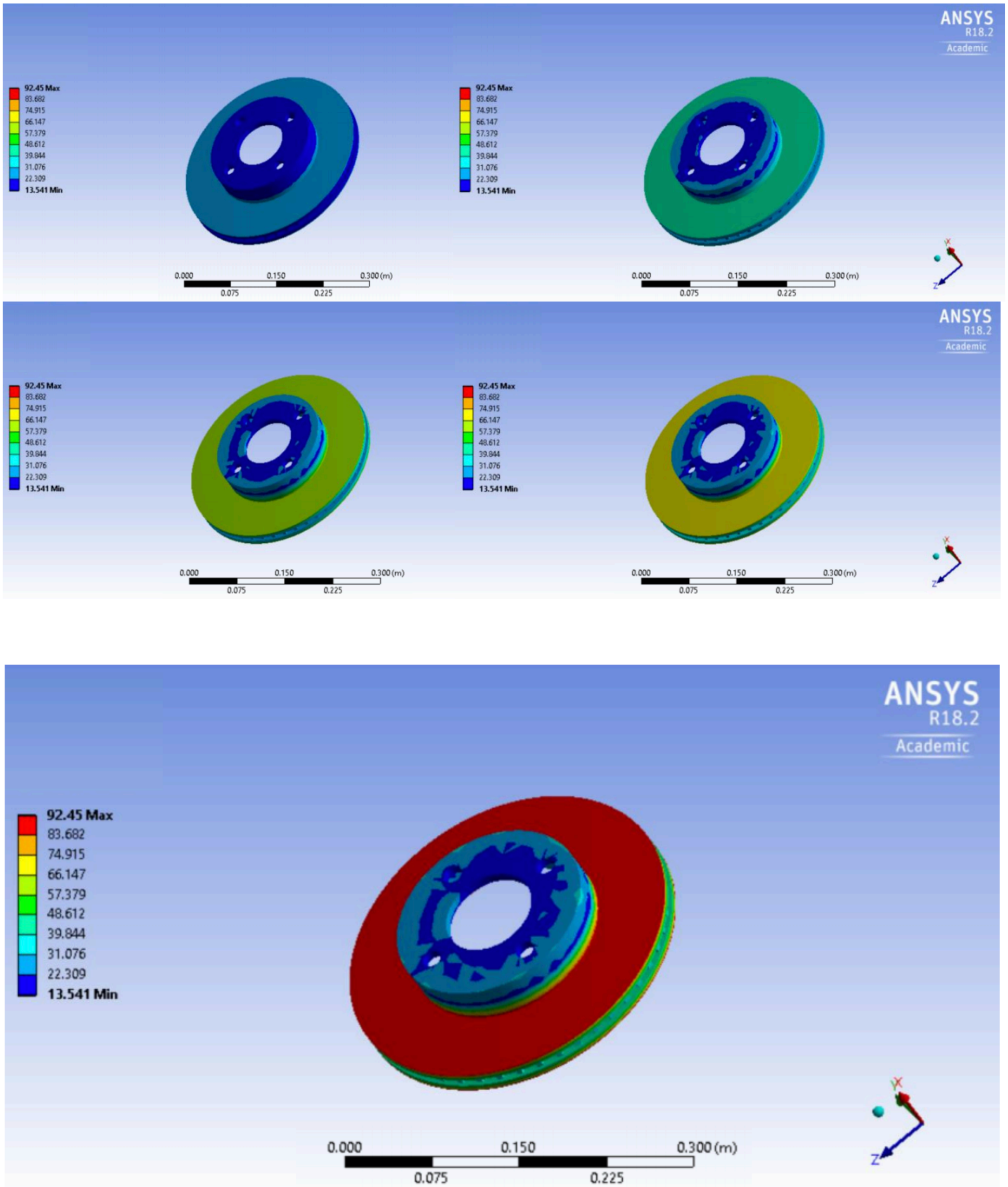
Where d is the disc's diameter, and k, ρ, μ, and C_p are for air.

Property	Disc	Pad	Air
ρ (kg/m³)	7300	2000	1.170
C_p (J/kg•K)	460	935	1100
k (W/(m•K))	47-80 (avg. 63.5)	8.7	0.026
ε	0.44	0.8	-
μ (Pa•s)	-	-	$1.8 \cdot 10^{-5}$

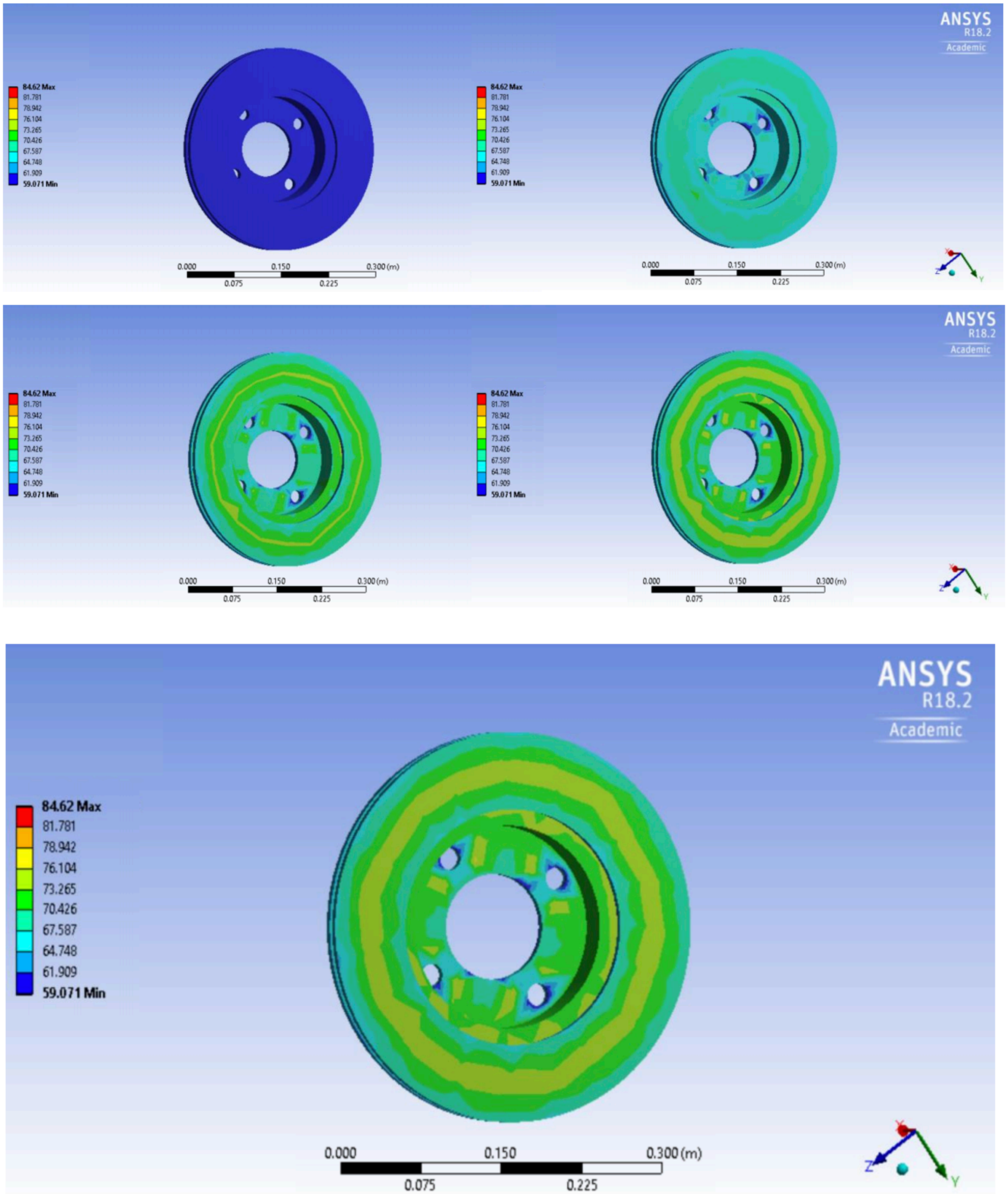
By inputting the specified values, we obtain a maximum temperature of 92.45ºC.



Graph A1: Neodymium Magnet Eddy Current Brake Torque-Speed Curve



Figures A1-A5: Maximum temperature and heat distribution throughout 2-second hydraulic braking process (full stop)



Figures A6-A10: temperature distribution throughout 2-second magnetic braking process (full stop)

Sample Arduino code for tachometer setup

```
#include<ShiftLCD.h>

ShiftLCD lcd(8,10,9);   // DEFINE LCD PINS

volatile byte REV;      //  VOLATILE DATA TYPE TO STORE REVOLUTIONS

unsigned long int rpm, maxRPM;  //  DEFINE RPM AND MAXIMUM RPM

unsigned long time;         //  DEFINE TIME TAKEN TO COVER ONE REVOLUTION

int ledPin = 12;          //   STATUS LED

int led = 0,RPMlen , prevRPM;  //   INTEGERS TO STORE LED VALUE AND CURRENT RPM AND
PREVIOUS RPM

int flag = 0;             //  A VARIABLE TO DETERMINE WHETHER THE LCD NEEDS TO BE CLEARED
OR NOT

long prevtime = 0;       //  STORE IDLE TIME TO TOGGLE MENU

 void setup()
 {
   Serial.begin(9600);   // GET VALUES USING SERIAL MONITOR

   lcd.begin(16, 2);     // INITIATE LCD

   attachInterrupt(0, RPMCount, RISING);     //  ADD A HIGH PRIORITY ACTION ( AN INTERRUPT)
WHEN THE SENSOR GOES FROM LOW TO HIGH

   REV = 0;      //  START ALL THE VARIABLES FROM 0

   rpm = 0;

   time = 0;

   pinMode(ledPin, OUTPUT);

   pinMode(3, OUTPUT);

   pinMode(4, OUTPUT);

   digitalWrite(3, HIGH);             //  VCC PIN FOR SENSOR

   digitalWrite(4, LOW);             // GND PIN FOR SENSOR

   lcd.print("TACHOMETER");           //   STARTUP TEXT
   lcd.setCursor(0, 1);
   lcd.print("- ELECTRO18");         //  THAT'S ME
   delay(2000);
   lcd.clear();

 }
```

```
void loop()
{
 long currtime = millis();                // GET CURRENT TIME

 long idletime = currtime - prevtime;       //  CALCULATE IDLE TIME

   if(REV >= 5 )               //  IT WILL UPDATE AFETR EVERY 5 READINGS
  {


    if(flag==0)                //  CLEAR THE LCD TO AVOID ANY GARBAGE TEXT
    {
     lcd.clear();
     lcd.print("SENSOR MEASURING");
     flag=1;                     //   AFTER FLAG = 1 , THE LOOP WILL NOT EXECUTE AGAIN
    }

    rpm = 30*1000/(millis() - time)*REV;       //   CALCULATE  RPM USING REVOLUTIONS AND
ELAPSED TIME

    if(rpm > maxRPM)
    maxRPM = rpm;                        //  GET THE MAX RPM THROUGHOUT THE RUN

    time = millis();

    REV = 0;

    int x= rpm;                            //  CALCULATE NUMBER OF DIGITS IN RPM
    while(x!=0)
    {
     x = x/10;
     RPMlen++;
    }



    if(RPMlen!=prevRPM)                        // IF THE RPM FALLS TO A LOWER NUMBER WITH LESS
DIGITS , THE LCD WILL GET CLEARED
    {
     lcd.clear();
     prevRPM = RPMlen;
     flag=0;
     lcd.print("SENSOR MEASURING");
    }

    lcd.setCursor(0, 1);
    lcd.print(rpm,DEC);                    //  PRINT RPM IN DECIMAL SYSTEM

    lcd.setCursor(6,1);
    lcd.print("RPM");
    delay(500);

    prevtime = currtime;                    // RESET IDLETIME

   }
```

```
  if(idletime > 5000 )                    //  IF THERE ARE NO READING FOR 5 SEC , THE SCREEN WILL
SHOW MAX RPM
  {

   if(flag==1)                     // CLEAR THE LCD
   {
    lcd.clear();
    flag=0;
   }

   lcd.clear();
   lcd.print("MAXIMUM RPM");
   lcd.setCursor(0, 1);
   lcd.print(maxRPM,DEC);                 // DISPLAY MAX RPM
   lcd.print("   RPM");
   delay(2000);
   lcd.clear();
   lcd.print("IDLE STATE");
   lcd.setCursor(0, 1);
   lcd.print("READY TO MEASURE");
   delay(2000);
   prevtime = currtime;
  }

 }

 void RPMCount()                          // EVERYTIME WHEN THE SENSOR GOES FROM LOW TO HIGH
, THIS FUNCTION WILL BE INVOKED
 {
  REV++;                                // INCREASE REVOLUTIONS

  if (led == LOW)
  {

   led = HIGH;                          //  TOGGLE STATUS LED
  }

  else
  {
   led = LOW;
  }
  digitalWrite(ledPin, led);
 }
//////////////////////////////////////////////////////////////          END        OF        THE        PROGRAM
///////////////////////////////////////////////////////////////////////
```

Component	Cost (CAD)	Donated Equipment and Material
OmniDrive AC Electric Motor	199.99	
7 inch Pulley	8.78	
3 inch Pulley	13.65	
Rubber belt	8.65	
Steel Shaft	10	
1/4 inch steel 10" x 10"	18.4	
1/2 inch steel 12" x 12"	13.7	
10 x Rare Earth Magnets	44.75	
5x [(½"-20 x 1-1/4") zinc finish hex cap screw]	13.49	
6x [(½ "-20 x 1 ¼ L) Coupling Nuts]	37.48	
1/2"x2'x4' Plywood	16.2	
2"x"3"X8' Framing Lumber	3.25	
3D Printed Caliper	40	
Rotor	20	
Hydraulic Brake Caliper	10	
Actuator	173.49	
Hydraulic Brake line	18	
Arduino Uno		✓
Electric Wires		✓
Master Cilinder		✓
Piston		✓
Hydraulic brake fluid		✓
Total	649.83	

Table A.1: Budget breakdown and element costs

Figures A11-A12: Infrared camera renderings and heat maps following braking procedure trials

Appendix 2: Additional visual support

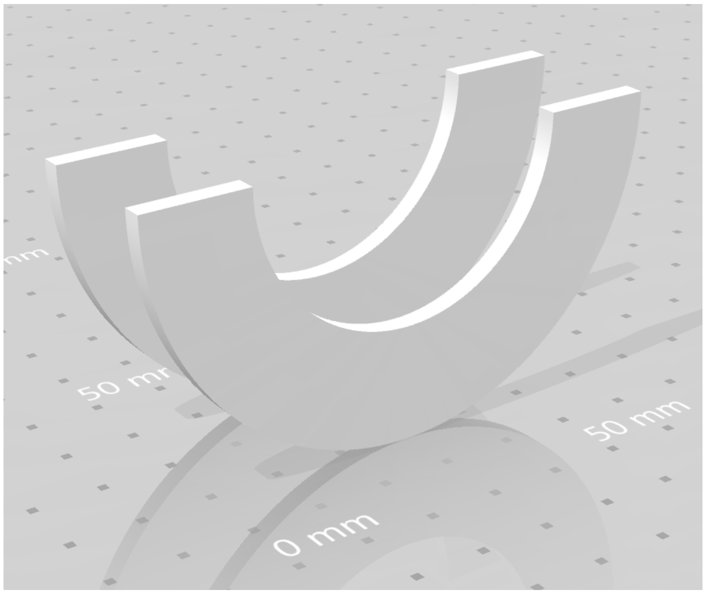


Figure A2-1: Early dual stator design

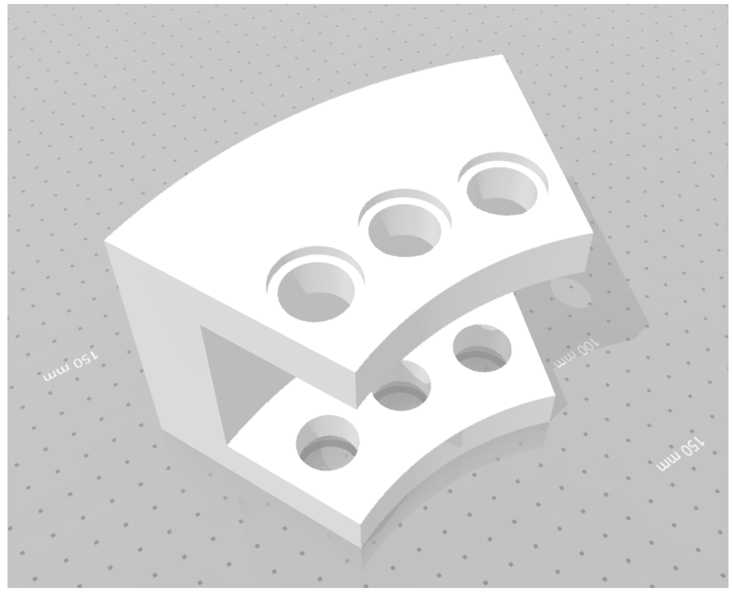


Figure A2-2: First prototype of single stator

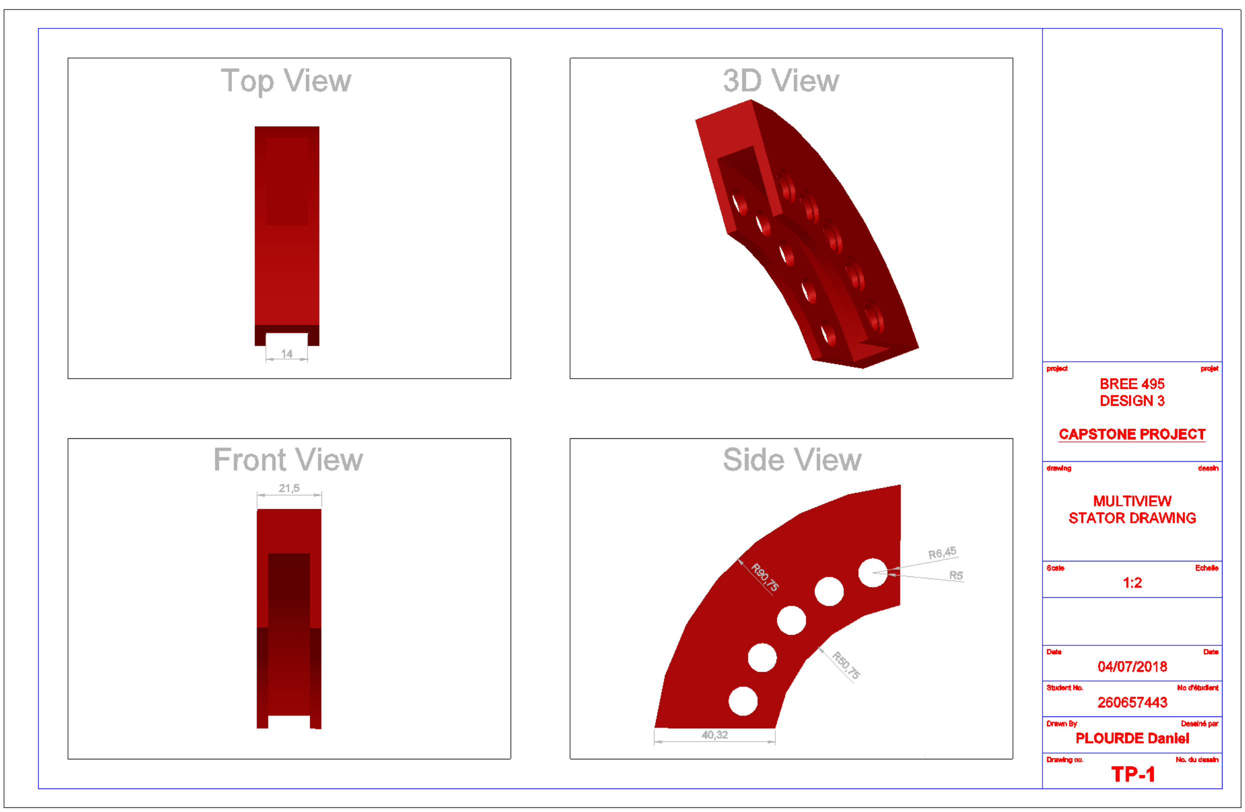
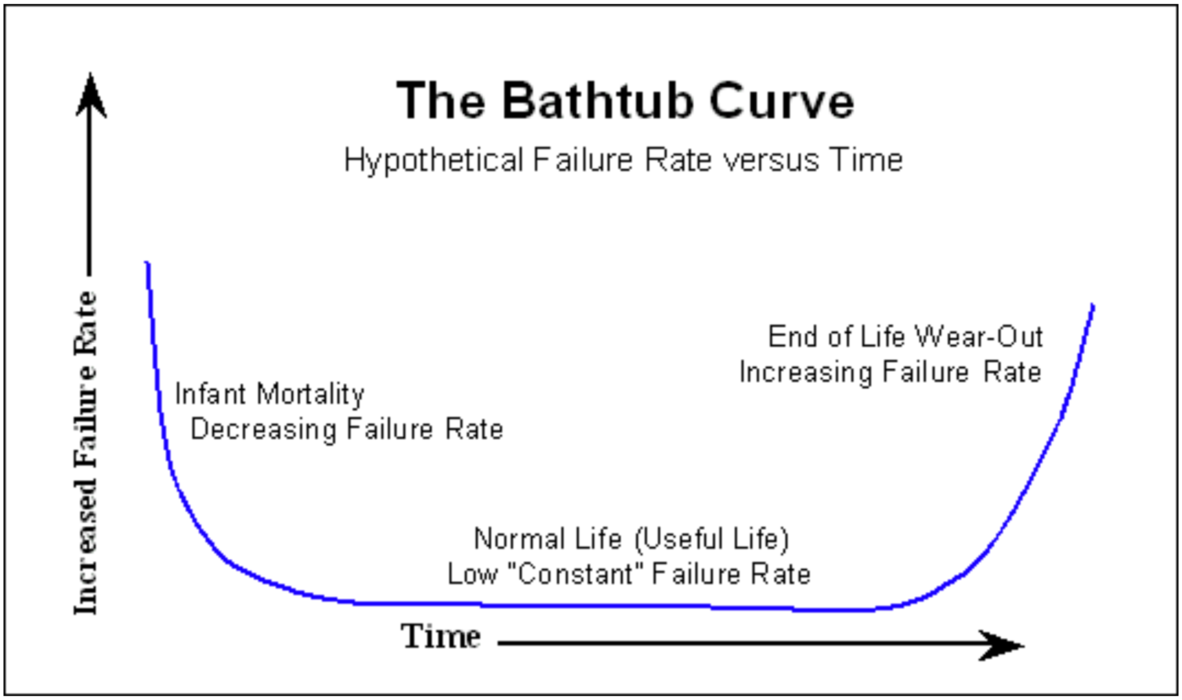


Figure A2-3 (TP-1): Technical rendering of final single stator design



Graph A2-1: Bathtub curve (Weibull.com)

Test Type	Priority (max. 10)	Feasibility (max. 10)	Affordability (max. 10)	Conducting (Yes: Green; No: Red)
Deformation test	7	5	6	18
Braking efficiency	10	10	10	30
Maximum Torque test	5	5	6	16
Thermal performance/Heat Transfer	10	7	5	22
Torque/Speed Test	7	4	8	19
Tachometer Accuracy	4	4	8	16

Table A2-1: Conducted tests decision process