Senior Design Team 05109
RIT Formula SAE Data Acquisition System
Preliminary Design Report

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# Table of Contents

1. **RECOGNIZE AND QUANTIFY NEED**  
   1.1. **COMPANY BACKGROUND**  
   1.2. **TEAM MISSION STATEMENT**  
   1.3. **DAQ DESCRIPTION**  
   1.4. **PRODUCT DESCRIPTION**  
   1.5. **SCOPE LIMITATIONS**  
   1.6. **STAKE HOLDERS**  
   1.7. **KEY BUSINESS GOALS**  
   1.8. **REQUIREMENTS**  
   1.9. **FINANCIAL ANALYSIS**  

2. **EXISTING ELECTRICAL SYSTEM ANALYSIS**  
   2.1. **OVERVIEW OF EXISTING ELECTRICAL SYSTEM**  
   2.2. **AREAS OF CONCERN**  

3. **CONCEPT DEVELOPMENT**  
   3.1. **DAQ CONCEPT DEVELOPMENT**  
      3.1.1. **DAQ CONCEPT DEVELOPMENT PROCESS**  
      3.1.2. **CONCEPT 1: “LONG LIST”**  
      3.1.3. **CONCEPT 2: “BASELINE”**  
      3.1.4. **CONCEPT 3/4: “INTERMEDIATE/HYBRID”**  
   3.2. **ELECTRICAL SYSTEM CONCEPT DEVELOPMENT**  

4. **FEASIBILITY ASSESSMENT**  
   4.1. **SYSTEM LEVEL ASSESSMENT**  
   4.2. **SENSOR LEVEL ASSESSMENT**  

5. **PRELIMINARY DESIGN**  
   5.1. **ELECTRICAL SYSTEM**  
   5.2. **DAQ SYSTEM**  
      5.2.1. **THE HYBRID DESIGN**  
      5.2.2. **BRAKE SYSTEM**  
      5.2.3. **DRIVETRAIN**
5.2.4. VEHICLE DYNAMICS
5.2.5. SUSPENSION
5.2.6. STEERING
5.2.7. CORNER LOADS
5.2.8. ENGINE

6. REFERENCES

Terminology

- DAQ – Data Acquisition
- SAE – Society of Automotive Engineers
- RIT – Rochester Institute of Technology
- RIT FSAE – Rochester Institute of Technology Formula SAE
- CDI – Capacitive Discharge Ignition
- CDS – Competition Data Systems Inc.
- SoC – State of Charge
- ECU – Engine Control Unit
- MAP – Manifold Air Pressure
1. Recognize and Quantify Need

1.1. Company Background

The Rochester Institute of Technology Formula SAE Racing Team is a group of approximately twenty students dedicated to the design, fabrication, racing, and promotion of a high performance formula-style racing vehicle. The all-volunteer team is responsible for every aspect of the project including engineering design, financial management, and public relations. Each year, the team builds an entirely new racecar with restrictions only to the car’s frame and engine to challenge the students’ knowledge, creativity, and imagination.

1.2. Mission Statement

Design, assemble, and implement a stand alone Data Acquisition (DAQ) System for a Formula SAE racecar. Sensor outputs will be recorded and manipulated to yield meaningful data about vehicle performance. Design emphasis will be placed on system layout, sensor integration, and electrical system capability.

1.3. DAQ Description

A data acquisition system is defined as one or more electronic devices whose primary purpose is to acquire data. Typically a data acquisition system involves at least three main components. First, sensors respond to a physical stimulus and transmit signals or change electrical property such as resistance. Second, a data logger measures the electrical signal, converts it to a number and stores either that value or some statistics on that value (average, maximum, minimum, standard deviation, etc.). Third, a PC uses some communications link (serial port, phone modem, radio modem, etc.) to retrieve the data from the data logger. The resulting data is only as good as the sensors can measure and the data logger can resolve. A stand-alone data acquisition system is one which can be completely removed from the vehicle, without affecting the vehicle’s ability to run. Data acquisition systems are commonly used by racing teams. The information
1.4. Product Description

Formula SAE is an intercollegiate design competition sponsored by the Society of Automotive Engineers (SAE). SAE is an international engineering society with over 60,000 members worldwide, dedicated to the advancement of land, sea, air, and space vehicles. During the four-day event, RIT competes among a field of over 130 universities from across the globe, and is judged on the vehicle’s design, cost, and performance, as well as the team’s ability to present the engineering concepts used to develop the final design.

The challenge to the design team is to design and fabricate a prototype racecar that can be manufactured on a limited production run for under $25,000 each. In keeping with RIT FSAE’s tradition of innovation, competitiveness, and quality in design, the team feels the need for a DAQ system for design verification, dynamic tuning, and driver training assistance.

1.5. Scope Limitations

The DAQ System shall be initially designed by the end of Winter Quarter. At this time, the following deliverables shall be presented during the Preliminary Design Review:

- Needs Assessment
- Concept Development
- Feasibility Assessment
- Preliminary Design Overview
- Project Budget
- Spring Quarter Timeline

At the end of Spring Quarter the following deliverables shall be presented during the Final Design Review:
- Functioning DAQ System
- Technical Drawing Package
- Operation and Training Manual
- Final Bill of Materials
- Final Design Overview

The Design Team shall not be responsible for the following:
- Design and Fabrication of Sensors
- Design and Fabrication of Vehicle Subsystems

1.6. Stake Holders

The primary stake holders are the current and future members of the RIT Formula SAE Racing Team. Secondary stakeholders include the faculty and staff of the Rochester Institute of Technology Mechanical Engineering Department.

1.7. Key Business Goals

The success of the project shall be determined by the following:
- Fully functioning, integrated Data Acquisition system
- Demonstration of usefulness (simple optimization) of the system
- The design package shall allow the system to be transferred to new cars in the future with relative ease.

1.8. Requirements

1.8.1. Redesign DAQ System

1.8.1.1. Team shall use a CDS Commander II Data Logger.
1.8.1.2. Evaluate current system capabilities.
1.8.1.3. Determine feasible vehicle parameters to log.
1.8.1.4. Determine appropriate sensors for use.

1.8.2. Integration on Vehicle

1.8.2.1. DAQ system shall not interfere with operation of car subsystems.
1.8.2.2. Components must be completely removable without affecting the vehicle’s ability to operate.

1.8.2.3. Optimize strength vs. weight of mounting pickups and sensors.

1.8.3. Electrical System Analysis

1.8.3.1. Determine current system loads without DAQ system.

1.8.3.2. Determine added load on system, with DAQ incorporated.

1.8.3.3. Optimize electrical system to increase excess capacity for DAQ system and other potential electrical systems without negatively affecting engine performance.

1.8.4. Demonstration of DAQ Capability

1.8.4.1. Demonstrate characterization of car capabilities

1.8.4.2. Demonstrate optimization of car characteristics

1.8.4.3. Document a procedure(s) used to demonstrate system capability

1.9. Financial Analysis

A $4500 budget has been proposed by the sponsor, RIT Formula SAE, for implementation of a Data Acquisition System on the racecar. This budget includes provisions for the following:

- Sensors, Wire, Connectors
- Laptop computer
- Raw materials for mounting brackets

We have been working with current sponsors of RIT Formula SAE, in an effort to obtain product donations in the form of sensors, and electrical equipment. The following is a detailed budget, outlining all purchases associated with our preliminary design.
<table>
<thead>
<tr>
<th>Line #</th>
<th>Vendor</th>
<th>Description</th>
<th>Item Total</th>
<th>Line Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Equipment Purchases Under $1500</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supplies-Office (includes printing, copying, computer supplies)</td>
<td>$ 50.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Postage and Freight</td>
<td>$ 75.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrical wire, connectors, heat shrink tubing</td>
<td>$ 350.00</td>
<td></td>
</tr>
<tr>
<td>71551733</td>
<td>MSC</td>
<td>(24) 0.220 Diameter/0.500 Thick Magnets</td>
<td>$ 23.52</td>
<td></td>
</tr>
<tr>
<td>SEN-9</td>
<td>CDS</td>
<td>1-1000 psi Pressure Sensor</td>
<td>$ 255.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tiger Direct</td>
<td>Laptop Computer</td>
<td>$ 700.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MC5</td>
<td>CDS 4 mb Memory Card</td>
<td>$ 575.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Omega</td>
<td>Strain Gauge Set</td>
<td>$ 200.00</td>
<td></td>
</tr>
<tr>
<td>WBo2 2CO</td>
<td>Tech Edge</td>
<td>Wideband O2 Control Unit (includes wiring and connectors)</td>
<td>$ 275.00</td>
<td></td>
</tr>
<tr>
<td>SEN-12S</td>
<td>CDS</td>
<td>(4) Strain Gauge Amplifiers</td>
<td>$ 1,200.00</td>
<td>$ 3,703.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Equipment Purchases Over $1500</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>COM2-30 CDS 24 Analog, 5 RPM Commander II Logger</td>
<td>$ 4,250.00</td>
<td>$ 4,250.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>TOTAL EXPENSES</strong></td>
<td>$ 7,953.52</td>
<td></td>
</tr>
</tbody>
</table>

**Income**

|        |        | Competition Data Systems Sponsorship              | $ 2,383.00 |            |
|        |        | Discount on COM2-30                              | $ 2,180.00 |            |
|        |        | 10% off SEN-9                                    | $ 25.50    |            |
|        |        | 10% off SEN-12S                                  | $ 120.00   |            |
|        |        | 10% off MC5                                      | $ 57.50    |            |
|        |        | RIT Formula SAE Project Sponsorship              | $ 1,000.00 |            |
|        |        | **TOTAL INCOME**                                  | $ 3,383.00 |            |

|        |        | **TOTAL ACCOUNT STANDING**                        | $ 4,570.52 |            |

Table 1.9 – Project Budget
2. Existing Electrical System

2.1. Overview of Current System

The RIT Formula SAE race car is powered by a standard wet cell 12 volt battery. The race car has several key electrical components, including:

- Starter Motor
- *Autronic* SM2 Engine Control Unit
- *Autronic* Capacitive Discharge Ignition Module
- Alternator
- Cooling Fan
- Fuel Pump
- Lights
The RIT Formula SAE Racing Team uses an Autronic SM2 Engine Management System on their Honda CBR600 F2 motorcycle engines. This system is coupled with an Autronic Capacitor Discharge Ignition System, providing power to the ignition coils.

### Autronic SM2 ECU Specifications

<table>
<thead>
<tr>
<th>Microcomputer</th>
<th>Intel 16 bit running @ 16Mhz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>Normal operation Safe limits</td>
</tr>
<tr>
<td></td>
<td>6.2V to 23V DC continuous</td>
</tr>
<tr>
<td></td>
<td>+/- 24V (5 min)</td>
</tr>
<tr>
<td></td>
<td>+/- 80V alternator load dump (0.5 sec).</td>
</tr>
<tr>
<td></td>
<td>+/- 1000V inductive spike (10 usec)</td>
</tr>
<tr>
<td>Current Drain</td>
<td>@ Engine idle @ Max Engine Load</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 Amp.</td>
</tr>
<tr>
<td></td>
<td>&lt; 16 Amp (less depending on injector type and number.</td>
</tr>
</tbody>
</table>

### CDI Specifications

<table>
<thead>
<tr>
<th>Supply Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational range</td>
</tr>
<tr>
<td>Range for operation to 16000 rpm (8cyl)</td>
</tr>
<tr>
<td>Safe limits</td>
</tr>
<tr>
<td>6.2 to 20 volts</td>
</tr>
<tr>
<td>&gt; 12 volts</td>
</tr>
<tr>
<td>+/- 24 volts (5 min)</td>
</tr>
<tr>
<td>+/- 80 volts (alternator load dump 0.5 sec)</td>
</tr>
<tr>
<td>+/- 1000 volts (inductive spike 10usec)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current Drain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutdown.</td>
</tr>
<tr>
<td>Engine stopped.</td>
</tr>
<tr>
<td>@ max spark rate.</td>
</tr>
<tr>
<td>&lt; 10 uAMP</td>
</tr>
<tr>
<td>&lt; 200 mAmp</td>
</tr>
<tr>
<td>&lt; 13 AMP</td>
</tr>
</tbody>
</table>

The current setup of the electrical system has not caused problems during races. However, it has shown signs of extreme battery discharge, after long periods of operation. As more electrical components are being added on to the race car, an underpowered battery may cause some, if not all electrical parts of the race car fail to operate. An analysis of the current electrical system shall be performed in order to track down possible problems and free up room for more power for future electrical parts.
2.2. Areas of Concern

Studies of the current system specifications have shown that several components may be inducing a large current draw on the battery and charging system. These components include the following:

- Cooling Fan
- Fuel Pump
- Capacitive Discharge Ignition (CDI)
- Starter Motor

Both the starter motor and cooling fan operate on non-continuous cycles, while the CDI and fuel pump run continuously. The cooling fan is programmed to turn on once the engine reaches a set operating temperature, and stays on until the temperature is lowered below this set value. This means that the fan is operating during the most vulnerable time for the electrical system, a high heat condition where the vehicle is most likely running at its limit. While it draws a significant amount of current, the starter motor is of minor concern since it draws this during a very short time interval on startup.
3. Concept Development

3.1.DAQ Concept Development

3.1.1. DAQ Concept Development Process
From the initial needs assessment and sponsor requirements, the team determined that it must design a system which utilizes a Competition Data Systems Commander II Data Logger. Due to this fact, a focus was placed on other aspects of the system, keeping the sponsor needs in mind. Concept development of the DAQ system and sensors was completed concurrently. Vehicular data needs were broken down into five categories including general, brakes, chassis/suspension, drivetrain, and engine. From this, a list was derived for each category of which types of data should be collected to best characterize the vehicle subsystem. Brainstorming sessions were held, with the focus on providing three possible system designs.

3.1.2. Concept 1 – “Long List”
Concept 1 is a compilation of every vehicle parameter which could be attained using instrumentation. Broken down by vehicle subsystem, this allowed for a starting point to develop more reasonable concepts.

3.1.2.1. General DAQ
- 20 Minute Logging
  - *Large Data Card*
- Real-time Telemetry Transfer
  - *Incorporate wireless boards*
  - *CDS telemetry transfer system*
- Onboard Video System
  - *Remote mounted camera*
  - *CDS data overlay system*
  - *Lipstick Cameras*

3.1.2.2. Brake Parameters
• Brake Bias
  • (2) Line pressure sensors
• Rotor Temperature
  • High Temp Infrared Pyrometer
• Pad Temperature
  • Embedded thermocouple with amplifier
• Fluid Temperature @ Pad
  • Thermocouple
• Caliper Stress/Deflection
  • Strain Gauge to determine dynamic deflection
• Brake Torque
  • Redesign Upright which will allow strain gauge to be calibrated to brake torque
• Brake Pedal Travel
  • Linear Potentiometer
  • Rotational Potentiometer
• Brake Pedal Input Force
  • Strain Gauge on Pedal
  • Calculate based on pedal geometry
3.1.2.3. Chassis/Suspension Parameters
• Lateral/Longitudinal/Vertical Acceleration
  • 3 axis accelerometer
• Yaw Rate
  • Gyroscope
• Pitch Angle/Rate
  • Use CDS Software calculations
  • Laser Ride Height Sensors
  • Trailing wheels
  • Gyroscope
• Roll Angle/Rate
  • Use CDS Software calculations
  • Laser Ride Height Sensors
  • Trailing wheels
  • Gyroscope
- **Steering Wheel Angle**
  - *String Pot mounted on Steering Rack*
  - *String Pot with Pulley on Steering Shaft*
- **Front Wheel Angles**
  - *Calculation based on Ackerman Geometry and steering angle*
- **Damper Travel (Position)**
  - *Linear Potentiometer*
- **Corner Weights**
  - *Load Cells in Suspension System*
  - *Strain Gauges on Push/Pull rods with math using Motion Ratios*
  - *Strain Gauges on Push/Pull rods with Calibration to Corner Loads*
- **A-Arm Loads**
  - *Application of Strain Gauge*
- **Steering Input Torque**
  - *Strain Gauge on steering shaft*
- **Ride Height**
  - *Laser Ride Height Sensors*
  - *Calculated in Software*
- **Tire Temperatures**
  - *Infrared Pyrometers*
- **Tire Pressures (Dynamic)**
  - *Wireless Pressure Sensors*
- **Shock Fluid Temperature**
  - *Thermocouple*
- **Shock Reservoir Pressure**
  - *Pressure Sensor*

### 3.1.2.4. Drivetrain Parameters

- **Front Wheel Speed**
  - *Hall Effect Sensor*
- **Rear Wheel Speeds**
  - *Hall Effect Sensor*
- **Differential Case Speed**
  - *Hall Effect Sensor*
- **Driveshaft Torque**
- **Remote Torque Sensors**
  - Gear Lubricant Temperature
    - Thermocouple
  - CV Temperature
    - Thermocouple
  - Engine Output Torque
    - Remote Torque Sensor
  - Differential Case Temperature
    - Infrared Pyrometer

3.1.2.5. **Engine Parameters**

- Engine RPM
  - Hall Effect Sensor on Crank Pickup
- Throttle Position
  - TPS Sensor
- Manifold Air Pressure
  - MAP Sensor
- Oil Temperature
- Oil Pressure
- Water Temp in/out of Radiator
- Water flow through Radiator
- Airflow Through Radiator
- Air Temp into Radiator
- A/F Ratio
  - Wideband O2 Sensor
3.1.3. **Concept 2 – “Baseline System”**

With Concept 1 outlined, the team focused on the opposite extreme, which was to compile a list of essential vehicle parameters that would be needed to achieve the goals outlined by the sponsor. This was set as the baseline concept, and included only necessary data.

3.1.3.1. **General DAQ**
- 20 Minute Logging
  - *Large Data Card*

3.1.3.2. **Brake Parameters**
- Brake Bias
  - *(2) Line Pressure Sensors*

3.1.3.3. **Chassis/Suspension Parameters**
- Lateral/Longitudinal/Vertical Acceleration
  - *3 Axis Accelerometer*
- Yaw Rate
  - *Gyroscope*
- Roll Angle/Rate
  - *Use CDS Software calculations*
  - *Laser Ride Height Sensors*
  - *Trailing wheels*
  - *Gyroscope*
- Steering Wheel Angle
  - *StringPot mounted on Steering Rack*
  - *StringPot with Pulley on Steering Shaft*
- Front Wheel Angles
  - *Calculation based on Ackerman Geometry and steering angle*
- Damper Travel (Position)
  - *Linear Potentiometer*
- Corner Weights
  - *Strain Gages on Push/Pull rods with math using Motion Ratios*
  - *Strain Gages on Push/Pull rods with Calibration to Corner Loads*

3.1.3.4. **Drivetrain Parameters**
- Front Wheel Speed
3.1.3.5. Engine Parameters

- Engine RPM
- Throttle Position
- Air/Fuel Ratio
- Manifold Air Pressure


With two concepts in hand, the team was able to begin merging Concepts 1 and 2 into a more feasible design. It became clear from the start that some vehicle parameters would not be feasible to attain with our current resources, both financial and technical. During this brainstorming process, several ideas began to emerge for ways to measure and derive certain vehicle parameters. Due to limited resources, a focus was placed on making the most efficient of the data collection requirements.

Compromises were made with respect to certain vehicle parameters, and the team derived an intermediate concept, which included all of the parameters included in the baseline system, with some extras as well. With Concept 3 (intermediate) created, the team began to assess the simultaneous logging requirements presented, and compared this to the channel limitations of the current Commander II setup. This assessment provided the team with the conclusion that the current data logger did not offer the capabilities handle the requirements of the intermediate concept, and thus would need to be upgraded. With budgetary concerns rising, the team re-assessed the simultaneous logging requirements and determined that a fourth concept would be feasible. Concept 4 (hybrid) was developed under the premise that the data acquisition system would be designed to be configured into several
setups, depending on testing goals. This includes a baseline competition setup, which would require all necessary simultaneous data to be collected for several runs in differing course layouts. In addition, provisions will be made for specific testing setups, including an engine testing package, and brake system testing package. These setups will be useful for collecting data which is only required for design verification purposes, or for testing prototype setups. For instance the engine testing package does not require the need for suspension parameters such as corner loads, so these channels can be freed up for use by other engine parameters during a test session. These additional setups are made possible because channels assignments can be reconfigured within the DAQ software, and setups can be saved for quick loading.

The following list includes simultaneous logging requirements, as well as testing packages.

3.1.4.1. General DAQ
- 20 Minute Logging
  - Large Data Card
- Onboard Video System
  - Remote mounted camera
  - CDS data overlay system
  - Lipstick Cameras

3.1.4.2. Brake Parameters
- Brake Bias
  - (2) Line Pressure Sensors
- Rotor Temperature
  - High Temp Pyrometer
- Pad Temperature
  - Embedded Thermocouple

3.1.4.3. Chassis/Suspension Parameters
- Lateral/Longitudinal/Vertical Acceleration
  - 3 Axis Accelerometer
- Yaw Rate
- Gyroscope
  - Pitch Angle/Rate
    - Use CDS Software calculations
    - Derivative of Laser Ride Height Sensors
    - Trailing wheels
    - Gyroscope
  - Roll Angle/Rate
    - Use CDS Software calculations
    - Derivative of Laser Ride Height Sensors
    - Trailing wheels
    - Gyroscope
- Steering Wheel Angle
  - StringPot mounted on Steering Rack
  - StringPot with Pulley on Steering Shaft
- Front Wheel Angles
  - Calculation based on Ackerman Geometry and steering angle
- Damper Travel (Position)
  - Linear Potentiometer
- Corner Weights
  - Strain Gauges on Push/Pull rods with math using Motion Ratios
  - Strain Gauges on Push/Pull rods with Calibration to Corner Loads
- Ride Height
  - Laser Ride Height Sensors
  - Calculated in Trackmaster
- Tire Temperatures
  - Infrared Pyrometers
    - 1/2 Corners

3.1.4.4. Drivetrain Parameters
- Front Wheel Speed
  - Hall Effect Sensor
- Rear Wheel Speeds
  - Hall Effect Sensor
- Differential Case Speed
  - Hall Effect Sensor
o Driveshaft Torque
  • Remote Torque Sensors

o Engine Output Torque
  • Remote Torque Sensor

3.1.4.5. Engine Parameters

3.1.4.5.1. Permanent
  • Engine RPM
  • Throttle Position
  • Manifold Air Pressure
  • Gearing
  • A/F Ratio

3.1.4.5.2. Summer Testing Package
  • Oil Temperature
  • Oil Pressure
  • Water Temp in/out of Radiator
  • Water flow through Radiator
  • Air Temp into Radiator
  • Exhaust Port Temperatures
  • Collector Temperature

The hybrid concept began to emerge as the most appropriate design, factoring in our financial and technological resources. This provided the team with a starting point for finalizing the chosen concept, and moving into a feasibility assessment of this design.
3.2. Electrical System Concept Development

The scope of this project requires us to assess the current electrical system, determine how adding the data acquisition system will affect this system, and make suggestions for future improvements. The first steps that were undertaken were to obtain as much information about the current system as possible. This included specifications for the engine control unit, wiring used, engine sensors, and battery. From this, we were able to assess which components might be causing large current draw on the system. From here, we developed a testing procedure, using the engine dynamometer, to obtain measurements of electrical loads on the system.

**Measurement Method:**
To measure the load of high output components, a simple voltmeter cannot be used. This is due to the fact that standard voltmeters are not rated to handle current beyond 10 amps. Thus, we proposed placing a high power resistor in series with the component and measuring the voltage across it. Using Ohm’s law, we may obtain the current draw through each component. After measuring the current draw on each component, we can derive a more accurate representation of the system model.

From initial measurements, the fuel pump draws 10 amps of current. The cooling fan uses a maximum of 6.6 amps, while the CDI unit draws 2.9 amps when the engine is running at max RPM. These three components account for the primary power consumption of the vehicle. Unfortunately, there is little room to decrease power drain from these electrical parts. Thus, our design focus will be primarily on the battery and the charging system of the race car.
4. Feasibility Assessment

The first step in the feasibility assessment was the development of questions relating to the concepts. Because there were three distinct aspects of our design, three sets of questions were formed for the DAQ system level, sensor level, and electrical system level covering the areas of technical, economic, scheduling, and performance feasibility. With the questions determined, we were able to rate the concepts on a 1-5 scores with 3 being the baseline score with an approximate 50/50 probability of completion, 1 being a concept area with a low probability of completion, and 5 being a concept area with a high probability of completion.

4.1. System Level Assessment

For the system level assessment the questions were derived to choose which Commander II Box setup will be used. The first box setup is running the current setup on the car. The second setup is trading in the current box for one with more capabilities, and the third setup is adding on a second box to augment the existing capabilities. The questions used in the assessment are as follows:

Technology Questions
1. Does the team have the skills needed to implement this technology?
2. Does the team have the necessary resources to implement this technology?
3. Is this technology readily available to the team?
4. Does this technology stand alone from the rest of the car functions?

Economic Questions
1. Does the budget allow this box to be purchased?
2. Does the box allow for future expansion?

Performance Questions
1. Does the box add significant weight?
2. Are there enough channels to be fully functional?

Schedule
1. Can this box be integrated in time for verification/optimization?
This assessment led us to choose box setup 2 (upgraded box). This setup seemed to be the most feasible in terms of our schedule, technological, and financial resources. The main advantages of it over setup 3 (two boxes) start with the fact that it is one central unit instead of two. Implementing two data loggers would cause several problems. The data that is captured would have to be exported, and manipulated to synchronize all of the signals with respect to the same time intervals. With this done, the data can no longer be viewed and manipulated in the DAQ software, but would require several post-processing.
steps before useful data could be analyzed. From an economic standpoint, we determined it would actually be more expensive to purchase a second unit, than it would be to trade in the current system toward the purchase of an upgraded system. From a performance aspect a second box would not only add weight, but would increase the complexity of the system wiring integration into an already small area of packaging. After settling on the single upgraded unit design, we determined that the most feasible option was to pursue the hybrid design. This would allow us to save some money, by only upgrading to a 30 channel unit, instead of a 38 channel unit. Due to the limited budget, we decided that it would be best to invest the $1000 saved into other aspects of the design.

4.2. Sensor Level Assessment

At the sensor level, anything currently owned by the sponsor was not evaluated. The sponsor has informed us they work fine and have no desire to replace them.

The remaining desired vehicle parameters left to be evaluated included those which were not already present in the system owned by the sponsor. These were assessed on two areas of concern. The first area was an evaluation of whether each parameter was valuable enough to the sponsor to procure at this time, or at a later date when more funding is available. The second area was to determine which method of monitoring the parameter was to be used for the chosen system design. The questions posed in this aspect of the assessment are as follows:

Technology Questions
1. Does the team have the skills needed to implement this technology?
2. Does the team have the necessary resources to implement this technology?
3. Is this technology readily available to the team?
4. Will this technology be compatible with the Commander II unit?

Economic Questions
1. Does the budget allow this sensor to be purchased?

Performance Questions
1. Does this sensor add significant weight to the vehicle?
2. Does the sensor provide accurate data for analysis?

Schedule Questions

1. Can this sensor be integrated in time for verification/optimization?

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<th>Sensor Type</th>
<th>TQ 1</th>
<th>TQ 2</th>
<th>TQ 3</th>
<th>TQ 4</th>
<th>EQ 1</th>
<th>PQ 1</th>
<th>PQ 2</th>
<th>SQ 1</th>
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Table 4.2 – Sensor Feasibility Results

When analyzing the onboard video system concepts, the CDS Data Overlay system stands out above all of the rest. This is due to the useful overlay of in car data onto the video signal allowing for ease in driver training. Without the overlay signal the video data, although useful, is no longer connected to the dynamic data which has been recorded. Unfortunately, this proprietary system available from CDS has a retail cost of $1350, making this economically infeasible within our project budget.
The pitch/roll angle and rate has an unclear winner. Laser sensors are perhaps the most accurate method for determining instantaneous ride height; however their main disadvantage lies in the cost. The next best alternative is by using gyroscopes, oriented laterally and longitudinally at the vehicle’s center of gravity. These will provide accurate data, and are slightly less expensive than laser ride height sensors. However, cost considerations eliminate this possibility as well. The software analysis provided by CDS has integrated math channels, which calculate pitch and roll rate based upon suspension travel, and known geometry constants. This however is not the most accurate way of measuring these parameters. One final concept which we came up with was to build small trailing wheels attached to potentiometers. These would then be attached to the chassis at four points of the vehicle, and would move up and down, depending on chassis attitude. The trailing wheels are very feasible to build and implement, but are also not as accurate as other methods. In addition, they would be very fragile, and can be damaged quite easily with any contact to an uneven road surface.

Steering angle and rate will be measured using a string potentiometer. There are typically two ways to implement this device on a racecar. One method take measurements of the steering rack travel, and the other is to take measurements on the steering column. In our case, we have determined that the most appropriate
method is to take measurements on the steering column. This is due to packaging constraints within the current chassis, as well as considerations for driver interference.

The assessment of how to measure dynamic corner loads came down to calibration accuracy. Our initial concept development provided us with two methods of calibrating the strain gauges, which will be placed on the pull rods of the vehicle. Calibrating the strain gauges to the actual measured strain on the pull rods is by far the most accurate method. Using data obtained from suspension kinematics software, a math channel can be created which relates the pull rod force to actual normal load on each tire. This is much more accurate than trying to directly calibrate the strain to normal wheel load, which can only be measured in static settings.

Remote torque sensors are virtually the only method which can be used to determine torque on the drive shafts. However, these sensors are extremely expensive, costing as much as $19,000 for a set of two. It is for this reason that we will not be able to implement these in our design.

The system and sensor level feasibility assessment provided us with several useful clues, to move forward with evaluation of the preliminary system design.
5. Preliminary Design

5.1. Electrical System

Improvement Considerations
At this time we are still evaluating the current loads on the existing electrical system. Some components such as the starter motor, rectifier, and cooling fan draw large amounts of current, which cannot be measured with conventional meters. Due to the limited resources available from the sponsor and the RIT Electrical Engineering Department a new method was derived for taking such measurements. We have ordered a one ohm 200-watt industrial resistor. The idea is to place the resistor in series across the load, and measure the voltage drop. The actual current value can then be derived from Ohm’s Law. Using Joule’s Law, we determined the largest value of current which could be obtained from the 200W resistor is 14 amps. From our preliminary assessment we believe that 14 amps is a sufficient value for measurement of high output components such as the cooling fan and the rectifier.

Specifications provided by the fan manufacturer show that the fan draws 8 amps on average during normal steady-state operation. The sponsors have indicated to us that the starter motor draws slightly more than 50 amps when cranking the vehicle. Even though this value is quite high, it is drawn on a very small time interval only at startup of the car.

The second phase of our analysis involves measuring the rate at which the battery discharges and the charging rate with the current alternator and rectifier. The method of finding the battery discharge rate is described in the following section. The rate at which the alternator and the rectifier are supplying the battery can be

\[
\text{Ohm’s Law } \quad V = IR
\]

Where: 
\( V \) is voltage measured in volts
\( I \) is current measured in amperes
\( R \) is resistance measured in ohms

\[
\text{Joule’s Law } \quad P = I^2R
\]

Where: 
\( P \) is power measured in watts
\( I \) is current measured in amperes
\( R \) is resistance measured in ohms
calculated from specifications of the rectifier and alternator. In all current measurements, we have assumed that everything is in the worst case scenario, meaning the engine is revving at high RPM and that it is drawing maximum electrical loads in order to withstand the endurance race. If the alternator and rectifier charging rates are less than the battery’s discharge rate, a few approaches can be taken to remedy the situation. The first area to investigate is in battery design. Several types of batteries are available, including NICAD, Lithium-Ion, and Gel Cell. Each type has positive and negative features for use in this application. Considerations which must be kept in mind are the high-heat environment in which these batteries are placed, as well as discharge rate within the electrical system. We are currently in the process of evaluating these features, and analyzing which type is most feasible for a racecar application.

In terms of the charging system, the sponsor has indicated to us that the rectifier has been running very hot during normal operations. It is essential that this component operate within its designed temperature range. The rectifier used by RIT Formula SAE is an SH693-12 from a Honda CBR600F3 motorcycle. This unit has molded fins, which act as a heat sink providing some cooling. These rectifiers work well for stock applications like that of the CBR600 motorcycle. However with the racecar application, added demands push the rectifier to its operational limits. The reason for using the current rectifier is due to its compatibility with the charging system in the engine. In an effort to balance weight distribution of the vehicle, and keep the center of gravity as low as possible, the battery has been placed inside the engine compartment, directly behind the firewall. This placement locates the battery critically close to the exhaust headers, in an area of high heat. We have hypothesized that excessive heating from the exhaust may cause rapid discharge, thus greatly compromising performance. We have suggested two solutions to this problem. One is to insulate the battery from the heat and/or place the battery far away from the...
exhaust. However, this may not be feasible due to packaging constraints within the chassis structure.

A second solution would be to replace the battery with a different cell type, or increased power. By definition, power is the rate of energy transferred. With more power, there can be more energy transfer to different electrical parts of the race car. This is readily obtained through the use of a larger battery. However, a larger battery results in increased size and weight, which is an undesirable feature for a race car application.

On a simple level batteries are purely energy storage devices, and thus need to be constantly recharged. An adequate charging system must be in place to ensure proper charging rate through the battery. The Honda CBR600F2 engine charging system is an industry standard system, which works on the principles described below.

The CBR600 uses separate a stator and rectifier to make up the charging system. The stator, internal to the engine, converts the power from the gasoline engine into three-phase alternating current. This 3-phase AC output is then converted
into DC by the external rectifier. This is then used to power system components, and recharge the battery. Please refer to Figure 2 for a circuit diagram of a 3-phase rectifier unit. A three-phase rectifier is used to account for the AC output from the stator.

The amount of current generated by the charging system of the racecar is directly related to the RPM of the engine. As long as the charging rate is higher than the battery discharge rate, the system will continue to operate with no performance degradation. To quantify the battery discharge rate, we can check the battery’s state of charge (SoC) after the surface charge is removed. If the battery’s SoC is consistently above 95%, then the charging system is fully recharging the car battery. Measurement of SoC consists of the use of a hydrometer.

Measurement of SoC:
A hydrometer (as shown in figure 3) is an inexpensive float-type device used to measure the concentration of sulfuric acid (Specific Gravity) of battery electrolyte ("battery acid"). From this reading you can easily and accurately determine a non-sealed battery's State-of-Charge. A hydrometer is a glass barrel or plastic container with a rubber nozzle or hose on one end and a soft rubber bulb on the other. Inside the barrel or container, there is a float and calibrated graduations used for the Specific Gravity measurement.

![Image of hydrometer](source: popular mechanics)
1. Remove the surface charge
2. Start with the cell closest to the positive terminal. Squeeze the rubber bulb and insert it into the electrolyte. Then release the bulb. Electrolyte will be sucked up into the barrel allowing the float to ride freely.
3. Squeeze the rubber bulb to release the electrolyte back to the cell.
4. Repeat the process several times to get a more accurate reading.
5. At eye level and with the float steady, read the Specific Gravity at the point the surface of the electrolyte crosses the float markings.
6. In the case where the hydrometer is not temperature compensating. Then compensate the reading using the Table 1. Otherwise, take the reading from Table 2.
7. Repeat the process for each cell and average them to get SoC.
8. Rinse the hydrometer thoroughly after finish.

<table>
<thead>
<tr>
<th>Electrolyte Temperature</th>
<th>Electrolyte Temperature</th>
<th>Add to Hydrometer's SG Reading</th>
<th>Add to Digital Voltmeter's Reading</th>
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<tr>
<td>Degrees Fahrenheit</td>
<td>Degrees Celsius</td>
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<td>110°</td>
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<td>100°</td>
<td>37.8°</td>
<td>+.008</td>
<td>-.008</td>
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<td>90°</td>
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Table 1: State of Charge, temperature compensation
Digital Voltmeter
Open Circuit Voltage at Rest

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<tr>
<th>Approximate State-of-Charge at 80°F (26.7°C)</th>
<th>Approximate Deep-of-Discharge at 80°F (26.7°C)</th>
<th>Hydrometer Average Cell Specific Gravity</th>
<th>Approximate Electrolyte Freeze Point</th>
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<tr>
<td>12.65 100%</td>
<td>0%</td>
<td>1.265</td>
<td>-77°F (-67°C)</td>
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<td>12.45 75%</td>
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<td>12.24 50%</td>
<td>50%</td>
<td>1.190</td>
<td>-10°F (-23°C)</td>
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<tr>
<td>12.06 25%</td>
<td>75%</td>
<td>1.155</td>
<td>15°F (-9°C)</td>
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<tr>
<td>11.89 or less DISCHARGED</td>
<td>100%</td>
<td>1.120 or less</td>
<td>20°F (-7°C)</td>
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Table 2: Low maintenance battery state of charge

5.2. DAQ System

Our feasibility study provided us with several useful clues which pushed us toward the chosen design, a hybrid concept based upon efficient use of hardware resources. Once the list of vehicle parameters was finalized, the team met with the sponsor to determine which data needed to be obtained simultaneously. This was a critical factor in determining whether or not the team could use the existing 20 channel logger, or if we needed to upgrade to a unit with more capability. Initial indications were that the system would require a 38 channel logger. However, after reviewing the simultaneous data collection requirements, the team determined that it would be acceptable to use a 30 channel unit. This was made possible with the creation of the hybrid design, which allowed for two data acquisition packages: an overall competition setup, and a secondary testing setup.
5.2.1. The Hybrid Design

Overall Competition Setup

The overall competition setup incorporates all simultaneous logging needs into a single configuration. This configuration uses 5 RPM and 24 analog channels.

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<tr>
<td>4</td>
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<tr>
<td>5</td>
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</table>
The CDS Commander II

The Commander II Data Acquisition System is a stand-alone unit manufactured by Competition Data Systems Inc. This is an attractive system for RIT Formula SAE due to its low cost, flexible configuration, and high accuracy. The system is powered by 12 volts from the main power of the vehicle. Interfaced sensors are operated by 5V and 12V excitation, supplied from the Commander II. Data is then fed back into the Commander II on a 0-5V DC scale. A removable Type II or III PCMCIA memory card is used to transfer data from the command module to a PC, where it can then be analyzed using the Track Master 2000 software.

The team chose to design the data acquisition system around a COM2-30 unit, which is a 5 RPM, 24 Analog Channel system. This was chosen on the basis of simultaneous data collection requirements, and its compatibility with the current system owned by RIT Formula SAE. We have worked closely with Competition Data Systems, who have provided us with a generous trade-in value of the old Commander II, towards the purchase of a new COM2-30. One requirement placed on the team by the sponsor was that the system be as lightweight as possible, and be robust. This unit affords the team both of these options. The Commander II is housed inside of an extruded aluminum
case, weighing just 1lb. This case has four rigid mounting points, with which anti-vibration mounts can be attached. One negative feature of this system is that the unit is not waterproof. This fact was taken into consideration when deciding on placement of the unit in the racecar. The team decided it would not be ideal to locate the unit on any area of the vehicle that was subject to damage during a collision. In addition, any location that is subject to rain or snow would not be acceptable. This left two possible locations for mounting the control unit: inside the cockpit, or under the front nose bodywork. Cockpit space is highly optimized by the designers at RIT Formula SAE, and thus no suitable location could be found here. A decision was made to mount the unit in a piggy-back configuration on top the ECU, underneath the nose of the vehicle. This is an ideal location, as it protects the unit from weather, and also provides safety in the event of a crash. The unit will be housed fully within the chassis tubular structure. This location also provides for efficient routing of all necessary wiring. Wires can be routed along with the main wiring harness, which feeds the ECU and dash. One consideration that was taken into account when choosing this location was the access to the memory card download port. Ideally, the team would like to be able to have quick access to the port, without removing body panels. However, after an evaluation of the driving patterns of RIT Formula SAE, it was determined that placement under the nose would be acceptable. Since most testing is performed without bodywork in place, the team would have quick and easy access to the port. The only times in which the body would need to be removed for data download would be in a competition setting, where this could take place in the pit area after each individual run.

**Track Master 2000**

**Features:**

Track Master 2000 is the bundled software package which accompanies the Commander II. This software is available for Windows 95, 98, 2000, and XP, and offers several user configurations. This allows the user to analyze data in
any way they choose, using X-Y plots, signal vs. signal plots, map plots, suspension animation displays, histograms, bar graphs, numeric displays, and driver controls graphics. This provides for quick analysis, without having to sort through raw data. However, for detailed analysis, data can be exported via a .cds file, which can then be opened in other analysis programs such as Microsoft Excel and Matlab. The software has the ability to generate track maps through the yaw rate gyro or accelerometer, and plot driver control displays of the steering wheel movement, braking force, and acceleration force. This is extremely useful for driver training and feedback, as the driver can review his laps, and reference points in which he slowed prematurely, or was on or off the throttle.

One other desirable option that is available in Track Master 2000 is the ability to create user math channels, and edit preset math channels. This allows for quick analysis to be performed entirely within Track Master 2000, without the need to export data to Excel or Matlab. This is extremely useful for testing
sessions where a variety of changes are being made to the vehicle to verify a setup, or tune for a specific event.

**How Data is Recorded in Track Master 2000**

Track Master 2000 uses the coupled software program Command Link to create sensor calibration and car files, which the Commander II then uses when recording. Command Link is the main communication interface between the Commander II, and the PC. This program is used to create a .car file, which included all necessary vehicle parameters and channel assignments. This is the interface in which suspension geometry, gearing, tire rollout, and other vehicle constants are entered. Sampling rates and resolution are set within the channel configuration window, for each analog and digital RPM channel.

This program is also used to provide sensor calibration to the Commander II. Once a .car file is created for the vehicle and the sensors have been calibrated properly, the file can be loaded onto the removable PCMCIA Memory card. Communication is also provided through a serial port connection from the PC to Commander II. This allows the upload of .car file data, download of data,
or the ability to view live readings from the sensors. Data collection can be triggered by a user presets, or by a manual on/off switch. For example, if we wish to warm up the car before a run, then begin recording once a set speed is reached, this can be programmed into the .car file. Conversely, we can manually select when to begin recording via the on/off switch located on the dash.

**General Design Considerations**

The overall design goal is to provide a competent, lightweight, robust, accurate, and financially feasible data acquisition system for the RIT Formula SAE racecar.

Electronic data acquisition equipment, in general, is significantly expensive and fragile. Significant care is required to outfit such equipment to the harsh environment of a racecar. The system must operate properly and reliably in all conceivable environments. Competition weather ranges from extremely hot (air temperature 40 deg C and track temperature 100 deg C) as seen in Australia to cold (air temperature 5 deg C) as can be seen in Detroit. The team competes in wind, rain, hail, and high dust conditions. On the Formula SAE vehicle, vibration is major consideration. With the engine/transmission solidly mounted to the chassis and spherical bearings at all suspension points, a wide range of vibration passes through the sprung and unsprung masses of the vehicle. Electrical noise, especially from the charging and ignition systems, is a further concern. It would be optimal to protect each sensor from contact with stones, other track debris, or pylon contact. In Formula SAE, the race tracks are marked by pylons, and RIT generally contacts a number of them throughout practice and competition. Occasionally, cones become wedged into the suspension system presenting a serious threat of damage, especially to delicate sensors. Collisions with other racecars or track barriers present yet another threat of mechanical damage.
The team and the data acquisition system are responsible for upholding the RIT Formula SAE tradition of excellence. RIT prides itself in producing a high quality product from initial mechanical design through machining and fabrication to final fit and finish. The data acquisition system and all components will be used on the racecar during competition, so the integration, packaging decisions, and design quality must be world class. Minimizing weight is a paramount concern. Preferably, the system will utilize existing fasteners for mounting and minimize the number of additional parts.

To meet these challenges, general design guidelines were followed throughout the system. All components must be water/weather-proof or mounted in a guaranteed dry location. Rubber vibration isolation mounts must be used where appropriate. All fasteners and mounting hardware must be secured from unintentional loosening by a positive locking mechanism – nylon lock nut, prevailing torque lock nut, cotter pin, safety wire, or Loctite threadlocker. Each piece of equipment will be mounted with brackets of reasonable stiffness/strength. Sensors and boxes should be located with consideration of protection from mechanical damage and elegance of packaging. Electrical noise will be countered with shielded data cabling and appropriate hardware.

Sensor sampling rates are of significant importance due to limited on-board memory capacity. We are still evaluating the individual sampling rates required by each sensor.

**Sensor Connections and Cabling**

Two areas for improvement of the existing system are cable length, cable construction, and cable connections. CDS systems are built standard with Switchcraft EN3 Weathertight Series Connectors. These are both 5 pin and 8 pin, male and female waterproof connectors, which are used at the sensor to main cable connection points. These connectors are military standard 202 rated for shock, vibration, moisture resistance, and insulation resistance.
characteristics. One downside is their high cost, at around $7 each for the 8-pin option. This quickly adds up when designing a system which operates 20+ sensors. However, after evaluating possible replacements, a decision was made to stay with the Switchcraft connectors. This will ensure that all connectors on the system will remain the same, as per the previous design. Commander II system wiring is provided by jacketed, shielded 22 awg signal cable. It is imperative that each wire is shielded to reduce noise and disturbance in the system. The cable insulation is also rated to withstand temperatures as high as 200 degC. This is a much needed feature for RIT Formula SAE, where temperatures can rise to above 100C inside the engine compartment. All wiring for the data acquisition system will be built in house at RIT, in conjunction with the mounting of sensors and main vehicle wiring. This will ensure that each cable is built to the exact length need to reach its associated sensor. This will cut back on un-needed lengths of cables, and reduce the overall weight of the system.

5.2.2. Brake System

Sponsor Needs:
In an effort to design a highly efficient braking system, the RIT Formula SAE Team has found the need to monitor several parameters of the braking system. After assessing the feasibility of needed parameters, a decision was made to monitor and collect data for the following:
- Front Brake Line Pressure
- Rear Brake Line Pressure
- Front and Rear Pad Temperature
- Front and Rear Rotor Surface Temperature

Dynamic brake pressure measurements are extremely useful for setting and tuning the braking force distribution between the front and rear. This “bias” must be tuned for each driver to ensure proper handling under braking conditions. In the past this tuning was done on the basis of driver feedback
after a practice session. However, without being able to quantify the actual bias distribution, no optimal settings were attained. In addition to setting the bias distribution, the team must be able to quantify the actual pressures present in the system lines. From this, the team can quantify the input forces present on the brake pedal, and clamping forces at the pad/rotor interface.

Working in conjunction with chassis sensors, this brake sensor package will enable the team to understand the pad/rotor temperature relationship to pad coefficient of friction and thus braking force. This will allow quantitative evaluation of different pad materials as well as controlled durability testing. The team will also know the actual braking loads experienced in service, which can then be used to optimize component design.

Pad coefficient of friction can be calculated by the following method:

\[
\text{Pad coefficient of friction} = \frac{\Delta W_x}{\text{area}}
\]

Where:

- \(\Delta W_x\) is the change in rear axle normal load (lb)
- \(h\) is the height of the center of gravity (in)
- \(l\) is the vehicle wheelbase (in)
- \(a\) is the distance from front wheel centerline to cg (in)

(Milliken, 685)
b is the distance from rear wheel centerline to cg (in)
W is the mass of the racecar (lb)
Ax is longitudinal acceleration (g)

$\Delta W_x$ will be provided at each time step by the corner load sensors. The rest of the inputs (h, l, a, b, W) are known from measurement. The following calculation will yield the braking deceleration, $A_x$:

$$A_x = \frac{\Delta W_x}{\frac{h}{l} * W}$$

Knowing the normal load on each axle and the deceleration, we can calculate the longitudinal braking force on each axle, since this force must be distributed according to the normal load on the axles. Thus, we have the longitudinal force on each tire. An implied assumption here is a constant tire to surface coefficient of friction for each tire. Multiplying by the loaded radius of the tire yields braking torque, which can easily be converted into a tangential caliper force using the rotor effective radius. Caliper clamping force is known via line pressure and thus, using Coulomb friction, we can obtain the pad-rotor coefficient of friction. The pad-rotor coefficient will be calculated at each time step and plotted vs. rotor or pad temperature.

Heat is a major problem faced when designing a brake system. It is for this reason that the RIT Formula SAE Team must be able to have a working knowledge of the operating temperatures of certain system components. Brake pad and rotor temperatures can be monitored to determine the temperature range achieved under certain loading conditions. Correlating these temperatures to deceleration rates provides a great indication of peak operating values. In addition, heat dissipation with respect to time can be quantified.
Data Acquisition Solution:

Front and rear brake pressures can be obtained quite easily using a pressure transducer. However, careful considerations must be made to ensure that the internal components of the sensor are compatible with highly corrosive brake fluid. In addition, the sensor must be capable of handling pressures in excess of 1000 psi. The formula team currently owns one SEN-9G pressure sensor, which is a 0-1500 psi wet fluid sensor supplied by Competition Data Systems. This is an instrumentation grade sensor that is brake fluid and fuel compliant. In addition, it is readily available for under $300. After researching possible alternatives, we found that it would not be feasible to purchase any competitive sensors. Our two main concerns centered on accuracy relative to the current CDS sensor, and the high cost of a replacement. By using the CDS sensor, and purchasing another that is exactly the same, we assumed that both will be manufactured by the same company, and thus have similar response characteristics. In addition, the 0.5% accuracy is well within the bounds of the team’s requirements. The RIT Formula SAE racecar uses two AP Racing Master Cylinders to provide braking force to both the front and rear wheels. Brake fluid is transferred through 0.1875” outside diameter 5052 aluminum tubing, running along the chassis structure of the vehicle. The two sensors will be teed off this hard line on the floor of the foot box, where they will be rigidly mounted to the tubular structure. Wiring will run parallel to the brake over-travel switch wire, and will be fastened to the upper frame member with high tensile strength nylon cable ties. The sensor arrives from the manufacturer with 2-point calibration values and has a 0 to 5 volt linear output.

Extensive research was done to determine an accurate way to quantify dynamic rotor temperatures. It became very clear early on in our research that the only way to ensure a reasonable measurement was through the use of an
infrared device. In the past RIT Formula SAE has experimented with
temperature sensitive paints, placed on the rotor surface in an area outside of
the pad interface. This did provide a general estimate of the peak temperature
range seen by the rotors, but was very inaccurate. In addition, the peak
temperature value could not be correlated to point in time, nor compared to a
known deceleration rate. In an effort to obtain this correlation, we have
proposed using narrow angle infrared temperature sensors. These sensors can
be purchased in a variety of configurations, which can handle various
temperature ranges. One disadvantage however is the high cost associated
with these sensors. These sensors output a millivolt signal, and thus require
an amplifier, which increases the cost.

Brake pad temperature is a primary concern for verification of assumptions
made in the heat transfer calculations performed by the brake group. After
brainstorming, we have concluded that the best solution for obtaining these
measurements would be embedded thermocouples on the pad backing plate,
and output their signal to an amplifier which can then feed the Commander II.
However, this can be a complex system to construct, as several wires will
need to run into the calipers, which is a high heat environment. In addition,
the thermocouples will need to be permanently affixed using a high
temperature resin or adhesive. While this has manufacturing complexity, the
overhead costs associated with this design are quite low.

5.2.3. Drivetrain

Sponsor Needs:
Primary data collection requirements for the drivetrain of the RIT Formula
SAE racecar include output torque on both left and right drive shafts. This is
due to the operation of the Zexel Gleason Torsen Type II differential. The
Type II is a limited slip differential that is torque, not speed, sensitive.
Monitoring drive shaft torques will yield the torque-bias ratio (TBR) of the
differential. The TBR can then be tuned through mechanical means inside the
differential to produce the smoothest power delivery and maximum traction on corner entry and exit. Also, knowledge of differential reaction time would be helpful in understanding and optimizing the transient operation of the differential, both under acceleration on corner exit and under trail braking on corner entry. In order to obtain this data, one torque sensor would need to be placed on each drive shaft. The racecar would then be driven through the series of corners the team is likely to experience at competition, and its performance accordingly tuned. It would even be possible to tune differential characteristics for each separate competition event. Another benefit of the torque sensor is the knowledge of actual dynamic driveshaft loading for design purposes. Under conditions of zero wheel slip, the sum of the left and right side torques yields engine output torque.

The torque sensors required for our application are available commercially but are extremely expensive (approximately $20,000) due to their size and complexity of design. Thus, after evaluating the priorities of the RIT Formula SAE Racing Team, and factoring in the high cost, we determined that it was not feasible at this time to directly measure the torque on each drive shaft. However, even without knowing the torque on the shafts, some useful data can be obtained by monitoring drivetrain rotational speeds. By placing speed sensors on the left and right rear wheels and the differential housing itself, we can quantify the differences in rotational speed between these three assemblies. This is useful when evaluating where in the corner the differential is locked and where it is freely differentiating. One area of concern for the Formula SAE Team is determining where the differential locks up on corner entry, both under a coasting scenario and a braking scenario.

These rotational speed sensors are also useful for quantifying the amount of rear wheel spin. This can be done by placing another rotational speed sensor on a single front wheel and plotting the relationship between front and rear wheel speeds. Of particular concern is the time delay at the start of an
acceleration run, when the rear tires have lost traction and are spinning freely. In order to produce the fastest run, rear wheel spin must be minimized. Preferably, the tire is held at its maximum traction capability – the peak of the longitudinal slip curve. By knowing the relationship between front and rear wheel speeds versus time, the team can better analyze acceleration run launching techniques and work to minimize wheel spin. This data can then be used to tune the traction control system, which will cut spark from the engine as a function of percent wheel spin. The traction control system will utilize signals from these same rotational speed sensors.

**Data Acquisition Solution:**
The team has limited options for rotational speed sensors, as the CDS logging box will only accept a 0 to 5 volt digital signal. This pointed us toward some type of Hall Effect speed sensor. A Hall Effect sensor detects changes in the magnetic flux produced when a ferrous target passes over the sensor. A Hall Effect sensor has several advantages over other types of speed sensing devices, namely high accuracy at low speeds and integrated signal processing electronics. Hall Effect sensors are readily available at relatively low cost. Due to packaging constraints, we needed to find a sensor that would be small enough to fit within the confines of the wheel and suspension, and still provide a high accuracy reading. Keeping weight, size, and price in mind, we settled on a Bosch HA-P speed sensor for collection of wheel speed data. This sensor was chosen for its small size and robust design. These sensors are specifically designed for harsh environments, and have been used by RIT Formula SAE for engine crank and cam position on their race engines. There is no need to calibrate this type of sensor, however, a strobe light will be used to confirm sensor output. The sensor is very easy to mount with bolt-on connection, via a reinforced high strength plastic housing. In addition, electrical connections are completely waterproof, which is of paramount concern for wet weather driving. Sensor excitation will be provided by MAG-
MATE™ round rare earth magnet material. This nickel-plated corrosion-resistant permanent magnet is available at MSC Industrial Supply for $0.98 each.

*Front Wheel Speed Sensor*

![Diagram of Front Outboard Suspension Assembly](image)

*Front Outboard Suspension Assembly*

(data acquisition components highlighted in green)
The front toning wheel will be CNC machined from AZ31B magnesium plate. The MAG-MATE™ magnets are located by radial holes and permanently retained by an aircraft-quality structural bonding agent, Hysol. This type of assembly offers minimum weight and optimal sensor performance. It is critical that the magnets be evenly spaced around the toning wheel, as even a 1 degree error will cause inconsistency in the data. The toning wheel-magnet assembly will be mounted to the inboard wheel bearing jam nut via tapped holes and 6-32 alloy steel cap screws. An additional requirement imposed by the team was that any rotating masses be symmetric such that it is rotationally balanced.

Magnets were chosen for targets as opposed to the traditional plain steel. Since the Hall Effect sensor works based on the change in magnetic field caused by the targets, the stronger magnetic field offered by a magnet allows the sensor to be run at a larger gap than does a steel target. The gap between the Hall Effect sensor face and the target is critical for ensuring reliability of the readings. The recommended air gap for steel targets is .040 to .060 inches. Wheels with magnet targets can run a gap as large as 0.180 inches. The larger
gap allows more margin to compensate for fabrication tolerance, toning wheel runout, and vibration-induced sensor movements. This is important, as the Formula SAE Team has experienced sensor failure in the past due to contact between the toning wheel and sensor. In the above assembly, the design gap is .075 inches. Also, the magnets ensure reliability of the data, which is absolutely essential to the system.

The Bosch Hall Effect sensor will be located by robust 4130 steel bracket as shown. The steel bracket, although heavier than an aluminum or magnesium counterpart, will conduct less heat from the brake caliper and also offers more stiffness.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m*K)</th>
<th>Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4130 Steel</td>
<td>42.7</td>
<td>205</td>
</tr>
<tr>
<td>6061-T6 Aluminum</td>
<td>167</td>
<td>69.8</td>
</tr>
<tr>
<td>AZ31B Magnesium</td>
<td>96</td>
<td>45</td>
</tr>
</tbody>
</table>

(matweb)

The bracket shall be welded from two separate pieces to facilitate fabrication. It is located and constrained by existing brake caliper mounting bolts. This design keeps the data acquisition components within the rim, providing some margin of protection and maintains serviceability of the wheel bearing jam nuts. The data cable will be run with the brake line along the lower forward a-arm tube.

Six targets were chosen for the toning wheel based on several considerations. First, the team referenced CDS documentation for target recommendations. It was devoid of engineering guidelines, recommending anywhere from one to three targets as sufficient for all measurements. Clearly, the greater the number of targets, the better the data resolution, which becomes especially important at low speeds. More targets also affords the ability to quickly detect wheel spin. Wheel spin can be determined by a difference between front and rear wheel speeds. The danger of numerous targets is, at high wheel RPM, the
target’s tangential velocity and/or frequency can exceed the sensor’s capabilities causing missed targets and erroneous data. The Formula SAE Team was able to provide valuable assistance in determining the required resolution for this application. Based on previous testing, the team determined that 4 targets on a 3.940 inch diameter wheel provided adequate data resolution throughout the range of racecar speeds.

Since Bosch Hall Effect sensor technical specifications were denied to the team, the specifications for an equivalent Honeywell sensor was used to evaluate the six target toning wheel. Honeywell recommends a 25 target, 4 inch diameter, steel toning wheel for general shaft speed measurements. The sensor is capable of reliable measurements up to 3600 RPMs of this wheel. Quick hand calculations using $v_{\text{tangential}} = \omega r$, yield the maximum target tangential velocity of 754 in/sec and maximum target frequency of 1500 Hz. With the existing transmission and final drive gear ratios, the maximum possible speed of the racecar, rounded up, is 100 MPH. Given the tire’s loaded radius (10.000 inches) and toning wheel diameter (4.306 inches), hand calculations show a 100 MPH vehicle speed corresponds to 1681 RPM of the toning wheel, target tangential velocity of 379 in/sec, and target frequency of 168 Hz. Clearly, a six target toning wheel of this size will run well within the capabilities of the competing Bosch sensor. Thus, the final decision lied in the compromise between required resolution and toning wheel mass/complexity. Based on the above considerations and Formula SAE advice, the team judged six targets to be a reasonable design for this application.
Rear Wheel Speed Sensor

Rear Outboard Suspension Assembly
(data acquisition components highlighted in green)
The first thought was to use an identical or at least similar front and rear toning wheel design. However, sensor mounting considerations and the geometry of the rear outboard suspension, a-arms, and constant velocity (CV) joint forced the team to devise a more compact packaging solution. The rear toning wheel is of similar construction to the front – a machined magnesium with bonded magnets for targets. It is located by slip fit over a machined diameter on the outside of the CV. The rear toning wheel assembly will be permanently attached via setscrews, which will seat into a mating drilled hole in the CV housing and be retained from unintentional loosening with Loctite threadlocker. The team was concerned that steel set screws, although smaller than the magnets, could excite the sensor as false targets and corrupt the data. After considering alternative mountings, it was determined that setscrew was the best method. Aluminum setscrews will be strong, durable, and should
eliminate the possibility of data problems. Screws of the proper size in 7075 aluminum are available from fastener-express.com at $0.10 each.

As in the front, 6 targets will be used. Here, due to the smaller toning wheel diameter, target tangential velocity is 213 in/sec and target frequency is 168 Hz at 100 MPH vehicle speed. The sensor to target gap is 0.053 inches by design. The goal was to retain the same generous 0.075 inch gap as the front toning wheel. However, this was not possible due to packaging limitations on the size of the toning wheel and concerns for fabrication simplicity of the sensor bracket. The sensor bracket is machined from 0.125 inch thick 6061-T6 aluminum plate. Aluminum was chosen due to its density, stiffness, machineability, and availability. The team judged that steel was not required for adequate stiffness due to the small size of the bracket. A single 10-32 button head cap screw with nylon lock nut will retain the bracket to the suspension camber shoe. To facilitate mounting of the bracket in the proper rotational orientation, a 0.125 inch reamed hole will be machined through the bracket tangent to the face of the camber shoe. With the assistance of a dowel pin, the bracket can be easily assembled in the proper orientation. This ensures that the Hall Effect sensor will be located in the center of the toning wheel, the best location for reliable measurements.

**Differential Case Speed**

The differential case speed will be measured via another Bosch Hall Effect Sensor. This time, however, fabrication of a toning wheel is not required. The 6 magnet targets will be bonded onto the face of the aluminum roller chain sprocket, which is bolted to the differential case. This design eliminates additional parts, complexity, and weight. The final design of the sensor bracket and sprocket are yet to be determined, pending Formula SAE vehicle construction.
The choice of sampling rate on these Hall Effect sensors will be governed by the vehicle speed of interest and the required data resolution. A simple spreadsheet tool was created to assist the Formula SAE team in choosing an appropriate sampling rate. The spreadsheet calculates the maximum allowable sampling rate for a given vehicle speed.

### HALL EFFECT SENSOR CALCULATOR

**INPUTS**

<table>
<thead>
<tr>
<th></th>
<th>Vehicle Speed of Interest</th>
<th>100 MPH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FRONT WHEEL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tire Loaded Radius</td>
<td>10.000 in</td>
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<tr>
<td>Toning Wheel Diameter</td>
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<td>Number of Targets</td>
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<tr>
<td><strong>REAR WHEEL</strong></td>
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<td></td>
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<tr>
<td>Tire Loaded Radius</td>
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<td><strong>DIFFERENTIAL CASE</strong></td>
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<tr>
<td>Toning Wheel Diameter</td>
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</tr>
<tr>
<td>Number of Targets</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

**OUTPUTS**

<p>| | | |</p>
<table>
<thead>
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<th></th>
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<tbody>
<tr>
<td><strong>FRONT WHEEL</strong></td>
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<tr>
<td>$V_{\text{tangential}}$ of target</td>
<td>379 in/sec</td>
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<tr>
<td>within sensor range?</td>
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<tr>
<td>Frequency of target</td>
<td>168 Hz</td>
<td></td>
</tr>
<tr>
<td>within sensor range?</td>
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<td></td>
</tr>
<tr>
<td>Maximum Sampling Rate</td>
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<td><strong>REAR WHEEL</strong></td>
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<tr>
<td>$V_{\text{tangential}}$ of target</td>
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<td>Frequency of target</td>
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<td>within sensor range?</td>
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<td></td>
</tr>
<tr>
<td>Maximum Sampling Rate</td>
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<td></td>
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<tr>
<td><strong>DIFFERENTIAL CASE</strong></td>
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<tr>
<td>Maximum Sampling Rate</td>
<td>168 Hz</td>
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5.2.4. Vehicle Dynamics

Sponsor Needs:
The RIT Formula SAE Team requires knowledge of the inertial properties of the racecar under all dynamic conditions. These inertial properties include roll, yaw, and pitch rates as well as X, Y, and Z accelerations. This data is essential to developing a quantitative understanding of the vehicle’s dynamic character. The roll, yaw, and pitch rate signals can be integrated to determine associated angles, which is extremely useful feedback to the chassis/suspension tuner and designer. Yaw rate and lateral acceleration values are used to determine track maps and evaluate vehicle understeer/oversteer balance. These sensors allow the measurement of a number of traditional vehicle performance metrics – understeer gradient, g-g diagrams, and skidpad performance. The inertial sensors also provide data for frequency response analysis, which is an essential tire testing and evaluation procedure. Vertical accelerations of the sprung mass are useful for ride analysis. Perhaps most important application is the quantitative evaluation of chassis setup changes and thus suspension tuning using design of experiments mentality. The result should be a stable, well-mannered racecar that takes full advantage of available tire grip.

Data Acquisition Solution:
To conduct these inertial measurements, the team was limited by financial constraints to one CDS single axis gyroscope and one CDS three axis accelerometer. The single axis gyroscope can be mounted in different orientations to measure roll, yaw, or pitch rates independently.

The gyroscope, CDS SEN-37, is a single axis solid-state rotational rate sensor. This sensor was chosen for its compact size, durable waterproof design, and high accuracy. Sensitivity is rated at 0.0222 volts/deg per second, with an accuracy of +/- 1%. The sensor is powered by 5 volts DC, from the Commander II, and outputs voltage values of 0.5 to 4.5 VDC, corresponding
to +/- 80 degrees per second. Vibration damping is provided by integrated rubber isolation stud mounts, which are rigidly attached to the racecar chassis. Sensor calibration is provided by Competition Data Systems. We do not have the resources available at RIT to perform this calibration, and thus, we must rely on values obtained from the manufacturer. For this particular application, the team estimates that a sampling rate of 200 Hz will be adequately accurate, although this is subject to test results. It is also recommended that the yaw rate sensor and accelerometer be operated at the same sampling rates to facilitate correlation between the data.

A Competition Data Systems SEN-28 three-axis accelerometer will be used to measure lateral, longitudinal, and vertical accelerations of the racecar. This accelerometer was chosen for its small size, durability, and the fact that it is currently owned by RIT Formula SAE. Internal components are housed within a lightweight, robust anodized aluminum case. The SEN-28 is a 3-axis, silicon strain gauge type accelerometer, with a 0-5 volt output range. Silicon strain gauge sensors are manufactured in a variety of configurations, with each exhibiting differing sensitivity characteristics. Due to manufacturer confidentiality, we were unable to obtain further information with regards to this particular sensor. However, for the purposes of this project, we have assumed that the sensor is a Wheatstone-bridge configuration exhibiting suitable performance characteristics. These are perhaps the most common production grade silicon strain gauge accelerometers. According to the specifications provided by CDS, this sensor is accurate to +/- 1%, with a 0.5% repeatability.
Sensor calibration is conducted at Competition Data Systems, eliminating the need for additional calibration prior to installation. The CDS calibration is easily confirmed by placing each face of the accelerometer on a true level surface.

The most important consideration in mounting the gyroscope and accelerometer is location in the racecar. Both must be mounted as close as possible to the vehicle’s center of gravity. The accelerometer takes measurements along three perpendicular axes, which are normal to the square faces of the outside housing. Thus, the sensor must be mounted perfectly perpendicular to the ground plane and carefully oriented rotationally. A 5 degree difference between the X-axis of the accelerometer and the car center plane is considerable. This will cause a true 1G longitudinal acceleration to register a 0.09G Y-axis measurement. Mounting locations fore or aft of the cg will cause accelerometer measurements to be biased toward the motion on that end of the racecar. Vertical locations above or below the center of gravity will involve roll and pitch accelerations in addition to the desired longitudinal and lateral values. Lateral placement error will induce analogous Z-axis errors.

The attachment method for the accelerometer is also critical. Rigid attachment to the chassis will cause the sensor to pollute good data with meaningless engine and chassis vibration. Conversely, a flexible rubber mount will cause error due to sensor float. It is generally accepted that Velcro is a reasonable compromise, and this method is recommended by CDS. On the Formula SAE car, the accelerometer will be mounted with industrial Velcro. Two cap screws with nylon lock nuts (just barely tight) will provide rotational orientation.

The gyroscope data can suffer from mounting error as well. Since this sensor only measures rotational rate about a single axis, any misalignment between
the desired measurement axis of the racecar and the sensor axis will induce error. In a dynamic situation, the sensor axis will be affected by sprung mass pitch and roll angles. The team is currently investigating a calculated correction for this type of error. It is general practice to mount a gyroscope on rubber isolation mounts to assist in damping engine and chassis vibrations.

The Formula SAE Team was able to provide a measured location of the racecar center of gravity:

Center of Gravity Location – RIT Formula SAE Racecar

Coordinates:

\[
\begin{align*}
X &= 33.120 \text{ in} \\
Y &= 0.000 \text{ in} \\
Z &= 12.083 \text{ in}
\end{align*}
\]
Unfortunately, mounting both sensors at the vehicle center of gravity was not practical. As can be seen in the picture above, the cg is very close to the engine and exhaust headers. Due to the necessity of a firewall between the engine and driver bays, this section of the racecar receives no cooling airflow. Temperature concerns forced the team to locate sensors elsewhere. The team judged that the best alternative was to maintain the longitudinal and lateral position of the cg and raise the sensors vertically until packaging became feasible. The resulting location is shown below:
Solid Model Assembly of Vehicle Dynamics Sensors (Shown in Green)

Significant care will be taken in the fabrication of the mounting plate to ensure that both sensors are level and oriented appropriately when the racecar is static on a level surface. If necessary, shims can be placed under the baseplate mountings.

Accelerometer error caused by sprung mass motions can be partially corrected through calculation. Correction to the lateral acceleration measurement due to chassis roll:

\[
ActualLateralG = \frac{MeasuredLateralG - \sin(RollAngle)}{\cos(RollAngle)}
\]
For a 1.5G true lateral acceleration and the accelerometer initially level:

<table>
<thead>
<tr>
<th>Chassis Roll Angle (deg)</th>
<th>Error (G's)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.017</td>
</tr>
<tr>
<td>2.0</td>
<td>0.034</td>
</tr>
<tr>
<td>3.0</td>
<td>0.050</td>
</tr>
<tr>
<td>4.0</td>
<td>0.066</td>
</tr>
<tr>
<td>5.0</td>
<td>0.081</td>
</tr>
</tbody>
</table>

This correction does not account for the roll acceleration that would be captured in the measurement due to the vertical height of the sensor above the cg. Differentiation of the roll rate data would provide the necessary value to subtract from the lateral acceleration prior to angle correction. Identical corrections should be made to longitudinal acceleration measurements to account for chassis pitch angle and pitch acceleration. In addition, the vertical acceleration measurement should be compensated for roll and pitch angle induced errors.

The actual values of pitch and roll angles and accelerations for the Formula SAE car are not known at this time. This data can be measured with either a laser ride height system (not financially feasible) or 3-axis gyroscope. Unfortunately, the team is currently limited to one single-axis gyroscope by
financial constraints. Thus, proper corrections to acceleration measurements are not possible. The team plans to evaluate this question further when the system is on the racecar by measuring roll and pitch rates independently and quantifying the magnitude of the total error.

5.2.5. Suspension

Sponsor Needs:
RIT Formula SAE would like to pursue a damper development program with the goals of determining optimal motion ratio and damping curves. The most critical phase of this program is measuring damper performance under dynamic conditions. On the Formula SAE racecar, the dampers are mounted inboard to minimize unsprung mass. Damper actuation is achieved by a pullrod attached to the upper a-arm and a bellcrank (rocker arm).
Data Acquisition Solution:
Four SEN20-2 linear potentiometers, supplied by Competition Data Systems, will be used to determine damper position at each corner of the racecar. The sensors measure displacement with a 5-volt infinite resolution, film type linear potentiometer. They have been chosen based on their accuracy and convenience – RIT Formula SAE already owns them. The SEN20 features an anodized aluminum body with stainless steel shaft. One disadvantage to these types of sensors is the fact that they are extremely fragile, and can be mechanically damaged quite easily. The sensors are instantly destroyed if over-stroking occurs in compression or rebound, as they are not robust enough to bear load. Spherical rod ends are supplied on both ends of the sensor with the intent to avoid binding within a limited range and the associated damaging bending load in the sensor shaft. Another major concern with sensor integration onto the racecar is utilizing the maximum amount of sensor electrical travel for the required measurements. A large range of sensor electrical output ensures the signal will not be confused with electrical noise. This will guarantees the best accuracy and reliability of the data. The design stroke was determined to be 75% of the maximum travel of the sensor to provide a margin of safety. Calibration is 2-point linear – one point at full compression (0 stroke) and one point at full extension (measure stroke with vernier calipers).
Each linear potentiometer will record a stroke measurement. The Track Master software can be configured to relate the linear potentiometer stroke to vertical wheel travel. Damper position is then determined as a function of wheel position. The resulting damper math channel can be differentiated to determine shaft velocity and acceleration. Knowledge of the pullrod load and coil-over spring rate essentially transform each corner of the racecar into a damper dynamometer. The intermediate step, the vertical wheel travel, can be used to determine approximate pitch and roll angles of the sprung mass.

Mitchell suspension analysis software was used to create a rigid body, spherical joint kinematic model of the front and rear Formula SAE independent suspension systems. The model can then be exercised in a number of ways while monitoring selected suspension parameters.
The kinematic model determines the stroke of the linear potentiometer over the operating range of the suspension, given the potentiometer mounting points. Calculation of this stroke is no trivial matter due to the complexity of the 3-dimensional suspension geometry and the changes which occur with vertical wheel travel (ride height). Several iterations of linear potentiometer geometry were required to achieve the desired stroke. It is critical that a constant linear relationship exist between linear potentiometer stroke and ride height due to the restrictions of Track Master software. To relate the linear potentiometer stroke to ride height, Track Master uses a hard-coded math channel that will only accept a constant value. The same is true for the relationship between damper travel and ride height. These relationships are expressed as the ratios of $\frac{\text{ShaftStroke}}{\text{RideHeight}}$, which is called the “motion ratio.”
The appropriate motion ratio values are given by the slope of the plots generated from the kinematic model output:
Integration of the linear potentiometers onto the racecar required much careful thought. Optimizing sensor travel, meeting the stroke goals above, and protection from track debris, and general packaging were paramount concerns. Sensor mounting brackets need to be accurate, appropriately robust, and preferably attached using existing fasteners. Significant effort was made working with the Pro/Engineer solid model to achieve these aims.

Both the front and rear bellcrank end mounting brackets use the existing shock end bolt as the sole fastener. Rotational orientation is achieved by utilizing existing features of the bellcrank geometry. The tub mount (chassis end) of the front and rear sensors are mounted to machined magnesium brackets that mount utilizing existent racecar fasteners.
General Location of Linear Potentiometers
Front Suspension Detail
(brackets and sensor highlighted in green)

Rear Suspension Detail
(brackets and sensor highlighted in green)
5.2.6. Steering

Sponsor Needs:
The RIT Formula SAE Team requested data on driver steering inputs. This can be correlated to the inside and outside tire steer angles. The steering wheel angle can be a revealing parameter for driver training purposes as well as vehicle dynamic analysis such as understeer/oversteer balance and skidpad performance. This year’s racecar will allow for adjustable Ackermann steering geometry. The data collected will be invaluable for tuning purposes.

Data Acquisition Solution:
The team chose to use an existing Formula SAE sensor, since it was low cost and available. The SEN38 is spring-loaded string potentiometer, used for displacement measurements. This particular sensor uses a .035” stainless steel cable, with a displacement range of 0-9 inches. All components are sealed within a 1.25” OD rigid plastic housing. A reasonable approximation of steering wheel angle can be obtained by calibrating the sensor through the following method. By securely fastening a digital level/protractor to the flat portion at the bottom of the steering wheel and turning the wheel left and right to its limits, we can calibrate steering wheel angle. However, a more useful metric for characterizing vehicle behavior is to determine the actual road wheel (tire) steer angle. Calibration is done through the use of rotating setup (“Weaver”) plates. One plate is set under each front tire and zeroed. Then, the steering wheel is set at a series of angles (measured by the digital level/protractor) and both front wheel angles are recorded. This yields a relationship between the steering wheel angle and the inside and outside road wheel angles. This will then be incorporated into a math channel.

Integration of the sensor into the racecar presented some packaging challenges. This type of sensor is usually used to measure linear displacement of the steering rack. However, this was not feasible due to the steering component layout and interference with the bodywork. Driver ergonomic
considerations were also important. The mounting arrangement below uses a cam to wrap the sensor cable as the steering wheel turns. This setup was easy to tune, via the cam diameter, to utilize 75% of the sensor’s mechanical and electrical travel. Both the cam and clamping brackets will be machined from 6061-T6 aluminum.

Steering Angle Sensor Shown in Green

Steering Angle Sensor - Detail
5.2.7. **Corner Loads**

**Sponsor Needs:**
The Formula SAE Team expressed the desire to monitor the vertical loads on each tire during dynamic racecar maneuvers. This will allow the direct measurement of load transfer, which can be used to tune understeer/oversteer balance, quantify the effect of spring rate and anti-roll bar rate changes, and evaluate transient vehicle behavior. Dynamic corner weights will also assist in tire and brake pad coefficient of friction measurements while providing a wealth of information for future racecar structural design.

The most practical method to measure the vertical load on each tire is to relate this load to a chassis/suspension force that is easy to measure. On the Formula SAE car, the most logical related load is the force in the suspension pullrod.

![Front Suspension Pullrods (shown by red arrows)](image)
The pullrod is a tension link that connects the upper a-arm to the inboard coil-over damper at each corner. Due to the spherical rod end bearings on each end and the nature of the installation, each pullrod is always loaded in pure tension under racing conditions. The only exception to this would be an airborne situation where a wheel is completely unloaded and traveled into full rebound. Under these conditions, the pullrod would be loaded in compression due to supporting the unsprung mass.

Data Acquisition Solution:
The team immediately recognized that load cells would be a convenient and effective method of measuring the force in each pullrod. However, load cells appropriate for the anticipated force range proved to be outside the project budget. The team then turned to a more cost-effective solution – the strain gage.

Strain Gage Basics
The strain gage is the most common method of measuring strain, with the bonded metallic strain gage being the most often preferred. The metallic strain gage contains a fine wire or metallic foil that makes up a grid pattern. This grid pattern is arranged to maximize the amount of metallic wire or foil to strain in the parallel direction while at the same time to minimize the cross-sectional area of the grid. This helps to reduce or eliminate the affect of shear strain and Poisson strain. The gage is mounted to the test specimen via the carrier, which is a thin backing. Therefore any strain undergone by the test specimen is transferred directly through the carrier to the metallic grid. Thus the strain gage is simply an electrical resistor that undergoes a linear change in resistance when subjected to a mechanical strain.
Selection Parameters

Important criteria when selecting a strain gage include gage length, pattern, resistance, material, and installation.

Gage length is the strain sensitive length of the gage. Gages can be as short as 0.008 in and as long as 4 in, however common lengths range from 0.125 in – 0.25 in. In our case the gages we choose should be at least ¼ inch in length. This provides for a quicker and easier installation because these longer gages are not as delicate and easier to handle. A longer gage will also dissipate heat better under cyclic loading conditions and is less expensive than the shorter gages.

Uni-axial or multi-axial and planar or stacked are terms that define a gage’s grid number and layout, respectively. For our situation uni-axial gages arranged in planar layouts will be sufficient. Uni-axial gages are less expensive than multi-axial gages and the planar layout will increase the accuracy and stability of our system.

Strain gages are most commonly found with resistances of 120Ω, 350Ω, and 1000Ω. The higher the resistance of the gage, then the higher the sensitivity of the gage to strain. Because our anticipated strain is so small, approximately 132µε, the gage resistance should be at least 350Ω.

The gage factor is an important characteristic of the strain gage. This number represents a strain gage’s overall sensitivity to strain. While most suppliers give this number when marketing their gage, it is important for the consumer to know the metal that the gage is composed of. Isoelastic alloy is commonly used in applications that require dynamic measurements. It has a high gage factor, approximately 3.6, which increases the signal-to-noise ratio and allows for our desired 350Ω resistance. The drawback to this alloy is that its’ extreme
sensitivity to temperature changes. This sensitivity can be reduced dramatically by using a half-bridge circuit, which will be discussed later.

The carrier and adhesive materials are important factors as well. Because we will be testing under dynamic conditions a glass fiber reinforced epoxy backing is recommended for the carrier. Polymide is the “standard” carrier material, but it is desirable only for static loading. An epoxy is also suggested for the adhesive compound because of its high bond strength.

It is common practice for suppliers to offer options for their strain gages. These options are not necessary, but they can ease installation as well as protect the gage from the environment. These options can include: built-in solder dots, pre-attached lead wire cables, integral terminals, encapsulation, and individual furnished resistance values.

**Strain Gage Measurement**

Measuring strain requires accurate measurement of very small changes in resistance. For instance, we expect the pull-rod to undergo roughly 132µε. An isoelastic alloy gauge with a GF of 3.6 will show a change in electrical resistance of only $3(500\times10^{-6}) = 0.0475\%$. This is equivalent to a resistive change of only $0.17\Omega$ for a $350\Omega$ strain gage.
The diagram below shows the general Wheatstone Bridge configuration. This allows the user to measure these small changes in resistance.

With \( V_O \) equal to:

\[
V_O = \left[ \frac{R_1}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right] \times V_{EX}
\]

The bridge is said to be balanced \((V_O = 0)\) when \( R_1/R_2 = R_4/R_3 \). Therefore any change in the resistance of any arm of the bridge will produce a nonzero output voltage. We can take advantage of this by replacing \( R_4 \) with a strain gage \((R_G + \Delta R)\) and letting \( R_1 = R_2 = R_3 = R_G \). Now when the test specimen undergoes a strain the resistance of the strain gage changes and the bridge produces an output voltage:

\[
\frac{V_O}{V_{EX}} = -\frac{GF \times \varepsilon}{4} \left( \frac{1}{1 + \frac{GF \times \varepsilon}{2}} \right)
\]

This is known as the Quarter-Bridge circuit configuration. There are two key drawbacks when using a quarter-bridge. The first is that the \((1 + GF \times \varepsilon/2)\) term in the output equation informs us that we are dealing with a nonlinear response. The second drawback is the circuit’s sensitivity to temperature changes. This effect can be minimized by using what is referred to as an inactive, “dummy” gage. Because this dummy gage undergoes the same...
temperature fluctuations as the active gage, the ratio of their resistances, as well as \( V_0 \), do not change. By taking this one step further and making the dummy gage an active strain gage we can not only eliminate the nonlinear term but also double the output of the bridge, which leads us to the Half-Bridge Circuit:

\[
\frac{V_0}{V_{EX}} = \frac{GF \cdot \varepsilon}{2}
\]

Further consideration must be given to the lead wires because they add offset error and desensitize the bridge. Lead wire resistance, \( R_L \), can be measured and compensated for in the strain calculations. Once again, temperature changes come back to haunt us. To eliminate the alterations in \( R_L \) due to temperature changes it becomes necessary to utilize what is known as a 3-wire connection. Part (b) of the below figure indicates that any change in \( R_{12} \) will not affect the ratio of the bridge legs \( R_3 \) and \( R_G \), effectively eliminating changes in resistance to due temperature.
Signal Conditioning

The basic concepts of strain gage measurement would leave one to believe that it is a relatively simple “plug-n-play” type system. Unfortunately this is far from the truth. Proper and accurate strain measurements can only be achieved by careful selection of specific signal conditioning elements that involve the following: bridge completion, excitation, remote sensing, amplification, filtering, offset, and Shunt calibration.

Bridge completion is basically self-explanatory. It involves the use of high-precision reference resistors ($R_1$ & $R_2$) to form a completion network of the half-bridge circuit. By letting $R_2 = 350\,\Omega$ and building $R_1$ as a series connection of a $300\,\Omega$ resistor and $100\,\Omega$ trim pot, this can be adjusted to offset the bridge output to zero volts when there is no strain being applied. The justification of the large trim pot is a precaution to avoid burning the pot itself out in the instance there is a need to deviate far from the total $350\,\Omega$’s of resistance.

The next area of concern is the excitation voltage. Common voltage levels range from 3V to 10V. Anything higher than 10V can cause errors due to self-heating. The CDS unit will produce a constant, regulated 5 or 10V excitation voltage, in the range of the industry standard.

Just as lead wire resistance is an issue in the connection of the strain gauges to the bridge, it is an issue with the connection of the excitation supply to the bridge. There can be a significant voltage drop due to the length of the wires as well as changes in resistance due to temperature. Because $V_O$ is an important component of the measurement we must be confident that the bridge is receiving the exact excitation voltage that we are using in our calculations. This excitation voltage can be regulated by the use of remote
sensing wires. These remote sensing wires use negative feedback amplifiers to make the appropriate adjustments to compensate for lead losses.

The CDS unit requires that the input signal from our strain sensor be in the 0-5V range. However, output from the bridge will only be a few milivolts. Further research directed us to Analog Devices where we found their precision instrumentation amplifier, AD8230. This unit has an adjustable gain from 1 – 1000 giving us the required 0-5V output signal.

Electronic noise may also be an issue. Fortunately the AD8230 has inherent filtering capabilities as well as a low-pass filter included in its’ wiring diagram (See Analog Devices AD8230 data in technical data package).

The final step in completing a working strain sensor involves Shunt calibration. By replacing a large resistor of known value in series along one of the arms of the bridge a known $\Delta R$ is generated. This will act as a simulation of an applied strain to the test specimen and produce an output voltage that can be measured and compared to anticipated results.

**Preliminary Design**

Below is a preliminary design of what our strain gage circuit will resemble. This diagram does not include a remote sensing feature because we are not quite certain of how much the excitation voltage will be affected by voltage drop caused by wire distance and resistance variations due to temperature fluctuations. If this does turn out to be a concern then a remote sensing circuit with negative feedback amplifiers will need to be developed.
The measured pullrod loads must be correlated with the actual vertical load on the tire. The same Mitchell kinematic models used for the suspension potentiometer analysis were applied here. The simulation was used to find the correlation between the tire normal load and the pullrod load in the front and rear suspensions. It is a simple matter to have the program calculate the pullrod force given a tire normal load. (The ability of the Mitchell software to calculate this type of load has been validated by RIT Formula SAE in the past through hand calculations and comparison to another simulation program.)

However, there is a complicating factor in the relationship between these two forces – the vertical position of the wheel (ride height). Depending on the suspension geometry, the relationship between tire normal load and pullrod force could be dependent on ride height. This dependence is due to the changing geometry of the suspension system with wheel travel. To quantify the magnitude of such a relationship, a sweep of anticipated tire normal loads was conducted at several different ride height positions for both the front and rear suspensions.

For the front suspension, three ride height positions were analyzed – ride height = 0, -1, and +2. This is the full operating range of suspension wheel travel. The results at ride height = +2 are shown in the table and plot below:

<table>
<thead>
<tr>
<th>Vertical Wheel Force (lbf)</th>
<th>Pullrod Force (lbf)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>50</td>
<td>121</td>
<td>-7.6</td>
</tr>
<tr>
<td>100</td>
<td>243</td>
<td>-7.6</td>
</tr>
<tr>
<td>150</td>
<td>364</td>
<td>-7.6</td>
</tr>
<tr>
<td>200</td>
<td>485</td>
<td>-7.6</td>
</tr>
<tr>
<td>250</td>
<td>607</td>
<td>-7.6</td>
</tr>
<tr>
<td>300</td>
<td>728</td>
<td>-7.6</td>
</tr>
<tr>
<td>350</td>
<td>850</td>
<td>-7.5</td>
</tr>
<tr>
<td>400</td>
<td>971</td>
<td>-7.6</td>
</tr>
<tr>
<td>450</td>
<td>1092</td>
<td>-7.6</td>
</tr>
<tr>
<td>480</td>
<td>1165</td>
<td>-7.6</td>
</tr>
</tbody>
</table>

Front Suspension at Ride Height = +2
As expected, the relationship is constant and perfectly linear. The slope of the above plot, \( \frac{\text{Pullrod Force (lbf)}}{\text{Vertical Wheel Force (lbf)}} \), is referred to as the force relationship, which is unique for each ride height position. The percent difference is a comparison between the pullrod load at ride height = +2 and ride height = 0. The summary of results at each ride height is summarized below:

<table>
<thead>
<tr>
<th>Ride Height (in)</th>
<th>Force Relationship (lbf/lbf)</th>
<th>Average % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>2.7148</td>
<td>3.4</td>
</tr>
<tr>
<td>0</td>
<td>2.6268</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>2.4272</td>
<td>-7.6</td>
</tr>
</tbody>
</table>

Front Suspension
Thus, the actual vertical load on the tire will be calculated by:

\[
VerticalTireLoad = MeasuredPullrodLoad \times \frac{1}{-0.0964 \times (\text{RideHeight}) + 2.6217}
\]

This equation will be programmed into Trackmaster as a math channel to yield the normal tire load for left and right front wheels. The ride height value will come from the respective suspension linear potentiometer.

The rear suspension force relationship is slightly different than the front. This can be attributed to entirely different geometry. Especially influential here is the change in the angle of the pullrod relative to the ground plane as ride height changes. This characteristic is mainly driven by the inboard damper and bellcrank geometry. Since the front and rear suspension differ in this regard, the following result is reasonable.
### Rear Suspension

<table>
<thead>
<tr>
<th>Ride Height (in)</th>
<th>Force Relationship (lbf/lbf)</th>
<th>Average % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>4.0174</td>
<td>0.1</td>
</tr>
<tr>
<td>0</td>
<td>4.0135</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>3.9464</td>
<td>-1.7</td>
</tr>
<tr>
<td>2</td>
<td>3.8306</td>
<td>-4.5</td>
</tr>
</tbody>
</table>

As you can see, the force relationship is a piece-wise linear function. It is constant in the range of ride height 0 to –1 and a linear fit through the positive ride height region. Thus, the math channel equation for the left and right rear wheels will be written:

\[
Vertical\ TireLoad = IF(RideHeight \leq 0, \left[ \frac{\text{MeasuredPullrodLoad} \times \frac{1}{4.0155}}{\text{MeasuredPullrodLoad} \times \frac{1}{-0.0194 \times (RideHeight) + 4.0216}} \right], \text{MeasuredPullrodLoad})
\]
5.2.8. Engine

Sponsor Needs:
The RIT Formula SAE Racing Team currently uses an Autronic SM2 engine management system on its Honda CBR600F2 motorcycle engine. Essential input parameters which are required by this are throttle position, Air/Fuel ratio, manifold air pressure (MAP), crankshaft speed, and camshaft speed. The Autronic SM2 has several user-programmable features for engine tuning. These include tuning the fuel map multipliers based upon load and air/fuel ratio. In addition, RIT Formula SAE would like to implement closed-loop control of the engine system. This can be done by feeding data collected from an O2 sensor to the ECU in real time. One requirement which the sponsor placed on us is that we utilize some, if not all of the current sensors which they have been running. This is due to the fact that they are proven to be highly accurate and robust in this application.

In addition to essential tuning parameters, the engine group would like to better quantify several cooling system parameters. Useful data should be collected for water and air temperatures on both sides of the radiator, and flow rate through the radiator. This data will be used to optimize cooling system design and verify heat transfer calculations.

Data Acquisition Solution:
Several factors were considered when assessing how to monitor engine parameters. The first problem which we faced was how to deal the excessive heat that is produced within the engine compartment. Compounding this is the tight packaging constraints within the engine bay itself. This is due to chassis structure optimization around the engine. Due to these factors, considerations were made to safeguard all components from heat. Every effort will be made to rout sensor cabling away from high heat areas. In areas where this is not feasible, silicone coated fiberglass hose (FireSleeve) will be used to insulate cables.
Beginning with the air inlet at the throttle body, a Bosch RP86 Rotary Potentiometer is used to provide angular throttle position. Power is supplied by the main vehicle wiring harness. This sensor is well suited for the data acquisition system, providing a 0-5 volt output signal, which is readily accepted by the Commander II. One problem faced by the sponsor is an aging O2 sensor and wideband control unit. Currently the team monitors A/F with an NTK L1H1 UEGO wideband O2 sensor, which is controlled through the B Model Autronic Exhaust Gas Analyzer. This system is a proprietary unit sold by Autronic, and retails for $1800. Both the sensor, and the controller are in poor condition, and have not been providing consistent readings. With the budgetary concerns in mind, the formula team is looking to upgrade to a more reliable and smaller unit. A control box is necessary for all wideband O2 sensors, and must be installed on the vehicle each time the O2 sensor is present.

Extensive research was conducted to determine how we could control a wideband O2 sensor without the Autronic analyzer, and still produce accurate results. Two features which are needed for this type of system are a 0-5V linear output to the Commander II, and a 0-1V linear output to the ECU. This will allow Commander II to record Air/Fuel ratio simultaneously with other engine parameters, and the Autronic ECU to operate on closed-loop control via the 0-1V input. This 0-1 volt input is related to A/F through calibrations provided by Autronic. Based upon industry and motorsports research, we have determined that there are two sensors which are used by a large majority of engine management manufacturers and race teams. These are the NTK L1H1 UEGO, and the Bosch LSU-4. Both sensors are 5 wire wideband pump
cell oxygen sensors, which are used by several OEM automobile manufacturers. Of the two, the NTK is a slightly higher quality laboratory grade sensor. Its accuracy has been found to be about 1.5% better than that of the Bosch LSU-4. However, the main disadvantage to the NTK is that it is much more expensive than the Bosch. The LSU-4 can be purchased for as low as $58, compared to $329 for the NTK. After assessing the costs and small difference in accuracy, we have determined that the Bosch LSU-4 is the most feasible for this project. The following excerpt, obtained from Tech Edge, offers an explanation of how the Bosch LSU-4 pump cell oxygen sensor works.

![Diagram of the Bosch LSU sensor](image)

The Bosch LSU sensor requires a controller because it is more complex than a standard switching type sensor. It can be thought of as being made up of a heated narrow band oxygen sensor (comprising the Reference cell & Nernst Cell in the image) coupled to a pump cell in contact with a small chamber with a diffusion gap to the outside (exhaust gas). The electronics (in the WB unit case) are represented by the yellow (op-amp) and green (resistor) symbols. The actual electronics is much more complex and not shown is the feedback loop that maintains the heater to a precise temperature.

The pump cell, in conjunction with a catalytic reaction at the surface of the cell’s electrodes, can either consume oxygen or consume hydrocarbon fuel in the pump cell cavity, depending on the direction of the Ip current flow.

During normal sensor operation, a
A small sample of the exhaust gas passes through the diffusion gap into the pump cell. That exhaust gas is either rich or lean and both conditions are sensed by the reference cell which produces a voltage $V_s$ above or below the $V_{ref}$ signal (this voltage has the characteristics of a narrow band switching type sensor as shown in the image below left).

A rich exhaust will produce a high $V_s$ voltage and the electronics produces a pump current $I_p$ in one direction to consume the free fuel. A lean exhaust produces a low $V_s$ and the electronics sends the pump current in the opposite direction to consume free oxygen.

When the free oxygen or free fuel has been neutralised, the $V_s$ feedback signal goes to about 450 mVolts (the same as the $V_{ref}$ value). The pump current (which is a measure of the number of electrons used in the chemical reaction) required to produce this equilibrium is a measure of the Lambda or Air Fuel Ratio. The electronics in the WB unit converts the $I_p$ into a number of signals including a Linear Voltage which is the output of the WB unit. Not shown is the $R_{cal}$, or calibration resistor, in the sensor's connector which compensates for manufacturing variations between sensors.
Wideband $O_2$ controllers are manufactured in a variety of configurations, with several use options. Some controllers have additional data acquisition capabilities built into the controller, as well as LCD displays, and even wireless download options. For our application, the three primary concerns are with size, weight, and the above-mentioned input-output parameters. Our initial thought was that we could design and manufacture our own custom controller for the LSU-4 sensor. However, after assessing our resource and schedule feasibility, we determined that it would be in the best interest of the project to purchase a proven production model. Each manufacturer we initially investigated marketed units which were well beyond our desired product. Several units have on-board data logging, displays, and several other options which are not necessary for our application. Further research did however result in a wideband controller that affords us every option needed, with no unnecessary extras. The WBo2 2CO wideband controller is manufactured by Tech Edge, an Australian-based company specializing in wideband oxygen sensors and controllers. The 2CO is a credit card sized unit with outputs for both the ECU and data logger. In addition, the 2CO is designed for exclusive use with the LSU-4 wideband sensor. Features of this unit include its compact size, light weight, and internal filtering of wideband heater switching and vehicle generated electrical noise. In addition, the unit can be purchased for under $300, as a complete kit, including wiring.

**WBo2 2CO Specifications**
- 3.54” x 1.97” x 0.98” Outside Dimensions
- Durable ABS Plastic Housing
- Internal Noise Filtering
- 0-1 volt Simulated Narrowband Output to ECU
- 0-5 volt Linear Wideband Output to DAQ
- Compatible With Bosch LSU-4 $O_2$ Sensor

*WBo2 2CO Wideband Unit and Bosch LSU-4 Sensor*
The primary method employed by RIT Formula SAE for determination of engine load is through the use of a manifold air pressure sensor (MAP), which is internal to Autronic. The main disadvantage to this set-up is that the ECU is unable to output this data. Thus, an external MAP sensor must be used in conjunction to the Autronic MAP sensor. For this application, we have proposed using the SEN-39 Pressure Sensor, available from Competition Data Systems. This is a small, lightweight absolute pressure sensor which has a range from 0 to full vacuum. The sensor can be mounted near the intake manifold of the vehicle. Pressures can be logged by both the ECU and Commander II, through the use of a tee in the plumbing exiting the intake. The sensor can be calibrated in PSI, mm of Hg, inches of water, or % load.

When evaluating how to collect engine speed data, we turned to the method used by RIT Formula SAE on their CBR600F2 engines. Engine RPM readings are obtained from a Bosch HA-P speed sensor, which is excited by a trigger wheel on the crankshaft. The output signal is then fed to the ECU and tachometer. This is by far the most accurate and proven method for obtaining engine speed, and thus we have proposed a similar design for this application to that of the throttle position. The sensor will be powered through the main vehicle wiring harness, and the signal will be output to the ECU, tachometer and Commander II.
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