School of Science, Engineering and Technology
Department of Engineering

DriverTech Remote Tire Sensor

By

Hiram Diaz (ME)
Ana Isabelle Ordonez (ME)
Andrea Ozaeta (ES)

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Supervising Advisors:
Dr. Juan Ocampo
ASSOCIATE PROFESSOR OF MECHANICAL ENGINEERING
Dr. Ben Abbott
INSTRUCTOR OF ELECTRICAL ENGINEERING
ABSTRACT

The purpose of this project was to develop a remote tire sensor for our sponsor, known as DriverTech, that can detect and record the number of wheel revolutions a truck tire has made while traveling, as well as the temperature of a wheel near the area of the drum brakes. This is information that can be cross referenced with travel distance data from a truck’s onboard GPS navigation system and used to determine risks of wheel failure and signal required maintenance on the vehicle by calculating tire wear. Tire wear is accumulated significantly while traveling on the road for long distances with any form of heavy-duty vehicle for transportation. This project required us to use our knowledge of vehicle dynamics to accommodate a design that considers the effects of acceleration, high velocity, and hard braking on a wheel through centrifugal forces, mechanical fatigue, and thermodynamics while keeping our device intact. This project also required us to use our knowledge of mechanical design to develop a product which can be easily attachable; while also abiding by set standards for off-the shelf parts, components, and materials which will minimize costs and any required forms of special maintenance or fabrication processes for our device to be built and be fully functional. Our device uses electrical components which required us to consider the effects of environmental factors on our device from traveling on less maintained roads or through harsh weather conditions. Our device would serve as proof-of-concept and will be used as a foundation upon which our sponsor will be able to manufacture and develop a final product appropriate for being sold in a high-demand industrial market.
ACKNOWLEDGEMENTS

We would like to begin by acknowledging our sponsor, Mark Haslam, the CEO, and owner of DriverTech. Without him we would not have been able to make this project possible; he was always so helpful and would always have answers to our questions. We would also like to thank our advisors, Dr. Juan Ocampo and Dr. Ben Abbott – they became our mentors during this project, and they always pushed us to do better. Likewise, we would like to extend our gratitude to Mr. Vernon Weir – engineering technician at the Richter Math-Engineering building, for assisting us throughout the fabrication of our project as we implemented manual machining. We also offer thanks to Ms. Gail Jaszcz, for continuously handling all our orders to make this project possible. Finally, we would like to thank the Mechanical Engineering faculty, Dr. Nazia Afrin, Dr. Morgan Bruns, Professor Miguel Cortina, and Dr. Amber McClung, because without their teachings and expertise, we would not have made it through these past four years and would not be in this position.
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1. INTRODUCTION

This project consists of developing a single-unit device with two measuring capabilities: temperature and revolution count of wheels for a smart trailer. The device will be installed on one wheel of the trailer and will connect to the truck computer, named the DT 4000, through Bluetooth wireless connection. This data will then be used to assess any gradual changes in wheel size or wheel function by calculating tread wear over extended periods of time. This information is then used to determine whether the long-haul vehicle requires maintenance or being decommissioned in cases of serious damage. Our device utilizes an ESP32 based microcontroller and peripherals running a C++ based code developed on the Arduino IDE environment. This code is used to record the requested data on a device with wireless connectivity and industry-leading power efficiency to achieve a two-year operating life on single cell batteries. The device is designed to use the microcontroller’s embedded hall effect sensor functionality paired with a magnet fixed to the wheel rim to count and record the number wheel revolutions during travel. The temperature at the brakes is recorded using an infrared contactless temperature sensor connected directly to the microcontroller. A metal bracket is fabricated using a slotted angle iron in order to attach both of those components near the proximity of the wheel as is required for optimal position, with an encasing and electrical tape used to ensure that any electrical components and their wiring are minimally exposed to outside environments as possible for their specific use cases.
2. COMPANY DESCRIPTION

DriverTech is a company based in Utah that creates durable and reliable mobile communications technology for the trucking industry and has been in business for around thirty years. They work in the development of fleet management tools, meaning that they manage the whole fleet of trucks to optimize profit, instead of focusing on the individual trucks. They currently have a device named the DT 4000, a Mobile Fleet Management Platform. This device monitors different aspects of the vehicles, for example, oil temperature, position of the vehicle, whether the driver is speeding, as well as other variables. DriverTech has recently expanded its focus to the trailer connections, which has recently resulted in the monitoring of the tire pressure through Bluetooth connected peripheral devices.

3. PROBLEM STATEMENT

In over thirty years of the company’s history in the industry, DriverTech has identified two scenarios with high rates of wheel failure for a semi-truck. The first scenario can occur at the beginning of a vehicle’s travel, if the truck and its trailer are not properly connected together, which is crucial when it comes to the proper functioning of the vehicle. Failure to attach the trailer properly can cause interference on the truck’s wheels and have a direct effect on the vehicles’ ability to move the way it is intended on the road. When this happens, wheels on the truck will not rotate properly, and in worse cases may not even rotate at all. As a result, it can lead to very serious wheel or truck damage and very expensive vehicle maintenance and repair costs.

The second cause of failure comes from the effects of tread wear on a tire after a truck has been traveling on the road using the same tires and wheels for an extended period of time. Both small and large supply chain and logistics companies often must meet very high demands for
delivery times of consumer goods and industrial tools, which also requires complying with very strict and extensive travel schedules for their entire fleet. As such, some companies do not have the time or capacity to be able to conduct extensive vehicle inspections and maintenance as would be required to make sure that the truck is performing optimally, which includes replacing failing brakes, maintaining a reasonable tire pressure and replacing the wheels and tires if they go flat or have high tread wear. Tread wear which accumulates after traveling very long distances across multiple environmental conditions can be determined through slight decreases in the wheel size of the vehicle. Significant amounts of tread wear on a tire will mean that the tire will have to be replaced as soon as possible to prevent accidents caused by the wheel slipping, where the momentum caused by the large mass of a heavy-duty vehicle traveling at high speeds on a highway can be very dangerous, since it will struggle significantly to recover balance while on the road. DriverTech, however, has identified that slight changes in wheel size can be calculated by using data of travel distance obtained through the GPS combined with data of wheel revolutions through our device, where the number of revolutions it takes to cover the same tangential distance increases as wheel size decreases. Wheel brake temperature is also useful at inferring whether the drum brake should also be replaced if it is operating in sub optimal conditions, where temperatures can reach up to 550 degrees Fahrenheit. With our device, we will be able to notify the driver that a wheel needs to be replaced without having to rely on a periodic maintenance inspection for both failure conditions, allowing the truck to be on the road for longer while minimizing risks of failure. The long reaching goal of this project is to assist further towards maximizing the efficiency of a supply chain and distribution network for companies to adhere to their strict and extensive delivery travel schedules.
4. OBJECTIVE

The objective of this project was to design, build, and test a prototype for a device that will be attached near or on the wheel which can measure the temperature and count the revolutions of the wheels of the trailer. This battery-powered device will be placed in each wheel of the trailer and will connect to a device that communicates the collected data directly to DT 4000 through Bluetooth, where all the data gathered by the device will go and be assessed and used to calculate for tread wear and changes in wheel size.

For this project, we have a few key objectives which we are looking to accomplish:

- The device must be optimized to maintain proper compatibility with DriverTech’s current DT 4000 Fleet Management Platform truck computer and other necessary peripherals through Bluetooth, which will use the recorded data for the necessary calculations. For this project, our job is not to handle the truck computer’s wheel size and tread wear calculations. Our job only requires us to ensure that the data is being recorded accurately and transmitted properly to the truck computer. This is of very high priority for this project.
- To potentially reduce complexity of design in terms of software and be able to produce and sell the full device as a single product, we are focusing our design such that all sensors which will be collecting the wheel revolution and temperature data are connected to the same microcontroller and use the same battery power source. All wheel and trailer attachments, however, are allowed to be separate entities if it is optimal for securing the components in place and for collecting the necessary data. This is of high priority for this project.
• Since a semi-truck is likely going to be traveling across different types of environmental conditions and encounter potential hazards, the device should be able to sufficiently resist most environmental conditions and should be very simple and inexpensive in terms of replacing broken or missing components if the truck were to encounter a very serious environmental factor. This is of high priority for this project.

• The device should consume as little power as possible in order to maximize battery life, which would likely be done by scheduling the microcontroller to sleep within certain time intervals and record data during brief but crucial moments of a truck’s wheel rotation movement. This is of medium priority, as it is more important to ensure that the device is able to maintain its position along the wheel during travel and able to record wheel and temperature data accurately before evaluating the power and required battery size for the components which will be required.

• The device should be roughly equivalent in size to other peripheral devices that the DT 4000 truck computer already uses, such as the tire pressure monitors. However, this is of low priority, the device proportions must be as they are required to ensure that the sensors are within proximity to function properly. The chassis for the microcontroller, battery, and circuit breadboard components are also subject to change depending on the desired battery size to maintain a good lifespan.
5. LITERATURE SEARCH

In researching products that are currently on the market which perform similar duties as the specifications asked by our sponsor, these being building a prototype that would measure wheel revolution count and temperature reading, we came across several gadgets. For example, Tire Linc: Tire Pressure and Temperature Monitoring Systems (TPMS), as shown below in *Figure 1*, is a monitoring system that alerts the driver at hand of any out-of-range increase or decrease in the pressure and temperature of the tire. A unique feature of this product is that it comes with a repeater that strengthens and amplifies the signal from the sensors to be sent to a specific application on iOS and Android devices. This application software allows the user to specify the manufacturer’s selected pressure and temperature range for each tire.

![Figure 1. Tire Linc: TPMS](image)

A second product which we came across includes the SmarTire Trailer-Link: TPMS, as shown below in *Figure 2*. This monitoring system allows drivers to view real-time temperature and pressure of the truck tires to stay on track with regular tire maintenance. The sensors mounted on each tire measure the aforementioned values every twelve seconds and wirelessly transmit this data to the trailer dashboard every 3 to 5 minutes.
A third product that is already on the market is Tymate: Tire Pressure Measuring System, as shown below in Figure 3. This product comes with six alarm modes; including: high pressure alarm, high temperature alarm, fast leak alarm, slow leak alarm, sensor fault alarm and sensor battery low power alarm – all of which prompt the driver of any abnormal conditions in a given tire. Tymate supports solar charging as well as USB cable charging, and it comes with four sealed external sensors for protection against environmental conditions. In identifying underlying issues which may elicit increased wear on any of the truck tires, Tymate endorses a two-year working life of its sensors with a pressure measurement error range of no more than 3 psi.
Other tire monitors already on the market include: BTech Wireless Solar Power TPMS, Vesafe TPMS, Jansite Universal TPMS, and TireMinder Smart Model TPMS-6. However, although all the aforementioned commercial products perform similar duties to our specified criteria, they do not meet it fully. There is no product currently being sold to the general public that measures the wheel revolution count along with temperature, specifically near the area of the brakes of a tire. We will therefore be building a prototype that our sponsor will then reduce to practice by using off-the-shelf components with an open-source design.

6. RELEVANT STANDARDS

One of the main focuses of our literature search was to identify different standards which are relevant to the trucking industry for which this device is being designed, as well as relevant technical specifications to ensure proper functionality of our device:

The first standard we identified was the SAE J1455 Standard for environmental practices involving electrical equipment being used in heavy-duty vehicle applications such as semi-trucks. This standard is implemented in order to ensure the optimal performance and reliability of all electrical components being involved with the purpose of reducing electronic waste which can be encountered in the event of improper implementation and a collision or accident of such a vehicle. This standard also exists to promote sound design and safety practices when handling such electrical equipment.

The Federal Motor Carrier Safety Administration (FMCSA) has implemented an Hours of Service (HOS) regulation, which dictates that a semi-truck should not be on the road for more than 14 consecutive hours. A truck driver should also not be at the wheel for more than 8 consecutive hours and if traveling alone must take a stop for at least thirty minutes before returning to the road.
These regulations are implemented to reduce driver drowsiness, which can lead to loss of consciousness on the road and cause serious or fatal accidents. These regulations were relevant because it gave us an initial estimate of maximum time our device would have been expected to consistently operate within a standard day. Our sponsor, however, has suggested that his clients usually do not drive more than twelve hours a day which reduces the expected operating time on our behalf.

The Bluetooth 4.0 standard has been identified as the wireless communication method that the DriverTech DT-4000 truck PC uses, which already has designated specifications for power consumption and speeds for data transmission, as well as security protocols to help prevent the device from being tampered with while on the road.

Every vehicle wheel uses a set standard of wheel weights in order to help maintain a proper wheel balance while driving on the road. For heavy-duty vehicles such as semi-trucks, we have identified this standard as being the i7 Style. An older version of this standard consists of weights made of lead material which weigh up to 16 Oz. These types of weights have largely been banned by regulatory bodies and state legislation for production and implementation since 2005 due to concerns with material safety. A newer version of this standard consists of weights made of Zinc material which weigh up to 6 Oz. Both wheel weights are clipped alongside the rim of a wheel while tucked between the tire and the rim. This standard was relevant to our project because it influenced our final design solution approach.

Another standard which we identified to be of utmost importance was the NMEA 0183 Standard, which defines electrical signaling requirements, along with transmission protocol of data and specified sentence formats for serial communication. NMEA data is transmitted one-way via
a single source (or “talker”) such as GPS, but capable of many listeners. Such data may incorporate information regarding time, position, and/or speed.

7. DIVISION OF LABOR

The division of labor for this project is shown in Table 1 where even distribution of work was ensured for each member. These divisions of labor serve only for the purpose of role designation; however, all team members are expected to contribute to all project requirements:

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<td>Assembly/Prototype</td>
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<tr>
<td>Ana Ordonez</td>
<td>Mechanical Calculations, Component Testing,</td>
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<td></td>
<td>Assembly/Prototype</td>
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<tr>
<td>Andrea Ozaeta</td>
<td>Prototype Design, Component Testing, Assembly/Prototype</td>
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*Table 1: Division of Labor*

8. PROBLEM CONSTRAINTS, REQUIREMENTS, AND SPECIFICATIONS

The device must fulfill multiple requirements which were provided to us by our sponsor based on their specific design goals, as well as taking into consideration certain standards which have been set forth by the industry for similar vehicle peripherals. To fulfill these requirements, the device must have:
- Single unit cell that accommodates both the revolution and temperature sensors concurrently
- Battery powered with a replaceable single cell for a two-year lifespan
- Resistance to different types of environmental hazards and conditions
- Built to SAE J1455 standard, the recommended environmental practices standard for electrical equipment in heavy duty vehicles
- Accurate rotation count measurements on a per mile basis
- Precise temperature readings with a ±5°F difference
- Proper time management to schedule sleep mode and active data recording mode on the microcontroller to help conserve power.

9. SUMMARY ON ENGINEERING METHOD

Our engineering methodology consisted of an iterative design process which began by brainstorming multiple design solutions utilizing different types of sensors and peripherals for our device. We then transitioned to brainstorming how we would attach our selected devices at several different positions to optimally collect the tire revolution and brake temperature data while ensuring that the components will not fall while the truck is in motion. We also had to ensure that our device would not cause interference to the wheel while it is rotating. Afterwards, we began to consider the ease of manufacturability of our device in order to be able to fabricate it in a short period of time. This was crucial so that we would be able to use it for testing based on our design goals. Our decisions were then supported through engineering calculations based on the dynamics of the wheel and the material properties of our device and its components.

9.1 INITIAL PROPOSED SOLUTIONS
During the initial stages of our iterative design process, we determined that a hall effect device paired with a magnet to be an optimal solution for getting our wheel revolution count measurements. This approach has a high degree of accuracy and was recommended to us by our sponsor, who has over thirty years of experience in the trucking industry. A hall effect device is designed for the sole purpose of detecting the presence of a magnetic field within close proximities and is already used commonly for other vehicle devices such as tachometers. They can also be programmed to operate in two separate methods depending on what the design approach requires. A hall effect device can produce a digital output or value upon the detection of a magnet when its normal state involves no magnetic field and can also produce a digital output or value when the device no longer detects a magnet in which its normal state places it in constant presence of a magnetic field.

Our first functional proposed solution shown in Figure 4 involves attaching the hall effect device directly onto the backplate of a wheel’s drum brake. This is a portion of the wheel which does not rotate while the vehicle is in motion as it also serves as the outward portion of the shaft that holds the wheel axle. The magnet would be placed along the outer circumference of a wheel drum brake using its natural magnetic strength. The wheel drum is a rotating portion of the wheel since it is responsible for handling the wheel brake system which activates when brake shoe materials located inside create friction with the outer surface of the drum. Since the hall effect sensor is stationary on the backplate, hanging almost over the edge, it would be in close proximity to the magnet as it completes a full wheel revolution. The hall effect sensor would produce an output the moment that each wheel revolution is completed. This design was the initial basis of
our design as we began to explore and further expand our understanding of the mechanics of an automotive wheel during our progress on this project.

Figure 4: First Proposed Design

A second proposed solution, shown in Figure 5, involves attaching the hall effect sensor to a metal bracket located at the bolt which secures the wheel to the backplate of the wheel drum brake system, allowing for it to maintain a fixed position on the side of the wheel just like the first design. This bracket would incorporate both the hall effect sensor and the magnet on the same bracket, meaning that both parts will be stationary, with an amount of space that is equivalent in distance as the thickness of the wheel drum. For this design, the hall effect sensor will be set to detect the absence of a magnetic field by creating an interference with a material attached to the wheel drum, with each interference being registered as one revolution. Compared to the first design, this bracket had a slightly better assurance that the hall effect sensor would be able to detect the magnet at any point in its revolution. This is due to the fact that both components are able to
maintain a fixed position at all times while still being able to count wheel revolutions. However, we would need a slightly larger bracket.

![Diagram of Second Proposed Design]

**Figure 5: Second Proposed Design**

As we proceeded with our next design iterations, we began to consider the potential consequences of having to place material along the outer rim of the wheel drum rim with the intended purpose of passing through a manufactured gate. We believed that continuing with this design approach increases the risk of causing interference for the wheel if the material were to move due to vibrations of the moving wheel drum, despite being able to potentially obtain more accurate data.
As such, our next design approach was a reiteration of the first design in which we would place the magnet along the outer circumference of the wheel drum. However, we observed through our testing that the hall effect sensor would need to be placed at a closer proximity to the magnet than it would be by maintaining its position directly at the backplate. We would still need to manufacture a bracket that positioned the hall effect over the wheel drum. However, we would be able to reduce the size and also significantly reduce the risk of causing interference on the wheel, given that the magnet would be placed in a horizontal position that is parallel to the circumference of the wheel drum. Through further research and feedback, we began to consider the effects of heat transfer which may occur on the magnet as the wheel drum forces the wheel to brake. Wheel drums can get very hot due to the high amount of friction that is required to stop a semi-truck from moving while traveling at high velocities like 75 mph and potentially exceeding temperatures of 550 degrees Fahrenheit. So, another metal bracket for the magnet was made with the intent of adding the necessary insulation to the magnet to minimize heat transfer from the wheel drum brake as shown in Figure 6.

Figure 6: Third Proposed Design
The second design was iterated on a little bit, as shown in Figure 7, attempting to potentially find ways to implement other aspects of circuitry into closer proximity to the hall effect sensor and magnet such as a mini breadboard to minimize length of cables required for the hall effect device and temperature sensors, in order to prevent them from getting tangled on a rotating portion of the wheel, before deciding that it would be much more efficient to use only one breadboard for all of the circuitry including everything for the microcontroller and the sensors and look towards using jumper cables with cable clips to prevent movement along with some level of resistance from the exterior to outside environments, since using a design like this would increase the size of the bracket we would need substantially. We also discovered upon further research that the microcontroller which we would be using for our device had an embedded hall effect sensor and battery connector within it and the infrared temperature sensor could be wired directly to it, thus eliminating the need for an external hall effect sensor and a breadboard as a whole.

Figure 7: Fourth Proposed Design
For our next iteration, we identified that all vehicles have a wheel weight standard which is used to maintain a wheel’s balance using material such as Zinc or lead which is attached along the circumference of a wheel rim using a clip which adheres to a specific standard and dimensions depending on the vehicle. Thus, it gives us a more reasonable alternative position for the magnet compared to having it placed directly on the wheel drum where it could be exposed to high heat transfer conditions. We could attach it by creating our own magnet clip based on the dimensions that we need following the same methodology as the wheel weights. Our new design approach incorporates a bracket attached along the bolt which holds the wheel drum to the backplate, just like the previous designs. However, the bracket for this design consists of an arm that extends vertically alongside one extending forwards to hover over the wheel drum. This is done for the purpose of being able to attach the magnet along the rim of the wheel, as shown in Figure 8. This design allows us to ensure that the magnet will not lose its magnetic force, which occurs when the magnet is exposed to at least 220 degrees Fahrenheit, while the wheel rims only go up to 170 degrees Fahrenheit. These numbers validate our approach while eliminating our need for insulation.

![Diagram of Fifth Proposed Design](image)

*Figure 8: Fifth Proposed Design*
In this design, the bracket would be manufactured using CNC machining; the microcontroller and hall effect sensor would be attached to the vertical arm, while the temperature sensor would be attached to the horizontal arm to point at the wheel drum. This is the first design to fully incorporate a space for both sensors that we need for this project, as we were mostly focusing on the primary objective of recording wheel revolutions for our previous designs.

Although the fifth proposed design showcased in Figure 8 above would have been our final proposed design, due to concerns regarding the cost to manufacture the bracket of the microcontroller using CNC machining, we began to consider other alternatives while maintaining the core functionality and positioning of our microcontroller and temperature sensors the same. Therefore, for our final iteration, we decided to go forth with the implementation of manual machining instead, allowing us to alleviate some of the added expenditures.

In addition, we also reconsidered the proportions of the bracket to ensure that the microcontroller and the hall effect sensor were positioned properly relative to the backplate that the bracket would be attached to. Given that the axle (and consequently the backplate) of the vehicle in which our prototype testing was going to be conducted extended inwards toward the center of the wheel, rather than being perfectly aligned with the wheel rim as showcased in Figure 8 above, a vertical arm alone extending upwards would not have guaranteed alignment of the hall sensor and magnet. Therefore, in maintaining the core functionality of the last proposed design, while accommodating for the differences in proportions brought forth by our testing vehicle—a backward bend (that is, away from the back plate) of the bracket could be implemented with enough length to then incorporate that same vertical arm once again, ultimately achieving optimal alignment of the hall sensor and magnet. The bracket would keep the additional arm extending forward to account for the placement of the temperature sensor, but instead of hovering over the
wheel drum, this arm would hover below it. Please refer to Figure 9 below for a visual depiction of the aforementioned changes to the design.

Figure 9: Final Proposed Design

9.2 FINAL DESIGN APPROACH AND MATERIAL SELECTION

To address the manufacturing concerns which were considered for our previous design, we decided to use a Zinc-plated slotted angle iron, which could easily be cut and bent to fit our design for the necessary proportions based on the wheel that it is being attached to for on-road testing. The specific angle iron we purchased can be found in Figure 10 below. The holes and slots on the angle iron also allow us to easily attach the bracket to the backplate using the bolts and nuts on the back by only making small adjustments to diameter size and width as was deemed necessary while attempting to attach it during our manufacturing process. The angle iron could be bent accordingly to make sure that the hall sensor directly faces the magnet, which is still being attached to the outer rim of the wheel using a porous metal screw and a clip of a similar wheel weight to the ones used
on the truck the device is being tested on. It was necessary that the screw was porous so that it would not affect the magnetic field between the magnet and the hall effect sensor. This approach also encouraged us to make a bracket which could then be supported by two backplate bolts instead of one by making it longer and incorporating a separate section where the temperature sensor can be facing the outer circumference of the wheel drum. All of this could be done utilizing only one angle iron of sufficient length without the need for additional components.

![Figure 10: Zinc-Plated Slotted Angle Iron](image)

Using this approach, the bracket needed to be cut in the middle to be able to fit accordingly due to the width of the axle shaft, as can be seen in Figures 11 and 12 below, followed by the engineering drawing on Figure 13. This was in order to ensure that the holes can be properly aligned such that the bracket is able to be attached to two bolts instead of one.
Figure 11: Isometric View of Final Design on Wheel

Figure 12: Isometric View of Final Design
Figure 13: Engineering Drawing of Final Design
For the magnet bracket, instead of building the bracket from scratch, we decided to use existing lead weights and removing the weight to leave the clip portion that attaches directly to the rim. We purchased neodymium magnets, as shown in Figure 14 below, as they are tested to be the strongest commercially available magnets that can be found in the market, and have a rated pull force of about 5 lbs. The magnets we used have a hole in the middle which can fit a 3/8 sized metal screw used to attach the magnet directly to the clip. We could not use a magnet that was too large, or too heavy, because then we would have disturbed the balance of the wheel. So, we decided to use a smaller magnet, if it was able to be detected by the hall effect sensor, which it was.

\[
\text{Figure 14: Neodymium Magnet}
\]

9.3 ELECTRICAL COMPONENT SELECTION

When selecting our components for the prototype device, there were three key components we needed to consider, the microcontroller, the hall effect sensor, and the temperature sensor. Other components that we had to select for this project were the magnets and the adhesive that we would be using to attach all the components on the device.

For the microcontroller, we discovered a part called the DFRobot ESP32-E Firebeetle IOT, as shown in Figure 15 below. It is compatible with the Arduino ecosystem of peripherals and only
utilizes approximately 10 μA of power while in sleep mode and 80 mA when in operation. It also has Bluetooth and Wi-Fi connectivity built into the device since it was developed in order to be incorporated into a network of wireless peripherals for industrial applications. This microcontroller has an embedded hall effect sensor which we could use without the need to incorporate another one, thus allowing us to make a simpler unit. The microcontroller is also compatible with the Arduino IDE programming environment and an extensive catalog of open-source software libraries which we could download and use while developing the code for the device, since the ESP32 architecture is widely supported by companies such as Espressif and Adafruit.

![Figure 15: DFRobot ESP32-E Firebeetle IOT Microcontroller](image)
For the temperature sensor, we decided to go with the Songhe GY-906 Infrared Temperature Sensor. At first, we considered using thermocouples to measure the temperature. However, we decided to use an infrared sensor instead because it can operate through non-contact. This specific temperature sensor, that is shown in Figure 16, was the one we selected because it had a broad range of temperature that it can work in. This temperature sensor can measure temperatures from -94°F to 719.96°F. And has a precision of 3 degrees Celsius from an inch distance. Most of the temperature sensors that we found were not able to measure the high temperatures the wheel drum can reach when in motion. It is also directly compatible with the pin layout of our ESP32 microcontroller and is supported by its own dedicated software library on Arduino IDE.

![Songhe GY-906 Non-Contact Infrared Temperature Sensor](image)

*Figure 16: Songhe GY-906 Non-Contact Infrared Temperature Sensor*
We have also selected jumper wires that have a jacket which are resistant to certain environmental factors such as water and will be used to connect the infrared temperature sensor to the microcontroller. They are also color sorted and can be chained together depending on the length which was required based on the size of our fabricated bracket. These are shown in Figure 17.

![Jumper Wires](image)

*Figure 17: Jumper Wires*

9.4. **STRUCTURAL STRENGTH CALCULATIONS**

To begin with the strength calculations, we first drew the free body diagram to find the reaction forces and the moment on the bracket where the hall effect sensor and the infrared temperature sensor were positioned, which can be seen in Figure 18. The 0.78 lbs that is seen in the free body diagram, is the weight of the bracket.

![Free Body Diagram](image)

*Figure 18: Free Body Diagram of Microcontroller and Temperature Sensor Bracket*
The reaction forces on the x and y axes were found by equaling the forces to zero, as is shown below in Equations 1 and 2.

\[ \sum F_x = 0: R_{ax} = 0 \]  
\[ \sum F_y = 0: R_{ay} - 0.78 = 0 \]

\[ R_{ay} = 0.78 \text{ lbs} \]

The moments were found using the same approach, by equaling the moments to zero, as is seen in Equation 3 below.

\[ \sum M = 0: 0.78(9) - M(18) + R_{ay}(18) + R_{ax}(18) = 0 \]

\[ M = 1.17 \text{ lb } \cdot \text{ in} \]

Using the results from the reactions and moment forces, we then developed shear and bending moment diagrams that can be shown in Figures 19 and 20 below.

*Figures 19 and 20: Shear and Bending Moment Diagrams*
We then found the principal stresses to be inputted into a Von Mises failure criterion. To find the principal stresses, we decided to use a cross-sectional loading approach with the shear and bending values, shown in Figure 21.

\[ \sigma = \frac{Mc}{I} = \frac{(1.17 \text{ lb})(1.5 \text{ in})}{0.04223 \text{ in}^4} = 41.56 \text{ psi} \]  
\[ \tau = \frac{VQ}{lt} = \frac{(0.78 \text{ lbs})(0.75 \text{ in}^2)(0.375 \text{ in})}{(0.04223 \text{ in}^4)(0.064 \text{ in})} = 81.17 \text{ psi} \]

\[ \sigma_1, \sigma_2 = \frac{\sigma_1 + \sigma_2}{2} \pm \sqrt{\left(\frac{\sigma_1 + \sigma_2}{2}\right)^2 + \tau_{xy}^2} \]

\[ \sigma_1, \sigma_2 = \frac{41.56}{2} \pm \sqrt{\frac{41.56}{2} + (81.17)^2} \]

\[ \sigma_1 = 102.078 \text{ psi} \]
\[ \sigma_2 = -60.52 \text{ psi} \]

\[ \sigma_{VM} = \left(\frac{(102.078 + 60.52)^2 + (-60.52)^2 + (-102.078)^2}{2}\right)^{\frac{1}{2}} = 142.339 \text{ psi} \]

To find the yield stress, we used a safety factor of two as is shown in Equation 8 below.

\[ S_y = (142.339)(2) = 284.678 \text{ psi} < 68,168 \text{ psi} \]
Given the yield stress that we calculated for the bracket, we determined that a Zinc-plated steel alloy was indeed an appropriate material for the device, since the yield strength of the material is 68,168 psi and will not fail.

9.5. FATIGUE STRESS CALCULATIONS

For the bracket of the microcontroller and the temperature sensor, which attaches directly to the backplate, it was necessary to conduct calculations based on fatigue that the angle iron would be experiencing based on the vibrations of the wheel which will occur as the truck is travelling through roads and terrain for extended periods of time. To determine the operating life of the bracket for this specific use case, we used the modified Goodman criteria based on the material properties of Zinc-plated steel and the principal stresses which were determined in the structural calculations demonstrated previously. For this approach, we first had to determine the average stress acting on the bracket along with the amplitude of stresses acting on the bracket as they alternate based on the vibrations acting upon it as shown in Figure 22.

![Figure 22: Cyclic Loads for Goodman Criteria](image)
Our research shows us that Zinc-plated steel has an ultimate strength of 8400 psi and thus a theoretical maximum endurance limit of 4200 psi, which will be incorporated into the criteria as shown below.

\[
\frac{1}{n} = \frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}}
\]

(9)

\[
\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}
\]

(10)

\[
\sigma_{max} = 102.078 \text{ psi} \quad \sigma_{min} = -60.52 \text{ psi}
\]

\[
\sigma_a = \frac{102.078 - (-69.52)}{2} = 171.598 \text{ psi}
\]

(11)

\[
\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}
\]

\[
\sigma_a = \frac{102.078 + (-60.52)}{2} = 42.558 \text{ psi}
\]

\[
S_{ut} = 8400 \text{ psi} \quad S_e = 4200 \text{ psi}
\]

\[
n = 22
\]

Since we determined a factor of safety of 22, which is greater than 1, the bracket is expected to be able to achieve infinite life based on the Goodman criteria while sustaining cyclic loads in motion due to the vibrations of the wheel.

9.6. CENTRIFUGAL FORCES CALCULATIONS

To begin with the centrifugal force calculations, we first draw the free body diagram assuming a maximum constant velocity of 80 mph, which is the maximum speed limit allowed in
a limited number of states in the U.S. but serves as a worst-case scenario for our device. We also assume the minimum average wheel size of 19.5 inches used frequently in semi-trucks. At constant velocity, the magnet will not experience other forces in motion. However, we also included the forced caused by the average tangential velocity of 2.4 ft/s^2 for semi-trucks to determine which force would be the most prominent on the magnet throughout a truck’s travel.

![Figure 23: Free Body Diagrams of Centrifugal Force Calculations](image)

\[
F_c = \frac{(0.08375 \, lb)((338.88 \, ft/s)^2)}{(1.625 \, ft/2)} = 1419.06 \, lbf
\] (12)

\[
F = ma = (0.02 \, lb) \left( 2.4 \, \frac{ft^2}{s} \right) = 0.048 \, lbf
\] (13)

The neodymium magnets used for our project have a rated pull force of approximately 30 lbf. This would mean that if we were to attempt to rely solely on the magnet’s pull force acting on the rim and weight of the wheel, it would not be able to maintain its position and fall off if the truck were to achieve this type of motion. However, the magnets which we selected have hole designed to be fastened with a Grade #8 5/8-inch style screw, which can be used in conjunction
with a wheel weight clip in order to achieve greater support. This particular screw is rated for a
tensile strength of 150,000 psi. In order to determine whether the screw and pull force together
could allow the magnet to sustain its position, we calculated the stress acting on the bolt based on
the larger centrifugal force and the cross-sectional area of the screw, which has a diameter of 0.17
in.

\[ a = \pi \frac{(0.17)^2}{2} = 0.01445 \text{ in}^2 \]  \hspace{1cm} (14)

\[ \sigma = \frac{(1419.06 - 30)}{(0.01445)} = 96,128.71 \text{ psi} < 150,000 \text{ psi} \]  \hspace{1cm} (15)

Based on these calculations, we can assume that the screw used along with the magnet’s
natural pull force are able to maintain the magnet at a fixed position alongside the rim of the wheel
without flying away while the heavy-duty truck is in high-speed motion. Additionally, due to the
fact that the surface area of the magnet comes into contact with the surface area of the tire, the
magnet will endure in motion, as the tire has an additional reaction force against the magnet.

9.7. POWER DRAW CALCULATIONS

To begin with the power draw calculations, we first had to do an approved timeline of the
truck. This was the case because we needed to know how much time the device was going to be
working in one trip. This ultimately gave us the watt hours that the device needed, to be able to
select a battery.

Some of the assumptions that we made to create this timeline were that the drive time for
one whole trip was 12 hours, that the driver was going to make three stops of 20 minutes each, and
that each driving interval was going to be of the same length. Given these assumptions, we created
the timeline, shown in Figure 24, where one can see that it totaled 19 minutes for a whole trip. With this value, we then computed that the device would be working for 231.2 hours for the two years that the device should work for on a single battery.

![Figure 24: Truck Timeline](image)

For our power, since our sponsor requested the use of single use cell batteries, we are looking to be able to provide power for all three electrical components the device is using with 9 Volts of power, which is the highest voltage available in these types of batteries. We would like to achieve this in order to allow the battery to operate at its highest energy capacity, and therefore being able to provide its highest Watt-hour capacity. If our components require more than 9 Volts of power to run properly, we would need to pair two batteries in parallel to provide the extra voltage necessary, however, by not utilizing the full 18 Volts of power available in a pair, we are lowering the battery’s energy capacity and Watt-hour capacity, meaning we would need more batteries than we would by running single 9V batteries in series, which is the goal to achieve the desired Watt-hour for two years. The testing would have to be done in order to determine if 9 Volts of power is sufficient. Assuming that we can, the number of batteries required will be streamlined
based on how low the working current can be. For these calculations, we created an Excel sheet where values can be adjusted based on our testing and validation in terms of operating time requirements. Currently, we calculate that we would need 8 9V batteries to run optimally.

<table>
<thead>
<tr>
<th>Operating Voltage (V)</th>
<th>Working Current (A)</th>
<th>Power Draw (W)</th>
<th>Estimated Hours of Operation (2 Yrs)</th>
<th>Required Battery Capacity (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.034</td>
<td>0.306</td>
<td>231.2</td>
<td>70.7472</td>
</tr>
</tbody>
</table>

Table 2: Power Draw Calculations Table

10. ELECTRICAL COMPONENT TESTING

The initial testing phase of our prototype served to field and validate the decisions made throughout our design process after conducting an extensive literature search. The goal was to identify any areas of improvement and make any necessary modifications or corrections prior to the development of the prototype to ultimately meet our sponsor’s needs. The initial testing phase consisted of testing the Hall Effect sensor to ensure that it was detecting the presence of the magnetic field produced by the neodymium magnet; and testing the Infrared (IR) temperature sensor to guarantee accurate non-contact temperature readings.

A3144 Hall Effect Sensor

The A3144 Hall Effect sensor has three terminals: VCC, GRD, and VOUT. 5V were initially applied to the input lead—VCC, using a DC voltage supply to serve as the base voltage for the output signal; GRD was connected to the ground of the circuit; and the output terminal—VOUT, was connected to a properly calibrated voltmeter. After connecting the supply pins to their
respective voltage terminals, the neodymium magnet was then brought near the area of the Hall Effect sensor to corroborate that its presence was being detected by the activation of the LED light. After making certain that the Hall Effect sensor was detecting the magnetic field, the neodymium magnet was then safely attached to the bottom of a wheel drum to be tested by spinning the shaft as a means of mimicking the real-life scenario of a rotating wheel.

Additionally, given that the A3144 is a digital output hall sensor, this meant that the output would remain high in the absence of the magnetic field; else, it would go low and approach a value close to zero. By bringing the sensor in close proximity to the rotating wheel drum, the sensor successfully registered the passing of the magnet after each revolution, as exhibited by the sudden drop in the output voltage, along with the activation of the LED light on the sensor itself. This is displayed in Figures 25 and 26 below. In addition, it is important to note that a pull-up resistor between the input lead and the output signal is of utmost importance in keeping the output high in the absence of a magnetic field; however, due to the A3144 Hall Effect sensor already having built-in resistance in it, this was not necessary.

Figures 25 and 26: Results from Testing the A3144 Hall Effect Sensor
**ESP32 Microcontroller Internal Hall Effect Sensor**

The hall sensor built into the design of the ESP32 microcontroller is located beneath its metal cover, as shown in *Figure 27* below. Unlike the A3144 hall sensor previously discussed, which provided a pin for the output measurement, the output voltage of the ESP32 internal hall effect sensor was measured by programming with Arduino IDE.

*Figure 27: Component Pinout*
The hallRead() function of the Arduino IDE – an open-source software where we wrote, compiled, and uploaded the code shown in *Figure 28* below, to the ESP32 microcontroller – allowed us to read the registered values from the ESP32 built-in hall sensor and consequently display these on the serial monitor.

```cpp
int val = 0;

void setup() {
    Serial.begin(9600);
}

void loop() {
    // put your main code here, to run repeatedly:
    val = hallRead();
    // print the results to the serial monitor:
    //Serial.print("sensor = ");
    Serial.println(val); // to graph

delay(40);
}
```

*Figure 28: Revolution Count Code*

To begin the testing, we first soldered the header pins onto the microcontroller to ensure a good connection between the electrical components. Once soldered, we powered the ESP32 microcontroller via a USB-C cable connected to a laptop and verified that the red LED on the ESP32 itself lighted up to confirm the supplied power. Using the same wheel drum showcased in *Figures 22 and 23* above, we placed the microcontroller in such a way that its metal cover (containing the hall sensor) made direct contact with the neodymium magnet. By spinning the shaft to mimic the real-life scenario of a rotating wheel as before, we proceeded to test the built-in hall sensor this way to ensure its detection of a magnetic field every full revolution of the magnet. The results, depicted on the serial monitor from the Arduino IDE using the aforementioned code—and displayed on *Figure 29* below, successfully showcased an output voltage reflective of the strength
of the magnetic field produced by the neodymium magnet. These results further highlighted the high voltage output upon the absence of the magnetic field, but low otherwise. Of note, the ESP32 microcontroller endorses integrated pull up resistance in its design that allowed for the output voltage of its internal hall sensor to remain at a high state while no magnetic field was being detected.

![Figure 29: Results from Testing ESP32 Microcontroller’s Built-in Hall Sensor](image)

MLX90614 Temperature Sensor

To begin connecting the MLX90614 infrared (IR) temperature sensor to the microcontroller, we first had to solder it, given that the sensor came with pull-up resistor separate from the board. The temperature sensor has four terminals: \( V_{\text{IN}} \), GND, SCL, and SDA. This IR temperature sensor has \( \text{I}^2\text{C} \) functionality which allows for communication between multiple components that reside on the same circuit. This \( \text{I}^2\text{C} \) interface consists of the serial clock pin (SCL) and serial data pin (SDA), both of which were connected to pins GPIO 22 and GPIO 21 on the microcontroller, accordingly, as shown in Figure 24 above. In order to get a temperature reading, we used a code using an Adafruit MLX90614 library already included in the Arduino IDE.
software. The code we compiled and uploaded intro the ESP32 can be found in *Figure 30* below. The code collects both the ambient and the object temperature and displays it in both Fahrenheit and Celsius. We decided to go with a code that collect these both temperatures so that we could determine both the temperature around the tire and the temperature by the area of the brakes, which gives the sponsor a better monitoring of the temperature as a whole.

```c
#include <Wire.h>
#include <Adafruit_MLX90614.h>
Adafruit_MLX90614 mlx = Adafruit_MLX90614();

void setup() {  
  // put your setup code here, to run once:  

  //This portion of the code sets up infrared temperature sensor  
  Serial.begin(9600);  
  Serial.println("Arduino MLX90614 Testing");  
  mlx.begin();
}

void loop() {  
  // put your main code here, to run repeatedly:

  Serial.print("Ambient = "); Serial.print(mlx.readAmbientTempC());  
  Serial.print("C\Object = "); Serial.print(mlx.readObjectTempC()); Serial.println("C");
  Serial.print("F\Object = "); Serial.print(mlx.readObjectTempF()); Serial.println("F");
  Serial.println();
  delay(500);
```

*Figure 30: Temperature Sensor Code*

When testing the temperature sensor, we decided to test out the one of our team member’s body temperatures. So, one of us touched the temperature sensor with their finger which gave us an accurate reading, as can be seen in *Figure 31* below.
11. PROTOTYPE FABRICATION

To begin with the fabrication of our working sample prototype, we first cut the Zinc-plated slotted angle iron into eighteen inches. Of the eighteen, (1) thirteen inches would account for the diameter of the back plate where the bracket would be attached; (2) three additional inches of length would allow us to bend the lower part of the angle iron towards the wheel, where the MLX90614 IR temperature sensor would be fixed; and lastly, (3) two inches from the top would allow us to bend towards the opposite side of the wheel where an additional (4) two-inch piece of the Zinc-slotted angle iron could be screwed on in a vertical manner to hold the microcontroller and A3144 Hall Sensor in place. Please refer to Figures 32 and 33 below for a visual depiction of the way the Zinc-plated slotted angle was bent to guarantee optimal positioning of all sensors.
Figure 32 and 33: Zinc-Plated Slotted Angle Attached to Back Plate
To attach our electrical components onto the bracket while ensuring protection against environmental factors (such as rain, mud, snow, etc.), a PVC junction box was utilized – as shown in Figure 34 below. Due to its excellent insulating and flame retardant properties, PVC (Polyvinyl Chloride) was chosen as the material that would enclose the microcontroller along with the hall and temperature sensor.

![PVC Junction Box Containing ESP32 Microcontroller and A3144 Hall Effect Sensor](image)

Provided that the ESP32 microcontroller endorses four holes on its four respective corners, four holes of equal measurements were drilled on the PVC junction box (as well as on the two-inch piece of slotted angle showcased as (4) in Figure 32 above) using manual machining. To attach these components together, carbon steel screws and nylon standoffs were utilized. In the same manner, given that the A3144 Hall Sensor endorses two holes on its top two corners, we also fixed this sensor onto the same junction box, but using nylon screws instead to prevent its magnetic field detection from being tampered with. Nylon screws also help minimize vibrations acting on them while the truck and the wheel are in motion. The same process was repeated a third time.
with a second junction box responsible for enclosing the temperature sensor (which also endorses two holes in its design) at the bottom of the bracket. This was performed under the supervision of the engineering technician, Mr. Vernon Wier.

More specifically, the hall sensor was screwed on to the junction box in a horizontal manner at the top, curved phase, as this was determined to be the optimal position in which it accurately detected the neodymium magnet placed along the circumference of the rim. The microcontroller, on the other hand, was fixed onto the face of the junction box containing the two screws showcased in Figure 34 above. Therefore, both the ESP32 and the A3144 Hall Sensor were positioned in such a way that they were making a 90° angle with each other. On the second junction box, the temperature sensor was positioned and subsequently screwed on where it was directly facing the drum brakes to ensure accurate measurements.

To connect the hall sensor onto the microcontroller, the supply pins on the former were connected to their respective voltage terminals on the latter. In the same manner, the terminals of the temperature sensor were connected to their corresponding pins on the ESP32 using a rubber cable that ran from the bottom portion of the bracket all the way to the top. This rubber wire was secured with zip ties along the edge of the bracket to avoid dangerous contact with hot surfaces or any moving parts while the vehicle is in motion. Although in a real-life automotive application, the electrical components would all be soldered directly together to ensure more reliable and stronger connections, the hall and temperature sensor were both connected to the microcontroller via female terminals in an effort to maintain the ability to rearrange serial ports and have access to other ground and voltage pins, if necessary, during our testing phase, as shown in Figure 35 below.
It is important to note that at the bottom of the junction box is located a hole, through which a UCB-C cable (responsible for supplying the microcontroller and hall sensor with power) and the rubber wire (connecting the MLX90614 temperature sensor and microcontroller) would run through. To prevent this cable from moving while the vehicle is in motion, and subsequently causing potential vibrations and a decrease in electrical support of the female terminals previously discussed, E6000 adhesive glue was utilized to keep the wires in place. Due to its non-flammable and water-proof properties, E600 adhesive glue was placed along the area covering the hole on the junction box. The same process was repeated with the junction box containing the temperature sensor, and the glue was then allowed to dry for 24 hours. Please refer to Figure 36 below.
To fix the neodymium magnet onto an existing lead weight, we first removed the weight off the lead weight itself using a saw machine, leaving only the clip portion that attaches directly to the wheel rim. The neodymium magnets, which already endorsed a hole in the middle, were attached to the clip using a 3/8 size metal screw. This was achieved by drilling a hole of correct diameter on the clip portion and using manual machining to cut threads as shown in Figure 37 below.

However, upon testing the A3144 Hall Sensor (located on the PVC junction box already mounted on the back plate of the vehicle) with this magnet, no readings were being detected. Therefore, a 3/4 neodymium magnet was instead used, specifically glued to the rim using an E600 adhesive — also shown in Figure 37 below. The E600 allowed the 3/4 magnet to successfully remain attached to the rim throughout the testing period, allowing us to collect the necessary data discussed in the next section, which ultimately confirmed our initial thread wear calculations where we successfully supported the relationship of revolutions per distance to tread wear and its effects on wheel size.
12. PROTOTYPE TESTING

The testing of our prototype was done on our advisor’s vehicle. He allowed us to attach the bracket to the backplate of his driver’s side rear wheel, as well as attaching the magnet to the rim of the wheel. To begin mounting our device, we utilized the spare tire, as this was the one that we performed testing on in the laboratory. So, we had to switch the tires to begin with our testing.

12.1 DATA COLLECTION

For our testing, we had to implement a GPS module receiver into our prototype, as we would need to collect the distance covered, to be able to show the revolutions per mile, and compare them to our expected number of revolutions from our calculations. The GPS module receiver Goouuu Tech GT-U7 shown in Figure 38 was used to get this distance, to simulate the data that the DT 4000 device would collect.
For the GPS module receiver to connect to the satellites accordingly, it was placed in the truck bed, because if it had any metal obstructions, then it would not give as accurate latitude and longitude coordinates. It was also placed in a junction box, so that it would be resistant to environmental conditions. It was important to make sure that the gold plate of the antenna was pointing upwards, as this is the face that connects to the satellites. Finally, it was connected directly to the computer using a micro-USB-A cable, as can be seen in Figure 39.

Figure 38: GPS Module Receiver GT-U7

Figure 39: Schematic of GPS Module Receiver with Antenna
Figure 40 shown above gives a closer look at the MATLAB code which would be used in the data collection procedure which we described below. Using this code allowed us to stream all the data created by both the ESP32 microcontroller and the GPS module directly into MATLAB by accessing the communications ports through USB that the devices are connected to on the computer. This code then creates separate variables which would store the values for wheel revolution counts, GPGGA data from the GPS, and temperature readings which can later be post processed and incorporated into plots and readable data. It also has the capability to be able to reduce errors in wheel revolution data to get an accurate final revolution count. The variables and data can then be stored into a created .mat file which allows us to seamlessly load the data into our code used for post processing.
Data Collection Procedure

To begin with the collection of data, a detailed procedure was written and shared with our advisor. The purpose of creating a data collection procedure was to ensure some variables remained constant for the post-processing. For example, we detailed that one route would be driven to keep the distance and road conditions constant and be able to compare the wheel revolutions per mile with different tire diameters.

1. Connect the microcontroller using the USB-C cable directly to the laptop to open a serial connection (COM port number would be designated automatically to the microcontroller depending on the laptop in use).

2. Connect the GPS to the laptop using a micro-USB-A cable through a different port than the one the microcontroller is connected to (COM port number would be designated automatically to the GPS depending on the laptop in use).

3. Open the MATLAB application on the laptop, click on “Open” at the top left of the screen and select the “gps.m” file which is shown in Figure 40 to access and run it.

4. Measure the radius of the wheel from the center of the rim to the bottom of the tire while stationary on level ground. Do this using the apparatus shown in Figure 41 below to keep the ruler or measuring device as level as possible. This will be important for preliminary wheel calculations.
5. Record the ambient temperature in Celsius while stationary, using Google (or the Weather app). This will also be important to consider when calculating the thermal expansion of the tire.

6. Measure and record the initial tire pressure in psi. We will use this in relation to the initial volume of the wheel, as well as verify the pressure which we will need to simulate a smaller radius due to tread wear.

7. Run the code on MATLAB and drive to this address: Circle K, 3890 N Loop 1604 E, San Antonio, TX 78247. Make sure to bring your tire pump before leaving home.
8. Once you have reached Circle K, park beside the Marlboro cigarette poster on the side of the road. This will be the starting point of the designated data collection route (These Google Maps photos are not updated but show where the poster will be).

9. Stop the code and write the following command in the Command Window: `save data_0.mat`. Every time, you save a log of the data, you will repeat this step, but changing the number on the file name (For example: `save data_1.mat`, `save data_2.mat`, `save data_3.mat`, …).

10. This initial data will allow the GPS to calibrate its location accuracy. This is where your data collection will start.
11. Rerun the code on MATLAB and start driving to this address: Valero, 5130 N Loop 1604 E, San Antonio, TX 78247. You will do this by getting directly on TX-Loop 1604 E. The road has a speed limit of 70 mph. If there is some traffic on the road, you may drive at a speed of 35 mph. The real goal is to have an average speed that is as consistent as possible. We will perform calculations for both scenarios on this route.

Figures 44: Driving Route

12. You will arrive at the Valero gas station by taking the exit toward Judson Road. Park by the air pumps in front of the gas station. This short route covers a real distance of 1.85 miles while also accounting for changes in elevation. We measured and recorded the distance ourselves across several iterations on the road as suggested by Dr. Ocampo.
13. Once you have reached Valero, stop the code, and save the data using the command shown in Step 8 (Remember to change the number, in this example, the command would be: `save data_1.mat`).

14. Send saved files to hdiaz7@mail.stmarytx.edu, aordonez@mail.stmarytx.edu, and aozeta@mail.stmarytx.edu for data post-processing.

15. Repeat this route three times and collect data for each trial so that we can observe if there is reasonable consistency in the data sets post processing.

16. Once you have completed all three trials, you should be at the original spot next to the Marlboro cigarette poster once more. Let air out of the spare tire. Adjust tire pressure so that tire sits at a radius of 1/8 inch less than the originally measured radius. In order to reach that decrease in radius, you have to let out approximately 6.5 psi of air from the tire. We will use Boyle’s law to calculate this pressure, verify this measurement with the apparatus and adjust accordingly.

17. Perform three trials of data on the same route as before. Remember to save the data using the same command shown on Step 8. Once this data has been processed, we should notice
revolution values per mile to be relatively higher assuming all other variables manage to be consistent.

This procedure was successful, as our advisor was able to follow the aforementioned steps to provide us with the necessary data to determine that our device was successful. Once we got this data, we moved on to the post-processing step in our testing.

12.2 DATA POST-PROCESSING

For the data post-processing, we decided to use MATLAB, as well. We decided to use this because the data collection was done through this same platform. Likewise, it would allow us to easily load the files that were saved during the data collection and provide us with graphs that would be used to compare the wheel revolutions per mile.

The MATLAB code, shown in Figure 47 that we used required the use of the navigation toolbox add on to access the nmeaParser function. This function allowed us to take a string of NMEA formatted GPGGA data and convert it into readable information regarding latitude and longitude coordinates, altitude above sea level, connection to nearby satellites, etc. The important part of this tool was to be able to obtain latitude and longitude coordinates to calculate the approximate distance travelled of the vehicle during testing. We conducted this data processing for all separate .mat files which were created during our data collection procedure for each trial. The .mat files which were created during the data collection procedure also gave us unique vector arrays for the number of revolutions and the changes in brake temperature and could be used to implement into a data plot by accessing them through MATLAB directly.
Figure 47: Data Post-Processing MATLAB Code

Through this method, we were able to accurately depict the distance travelled amongst each trial of our data collection procedure. The data plots from our first trial are shown below in Figures 49 and 50. For this trial, the starting wheel radius from the center of the wheel rim to the bottom of the tire was measured to be 13.54 in. (or 34.4 cm), with our advisor using an initial tire pressure of 39.7 psi. We also made sure that the initial temperature of the wheel was approximate to the ambient temperature to ensure that no prior thermal expansion from travel was occurring before we took our measurements, as is shown in Figure 48.
Figure 48: Wheel Radius, Tire Pressure and Temperature for 1st Trial

As we can observe in Figure 49, we created a plot which depicts the distance in meters on the blue line, wheel revolutions on the blue line, and the temperature in degrees Celsius with the red line, all along the same Y-axis with respect to time of data collection per second on the X-axis. The GPS coordinates collected throughout the travel were measured to be 2901.3292 meters in distance travelled. Over this distance, the rear wheel to which our prototype was attached was able to record 1103 revolutions. We were also able to observe that the peak brake temperature over this trial was measured to be 43.59 degrees Celsius.
An important distinction which we can observe between the data for distance traveled and revolutions is that they closely mimic each other’s shapes. We can further verify this linear relationship by plotting the wheel revolutions versus the distance travelled.

Figure 49: Wheel Revolution, Distance, and Temperature Plot for 1st trial
For this initial trial, the ratio between number of revolutions and distance travelled in meters is calculated to be 0.3827, as shown in figure 50. This observation is important because the wheel must always be able to maintain this linear relationship, and it is further demonstrated as we proceeded with our post processing of our data collected for the second trial. For this second trial, our advisor decreased the tire pressure to 32.7 psi in order to simulate the effects of tread wear leading to a decrease in tire size. For this trial, the new radius was measured to be 13.46 in (or 34.2 cm), as is shown in Figure 51.
Figure 51: Wheel Radius and Tire Pressure for 2nd Trial

The data plots for the second trial are shown below in Figures 52 and 53. As we can observe, the GPS coordinates collected throughout the travel was measured to be 2898.1851 meters in distance travelled. Over this distance, the rear wheel to which our prototype was attached was able to record 1117 revolutions. This change in revolutions to complete the travel path of our testing procedure is significant for our testing and data collection procedure. The second trial is already able to provide conclusive evidence of the effects of wheel revolutions taken during travel as the size of the wheel decreased. We were also able to observe that the peak brake temperature over this trial was measured to be 52.37 degrees Celsius.
Over this trial, we continued to observe the linear relationship between revolutions and distance travel by plotting the wheel revolutions vs distance travelled once again, however noting that the ratio between the two values has increased to 0.38784.

**Figure 52: Wheel Revolution, Distance, and Temperature Plot for 2nd trial**
For the third and final trial, the tire pressure was decreased once again to a value of 25.4 psi, which created a further decrease in radius of the wheel to 13.14 in (or 33.4cm). This would be the lowest value at which we tested since testing at even lower tire pressure levels, especially below 20 psi, would have been too dangerous as it is below recommended levels by the manufacturer, as is shown in Figure 54.
The data plots for the third trial are shown below in Figures 55 and 56. As we can observe, the GPS coordinates collected throughout the travel was measured to be 2900.5539 meters in distance travelled. Over this distance, the rear wheel to which our prototype was attached was able to record 1185 revolutions. This is another significant increase in revolution count which we are observing as the tire continues to decrease in size. The third trial continues to provide conclusive evidence of the effects of wheel revolutions taken during travel as the size of the wheel decreased. We were also able to observe that the peak brake temperature over this trial was measured to be 69.39 degrees Celsius.
Once again, we can continue to depict the linear relationship between the revolutions and the distance travelled using these values, only this time, the ratio between the two values had increased substantially to 0.41259.
Figure 56: Wheel revolutions versus distance plot for 3rd trial

We also did some calculations using our collected data to determine whether our data is consistent with our expected outcome and put them on an Excel spreadsheet as shown below in Table 3.

<table>
<thead>
<tr>
<th>Trial 1</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire Pressure (psi)</td>
<td>Radius (in)</td>
<td>Circumference (in)</td>
<td>Average Speed (mph)</td>
<td>Speed (in/sec)</td>
<td>rev/sec</td>
<td>Time (s) to complete a mile</td>
</tr>
<tr>
<td>39.7</td>
<td>13.54</td>
<td>85.031</td>
<td>25.047</td>
<td>440.827</td>
<td>5.184</td>
<td>143.72979</td>
</tr>
<tr>
<td>Trial 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tire Pressure (psi)</td>
<td>Radius (in)</td>
<td>Circumference (in)</td>
<td>Average Speed (mph)</td>
<td>Speed (in/sec)</td>
<td>rev/sec</td>
<td>Time (s) to complete a mile</td>
</tr>
<tr>
<td>52.7</td>
<td>13.46</td>
<td>84.529</td>
<td>26.356</td>
<td>465.866</td>
<td>5.688</td>
<td>136.59129</td>
</tr>
<tr>
<td>Trial 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tire Pressure (psi)</td>
<td>Radius (in)</td>
<td>Circumference (in)</td>
<td>Average Speed (mph)</td>
<td>Speed (in/sec)</td>
<td>rev/sec</td>
<td>Time (s) to complete a mile</td>
</tr>
<tr>
<td>25.4</td>
<td>13.14</td>
<td>82.519</td>
<td>23.252</td>
<td>409.235</td>
<td>4.959</td>
<td>154.82539</td>
</tr>
</tbody>
</table>
Table 3: Change in Revolution Calculations Due to Simulated Tread Wear

<table>
<thead>
<tr>
<th>Distance (mi)</th>
<th>Expected Revolutions of Drive</th>
<th>Actual Revolutions of Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.802</td>
<td>1342.74</td>
<td>1103</td>
</tr>
<tr>
<td>1.801</td>
<td>1349.97</td>
<td>1117</td>
</tr>
<tr>
<td>1.802</td>
<td>1383.61</td>
<td>1185</td>
</tr>
</tbody>
</table>

Based on our results, the actual data consists of slightly lower revolutions counts overall, which is to be expected since tire size is nonlinear while on the road and is very likely to experience thermal expansion while it is in motion. This therefore would create a slightly larger working radius than what is measured during the beginning of each trial. However, since our tests were conducted on the same path under identical road and weather conditions, the similar changes in revolution count due to the prior decreases in tire pressure and size were able to be replicated in a consistent fashion with our calculations.

The calculations to model tread wear were done as follows:

\[ Tread \, Wear = Radius(in) - Initial \, Radius(in) \quad (16) \]

\[ Circumference(in) = 2\pi \times Radius(in) \quad (17) \]

\[ Revolutions \, per \, Second = \frac{Average \, Speed(\text{in/sec})}{Circumference \, of \, Wheel(in)} \quad (18) \]

\[ Revolutions \, per \, Mile = Revolutions \, per \, Second \times \frac{1}{Average \, Speed(mph)} \quad (19) \]

\[ Total \, Revolutions = Revolutions \, per \, Mile \times Total \, Distance(mi) \quad (20) \]

For our calculations, we also ensured to consider the accuracy of GPS location data while
the truck was in motion, to determine how much of the distance was calculated accurately. Our procedure is shown in Table 4 below.

<table>
<thead>
<tr>
<th>GPS Radius of Accuracy (m)</th>
<th>Time to complete a mile (s)</th>
<th>Inaccuracy in a Mile (m)</th>
<th>Inaccuracy in a Mile (mi)</th>
<th>Accuracy in a Mile (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>143.73</td>
<td>359.32</td>
<td>0.22</td>
<td>0.78</td>
</tr>
<tr>
<td>2.5</td>
<td>136.59</td>
<td>341.48</td>
<td>0.21</td>
<td>0.79</td>
</tr>
<tr>
<td>2.5</td>
<td>154.83</td>
<td>387.06</td>
<td>0.24</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Table 4: GPS Accuracy Procedure

For this calculation, we used the worst-case scenario of the GPS’ radius of accuracy, which is 2.5 meters and compared it to the calculated time driven per mile in seconds relative to the truck’s average speed as was calculated before, since we know that the GPS updates its position once per second. Doing this multiplication gives us the total amount of meters which could potentially be inaccurately measured.

Converting the number of meters which could be inaccurately measured to a value in miles and subtracting that value by one gives us the amount of a mile that is accurately measured. It is shown through this procedure that the GPS is more accurate at higher speeds. For our testing, we were able to determine that, at least 1.40 miles in travel distance were accurately measured for trial 1, at least 1.42 miles were measured accurately measured for Trial 2, and at least 1.37 miles were measured accurately for trial 3. Since the discrepancies in values for each of the three measured distances do reach these thresholds while following the same path for each trial, we can confirm that the GPS measured distance travelled with a very high degree of accuracy.
13. ECONOMICAL, PUBLIC HEALTH, SAFETY, WELFARE AND ENVIRONMENTAL ANALYSIS OF RESULTS

In analyzing public health and welfare, our proof-of-concept prototype will minimize any potential risks on the road, extend tire’s lives, and guarantee that we are always safe and prepared for the roads ahead of us by communicating with the driver at hand of any out-of-range events in the wheels of their heavy-duty vehicle. In this manner, this proof-of-concept prototype would minimize any disruptions on the delivery timeline by preventing tire blowouts (or potential accidents on the road), and instead promoting timely tire maintenance and travel efficiency. In terms of environmental factors – by being able to provide the driver at hand with the necessary information that he or she needs to prevent a tire blowout, we would also be preventing any devastating effects posed by debris to the environment, while also reducing litter on the side of the road.

14. FURTHER IMPLEMENTATION

From our working prototype, DriverTech will convert it into a device that will be mounted on all tires in long-haul trucking vehicles. The data will be transferred to the DT 4000 through Bluetooth connection, which will result in these two devices working together to calculate tread wear and act as preventive measures, such as preventing a tire blowout in the middle of the road. Some additional further implementations that DriverTech can perform, is create a sizing standard to make sure that this device can be placed in any kind of tire, on a truck of any size. Our prototype was fabricated using measurements of our advisor’s truck, therefore, to be able to fit accordingly in a long-haul trucking vehicle, then the size would need to be altered, so by creating a size standard, this device will be able to fit in different sized vehicles.
15. CONCLUSION

In conclusion, we were able to create a working prototype that measures wheel revolutions and temperature. It uses a hall effect and magnet system to detect wheel revolutions and uses an infrared temperature sensor for the temperature. The purpose of these two measurements is to be able to calculate tread wear of a tire, using the GPS data from the DT 4000. The prototype went through several design iterations, until it was finally fabricated and tested in our advisor's truck. This test showed us the significance of this project and the value that it adds to the trucking industry by being able to accurately predict the need for tire maintenance using the changes in revolution count over time. Our data collection and testing procedure confirms to us that over time, the number of revolutions which a truck’s wheel needs to partake to complete any particular distance will increase as the tire size begins to experience changes due to tread wear.
16. REFERENCES


The following appendix shows the exact same plots shown in *Figure 49* to *Figure 56* which depict distance travelled in meters, number of revolutions, and brake temperature over travel time in seconds, as well as the linear relationship between number of revolutions and distance travelled. An additional plot, however, has been created which gives a closer look at temperature over time for each trial to showcase how the temperature sensor is able to model brake behavior as the truck slowed down and stopped during each trial.

*Appendix: Wheel revolution, distance, and temperature plot for first trial*
Appendix: Wheel revolutions vs distance plot for first trial
Appendix: Wheel temperature plot over time for first trial
Appendix: Wheel revolution, distance, and temperature plot for second trial
Appendix: Wheel revolutions vs distance plot for second trial
Appendix: Brake temperature plot over time for second trial
Appendix: Wheel revolution, distance, and temperature plot for third trial
Appendix: Wheel revolutions vs distance plot for third trial
Appendix: Brake temperature plot over time for third trial

18. SMC CAPSTONE REFLECTIONS

Hiram Diaz - Reflection

My experience at St. Mary’s has been a transformative one beyond levels that I could have ever imagined, in both a personal and a professional perspective. Throughout most of my life, I was a person who was very passive, fearful, not always willing to take necessary steps outside of the comfort zone, but at St. Mary’s I have learned the importance of being able to act upon my ambitions and make quick, tough, and necessary decisions to push my work and my life forward towards the path that I envision it to be. Since my freshman year, it has been my goal to transform myself into a stronger and more well-rounded person. A person who is bold, can speak the truth, and can always understand others and be relied upon in good times and in bad times, even when
not all of the answers to a given problem are obvious or easy to handle. St. Mary’s has always promoted a vision of a community who contributes to itself and others on a fundamental level.

Foundations of Reflection: Ethics is the class that I believe has been the most useful for me as an engineering major. Dr. Andrew Brei and Dr. Juan Ocampo were able to give me a much wider perspective on the type of challenges that engineers face and must attempt to solve every beyond what is found in mathematical calculations, drawing boards, and computer programs.

The entire school of Science, Technology, Engineering, and Mathematics at St. Mary’s has my gratitude as it has taught me the importance of dedication to my work as opposed to relying solely on my natural intuition to solve all my problems. It has also allowed me to reinforce my vision for what my career goals are as an engineer in promoting and developing technologies that are ethical and sustainable.

One will always continue growing as life progresses, but St. Mary’s has allowed me to take a huge leap forward in a positive direction as I write perhaps the most important chapter of my life.

Ana Ordonez - Reflection

I am so grateful to St. Mary’s for shaping me into the person I am today. If I were to go back in time and ask myself what experiences would shape me, I would not have thought that it would have been the St. Mary’s core classes (SMCs). These courses are what made me the engineer I can call myself now. They did not just prepare me for my future professional life, but also my personal life. They changed my way of thinking about the world and the people around me. Before these classes, I was a just shy girl who just came from another country to study here in the US. I
did not know how to build a new life in a new country, but the professors and their knowledge showed the way, and because of them I find myself now, after four years, graduating with a Mechanical Engineering degree.

The class that I would say I enjoyed the most and that gave me the most accurate preparation of what life as a professional engineer looks like, was Ethics lab with Dr. Andrew Brei and Dr. Morgan Bruns. In this lab, we were given case studies about situations that we could be presented with in our jobs, and we were instructed to determine what was the right way to deal with the situation, taking the Engineering Code of Ethics into account. When discussing these cases, I was presented with different points of views and different approached that I might not have initially thought of. So, after taking this class, I can say that if I am presented with similar situations, I will be able to deal with them in the right way. Yet, the SMCs are not the only classes I can be grateful for. If it was not for the Engineering program at St. Mary’s, I would not be able to call myself an engineer now. This program granted me the necessary knowledge to become a professional and be able to make a name for myself in the industry.

Today, I can call myself an engineer who is ready to take on the world and be the best version of myself, thanks to St. Mary’s University.

Andrea Ozaeta - Reflection

I am beyond grateful for the holistic education that St. Mary’s University provided me with as an undergraduate student pursuing an Engineering Science degree—pre-medical concentration. Incorporated into my curriculum were a set of courses, known as the St. Mary’s Core classes (SMCs) that stood essential in establishing the foundation to the skills valuable to my own personal, academic, and professional success.
Overall, the SMC course I believe had the biggest impact on me throughout my educational endeavors these past four years was SMC Ethics with Dr. Andrew Brei. This class thoroughly showcased the ambiguity and complexity behind the ethical problems that may arise in engineering practice, ultimately fostering awareness to them and guidance as to how to deal with them. Ethical problems may have more than one solution to them depending on the ethical lens through which a moral agent assesses a given situation and assessing workplace ethical issues require a balance between our responsibilities not only to our profession and client, but also to ourselves and our society.