Final Design

Pneumatic Paddle Shifting
Senior Design Capstone
Team 17

Chosen Solution

An electro-pneumatic paddle shifting test bench will be designed to optimize a system that will eventually be implemented to the TFR car. In this design, an input signal from a user will control a solenoid that controls the flow of a gas from a tank. The input signal will be given to the system using software so mass amounts of data can be collected on the system. The option to give input to the system using a button will be implemented for display purposes. After the solenoid receives the user signal to shift up or down the system will release gas from the tank to control the movement of an air cylinder. This cylinder will then generate the required force to push on a lever, simulating the mechanism to shift on an FSAE car. The optimal working pressure of the system will be determined using the data collected by the system. Pressure, temperature, and shifting time will be measured while running the system.

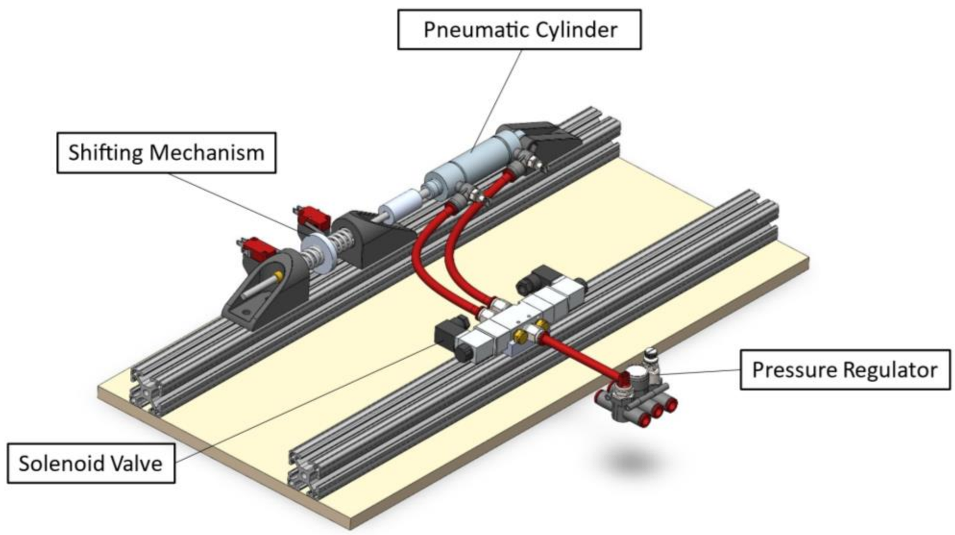


Figure 1: Test Bench Prototype Model

Design constraints and criteria must be met for the system to be considered successful. This system will be designed to follow the rules of the FSAE competition so that it may be implemented on to an FSAE car in the future. Relevant rules include mounting a pressure regulator to the gas tank, appropriately fitting gas lines, ensuring working pressure will not exceed 121psi, selecting a commercially manufactured gas tank, and selecting a non-flammable working gas. Along with this, all electrical components must be compatible with the current battery and ECU used by TFR to ensure the system can be integrated in future years. Due to the nature of racing, the overall weight of the system must be under 10 pounds. To achieve these goals, lightweight, rule-compliant components will be selected.

The selected pneumatic cylinder must produce enough torque to shift the gears of the transmission. This requirement will be met by calculating the needed cylinder rod and bore diameter to produce the required toque within the pressure range of the system. It must be possible for a shift to occur every 0.3 seconds. This will be achieved using an electro-pneumatic solenoid valve. The solenoid valve will open and close as directed by electrical signals as opposed to slower mechanical signals. Each gas tank contains a finite volume of gas and therefore a finite number of shifts. To ensure each tank contains enough gas to actuate 500 shifts the mass of gas required per shift cycle will be calculated.

The motivation of this project is to improve vehicle performance and seeks to decrease the time to actuate by 5%. This goal will be achieved through data analysis to determine the optimal system conditions for performance. To collect data, a microcontroller will facilitate input and output interactions.

Due to the experimental nature of the test bench, component adjustments will be made frequently. The testing bench must be modular and easily serviceable as a result. To meet this goal consistent hardware will be used throughout the bench and components will be able to slide along 8020 Aluminum T-slots. Data will be displayed after each shift, so the results of a test run are known immediately. This will be done by integrating the microcontroller and software with a digital display.

Engineering Design

Preliminary Testing

This design is being implemented on a stock Honda CBR600RR engine. The transmission of which is has constantly meshed gears that can be engaged or disengaged by sliding engagement collars, or "dogs", from one set of gears into another. The engagement of the dogs is actuated by a series of internal linkages that connect to a single external lever arm called the "shifting link". Preliminary testing will be done to quantify the amount of distance and force required to successfully shift the transmission through each gear.

During preliminary testing, the total force that the linear actuator must supply can be solved knowing the relationship between torque and force:

$$F = \frac{M}{x}$$

Equation 1. Required Force to Shift

where F is the required actuator force, M is the torque needed to shift gears, and x is the length of the shifting linkage moment arm.

The preliminary experiment consisted of using a live read-out torque wrench to record the amount of torque required to shift the engine. Data for the experiment can be found in the appendix. The collected torque data can then be converted to a required actuator force, knowing the length of the original Honda CBR600RR shifting link. The experiment setup is shown below:

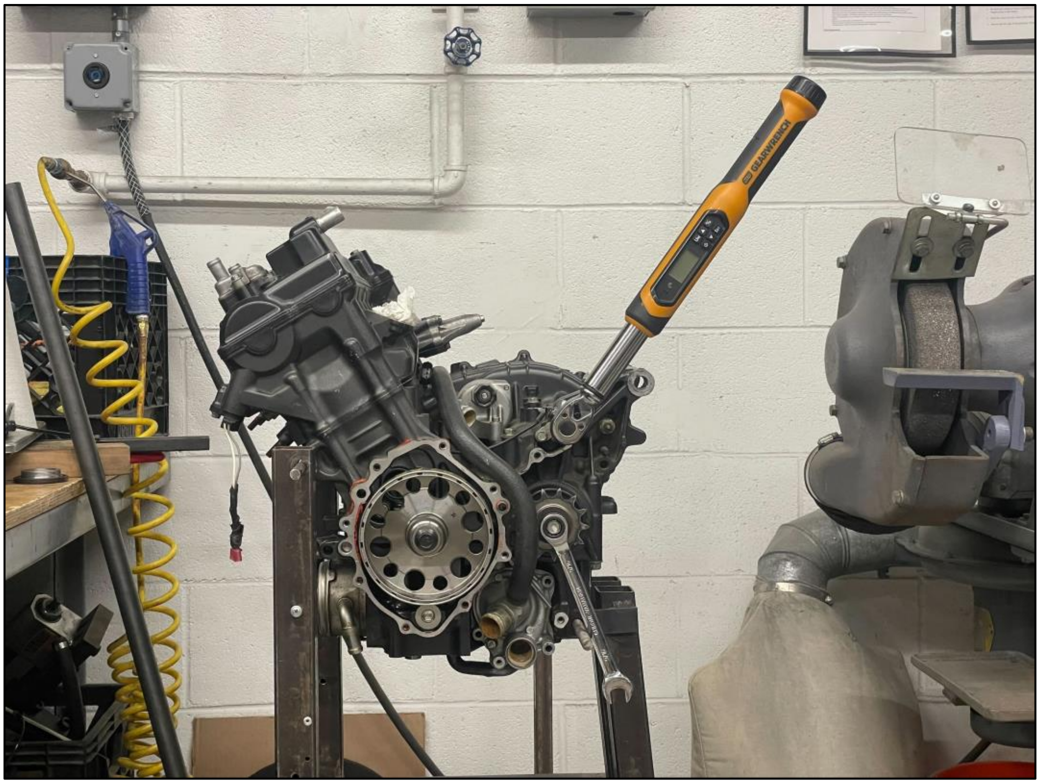


Figure 2. Preliminary shifting torque test setup

To obtain the distance the actuator must actuate at, a simple test was performed using a magnetic base machinists' stop. While stop's base was placed on a rigid surface within proximity to the shifting link, the stop's arm was push flush against the shifting linkage. Then, the shifting linkage was manually actuated until a successful up-shift occurred, which pushed the stop's arm back. Once the shifting linkage returned to the center position, the distance between it and the stop's arm was recorded. This was repeated in the opposite direction for a down-shift. These distances can be written as:

$$X_{total} = X_{up} + X_{down}$$

Where Xtotal represents the minimum total actuation length for a pneumatic cylinder. An example of the measurement is shown below:

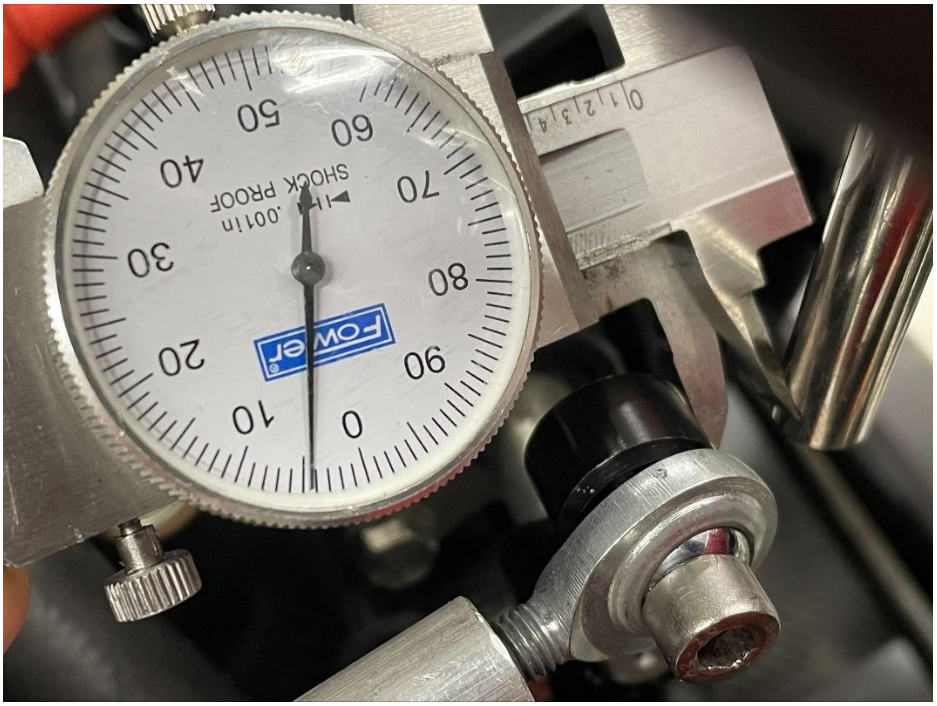


Figure 3. Measuring shift linkage actuation length

Pneumatic Components

When selecting the pneumatic components, the working pressure was restricted through the selection of the pneumatic solenoid. The solenoid is a critical component to the system as it acts as an on/off switch to let the gas pass through the pneumatic cylinder. The pneumatic solenoid needed to be four-way directional operation and three position valves. The four directional operations account for the movements required for the actuation and return of gas for the up and downshifts. While the three position accounts for the position of the linear actuator for the upshift, downshift and middle/resting position. The solenoid was selected with an exhausted center so the pressure would return to atmospheric when no actuation is happening, thus returning the piston to a chosen established resting position. It was decided that the solenoid should require a 12 V power supply in order to use a standard wall outlet. The only solenoid that fit this requirement contained a working pressure range of 21-121 psi. Thus, the pneumatic solenoid provided a constraint on the working pressure of the system.

The required working force was established as about 90 lbs through the engine transmission physical testing. With this metric, the bore diameter could be solved for using the following equation:

$$Required\ Bore\ Diameter = \sqrt{\frac{4 * Force}{\pi * Pressure}}$$

Equation 2. Required Bore Diameter

For selecting a pneumatic cylinder, it is recommended that 25% is added to the required force to account for friction losses, pressure drop and other factors. With the required force and pressure limitations, the selected pneumatic cylinder contained a bore diameter of 1-1/16, 1-inch stroke length, and 1/8-inch NPT fittings. A single actuating cylinder has an internal spring that returns the rod to position. This was not desirable as the cylinder should be able to move in both directions with a resting position at the middle point of the stroke length. A double-actuating cylinder was chosen to account for the change in direction for up and down shifts as well as the resting position.

Pneumatic hardware was selected based on compatibility with the solenoid and pneumatic cylinder and for optimal serviceability. Automation Direct is an industrial controls supplier with a wide variety of pneumatic components. Chip McDaniel, salesman for Automation Direct, served as an industry advisor for selecting compatible hardware. The components displayed in the table below were donated to the team and selected with the guidance of Chip. Push-to-connect fittings were chosen for the pneumatic system for ease of serviceability.

Table 1. Selected Pneumatic Components

Item	Description
Cylinder	Linear actuator with 1-1/6-inch bore, 1-inch stroke, double acting cylinder, 1/8-inch NPT fittings
Flow control valve	Elbow flow control valve used to adjust flow for faster actuation. Contains push-to-connect fitting and 1/8-inch NPT
On-off Valve	Inline manual shutoff valve with push-to-connect fittings.
Exhaust silencer	Used to muffler system noise. Contains 1/8in male NPT.
Air pressure gauge	Inline pressure gauge for monitoring working pressure. Contains push-to-connect fittings and working pressure range of 0-170 psi.
5/16” air hose -100 ft roll	Pneumatic tubing compatible with push-to-connect fittings.
Male 1/8 NPT push to connect fitting	5/16-inch tube to 1/8-inch NPT connection.

Gas Tank Selection

For any system that is implemented on the Temple Formula Racing vehicle, one of the most important goals is to minimize weight. Thus, the goal of gas tank selection is to select the tank that will provide the required number of shifts for the FSAE endurance race with an accounted for reasonable factor of safety. A tank that provides more than the required number of shifts would not be optimized for weight or performance. A gas tank selection code was constructed to predict the quantity of mass needed for a single shift and consequently for the entirety of the race. The SOLVEM method (Sketch, Observation or Objectives, List Variables and Equations, and Manipulation) was utilized to brainstorm the required inputs and outputs for the code.

The schematic below was used to visualize the interaction between the tank and pneumatic cylinder.

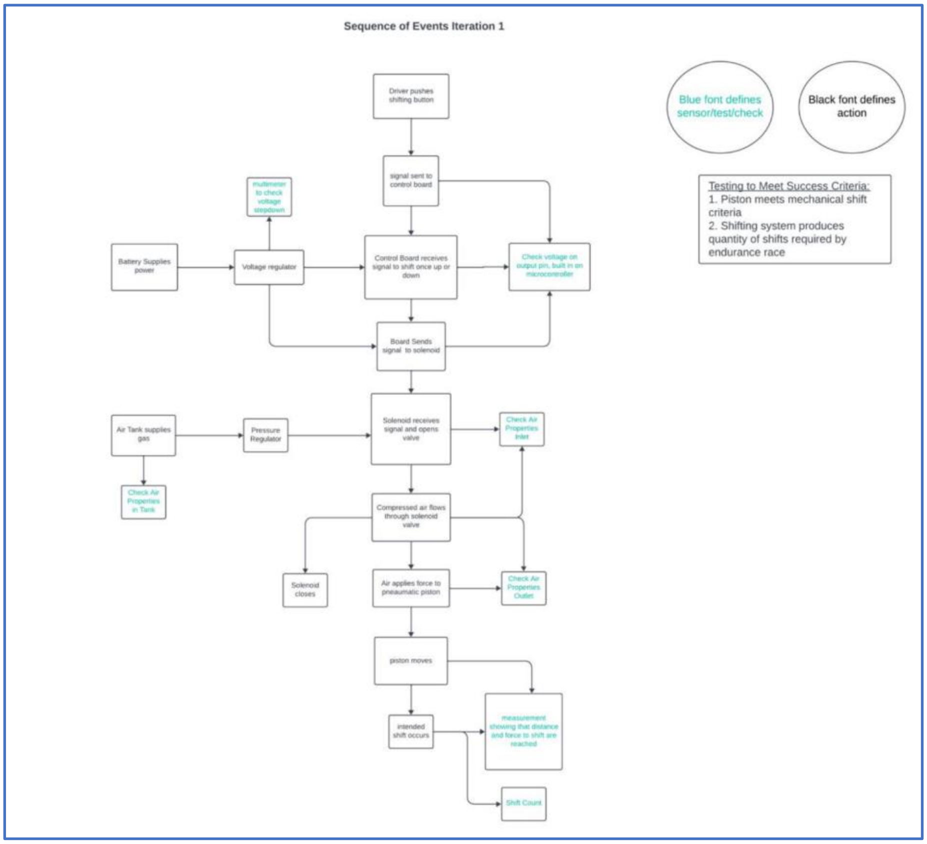


Figure 4. System Sequence of Events

The known and unknown values of the system were listed in the table below. The temperature of the gas at the working pressure of the system is a critical value that is currently unknown. This value will be obtained through a temperature sensor that is mounted to the pneumatic lines once the test bench is constructed.

Table 2. Pneumatic Variables

Variable Description	Symbol	Unit	Status
Bore Diameter	Db	in	Known
Rod end Diameter	Dr	in	Known
Actuator Stroke Length	Ls	in	Known
Hose Inner Diameter	DI	in	Known
Area rod	Ar	in^2	Calculated
Area bore	Ab	in^2	Calculated
Net Area in Cylinder	Ac	in^2	Calculated
Volume in lines	Vl	in^3	Calculated
Length line	Ll	in	Known
Volume of extended cylinder	Ve	in^3	Calculated
Total Volume extended cylinder	Vet	in^3	Calculated

Volume of retracted cylinder	Vr	in^3	Calculated
Total volume retracted cylinder	Vrt	in^3	Calculated
Reduced Pressure	Pr	unitless	Known
Working Pressure	P	psi	Calculated
Critical Pressure	Pc	psi	Known
Reduced Temperature	Tr	unitless	Unknown
Working Temperature	T	K	Unknown
Critical Temperature	Tc	K	Unknown
Specific Volume	v	m^3/kg	Calculated
Compressibility Factor	Z	unitless	Calculated
Universal Gas Constant	R	KJ/Kmol*K	Known Constant
Mass to retract Cylinder	mr	kg	Calculated
Mass to extend Cylinder	me	kg	Calculated
Total Mass per Shift Cycle	mt	kg	Calculated

First, the area of the pneumatic components was measured and calculated to then calculate the volume the working gas will occupy. The are of the rod was calculated as:

$$Area\ Rod, Ar = \pi * \left(\frac{Dr}{2}\right)^2$$

Equation 3. Area of Rod

Where Dr, is the diameter of the rod inside of the pneumatic piston. The area of the bore was calculated as such:

$$Area\ Bore, Ab = \pi * \left(\frac{Db}{2}\right)^2$$

Equation 4. Area of Bore

Where Db is the diameter of the bore. Next, the next area of the pneumatic cylinder could be calculated with the following equation:

$$Net\ Area\ of\ Cylinder, Ac = Ab - Ar$$

Equation 5. Net Area of Cylinder

With the net area of the cylinder calculated, the volume of gas could be calculated with the equation below:

$$Volume\ of\ Retracted\ Cylinder, Vr = Ac * Ls$$

Equation 6. Volume of Retracted Cylinder

Where Ls is the length of the stroke. The volume of gas in the lines was calculated as such:

$$Volume\ in\ lines, Vl = \pi * \left(\frac{Dl}{2}\right)^2 * Ll$$

Equation 7. Volume in the Lines

Where Dl is the diameter of the line and Ll is the length of the line. The total retracted volume was calculated with the equation below:

$$Total\ Volume\ Retracted\ Cylinder, Vrt = Vr + Vl$$

Equation 8. Total Volume of Retracted Cylinder

Next the total volume of the extended cylinder was calculated with the same equation as for the retracted volume:

$$Volume\ of\ extended\ cylinder, Ve = Ac * Sl$$

Equation 9. Total Volume of Extended Cylinder

The total volume of the extended cylinder was calculated to account for the volume of gas in the lines:

$$Total\ Volume\ Extened, Vet = Vl + Ve$$

Equation 10. Total Volume of Extended Cylinder

In order to calculate the mass required per shift, the textbook Fundamentals of Engineering Thermodynamics (reference) was referenced specifically on the topic of compressed gases. The compressibility factor, Z, is expressed as:

$$Z = \frac{p\bar{v}}{RT}$$

Where p, is the pressure, v, is specific volume, R, is the universal gas constant, and T is the temperature. The units should allow for Z to be dimensionless. The compressibility factor is plotted against a dimensionless reduced pressure, pr, and reduced temperature, Tr, which are expressed as:

$$p_R = \frac{p}{p_c}$$

Equation 11. Reduced Pressure

$$T_R = \frac{T}{T_c}$$

Equation 12. Reduced Temperature

In which, pc and Tc denote the critical pressure and temperature found in table A.1 of the textbook. The figure below displays the generalized compressibility chart utilized to determine Z.

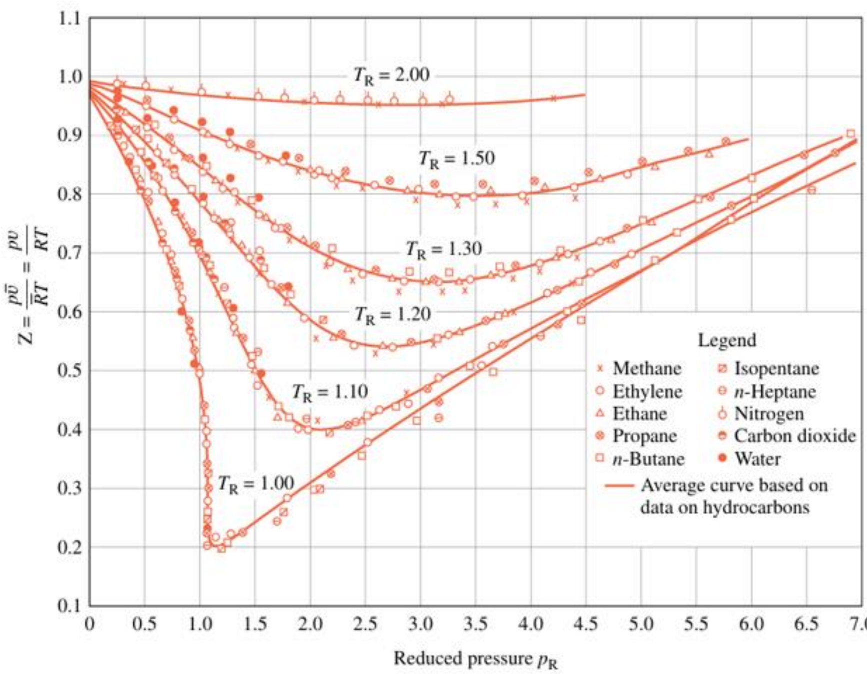


FIG. 3.12 Generalized compressibility chart for various gases.

Figure 5. Generalized Compressibility Chart

If the Z-value is close to one for the given pressure and temperature, the gas can be treated as ideal. With the Z-value obtained, the specific volume can be calculated by rearranging the equation:

$$\bar{v} = \frac{ZRT}{p}$$

Equation 13. Specific Volume

Finally, to calculate the mass, the following equation is used:

$$m = \frac{Vtotal}{\bar{v}}$$

Equation 14. Mass per shift

As the temperature of the working gas is unknown, an estimation of -10 degrees C was input into the calculator for initial results. The code is modular, and testing will provide an experimental temperature for a more accurate estimation of shifts within the tank. For testing purposes, the tank was oversized for data collection so that design decisions could be made by the FSAE team in the future. The two selected gases for testing were carbon dioxide and nitrogen gas. These gases were selected as their application in paint balling allow for the gas, tanks, and required hardware easy to find and access. The two gases will be tested for their reliability and influence on the number of shifts.

Electrical Components

When selecting the electrical components for this design, there were two primary systems that had to be considered, power and data.

The power system provides power to all necessary components, like the solenoid valve, sensors, and microcontroller. Our solenoid valve has the highest voltage rating of any of our components, at 12 VDC. As a result, we chose a 12 VDC, 6 A power supply to provide power to the system. We chose a high current rating to ensure it could handle all the devices attached to it. Downstream from the power supply are three components, a 12 VDC 4 channel relay module, a 12 VDC to 5 VDC buck converter, and our microcontroller. Two relay modules are used, with each one controlling one of the two solenoids on the solenoid valve. The buck converter is used to get the 5 VDC necessary for some of the sensors that are being used by the system. The microcontroller we chose, the Arduino Mega Rev3 2560, has an operating voltage of 7-12 VDC, so the power supply can provide sufficient power to it.

The data system consists of sensors, and the Arduino Mega Rev3 2560. We are using two identical pressure-temperature sensors, which each have analog outputs for the pressure readings, and a PT100 sensor for the temperature readings. Because the PT100 sensor measures temperature based on resistance, it cannot be directly configured with the Arduino. Instead, we must use the MAX31865 breakout board from Adafruit, which allows us to accurately read the resistance from the microcontroller, and then calculate the resistance based on the sensor's datasheet. The Arduino will be facilitating the collection of the data from this sensor and sending it to an external device for logging. The other primary function of the Arduino will be sending the signal to the relay to activate the necessary solenoid depending on what the user requests.

Software Development

The primary function of this test bench is for the user to run tests on a pneumatic paddle shifting system, so the software's design revolves around running specific tests. There are five functions that will be written for the Arduino to ensure this functionality:

- readSensorData()
    - Functionality: This function will read instantaneous data from the two pressure-temperature sensors and output it to the serial data line. The serial data line is what will be sending data to the host device, which is what will be doing the data processing and logging.
    - Inputs: N/A
    - Outputs: Sensor data to serial data line
- controlSolenoid(solenoidPin, duration)
    - Functionality: Controls the opening and closing of the solenoid valve that allows gas to flow. There is a defined duration for which the valve is open, but there is also a limit switch that is defined by which solenoidPin is being used, where the solenoid will automatically close if the limit switch is activated, as that will mean that the lever has traveled enough of a distance to shift.
    - Inputs
        - solenoidPin: Defines which solenoid we are controlling, as one controls the valve for upshifts, and the other controls the valve for downshifts
        - duration: The length that the valve should be open if the limit switch is not activated
    - Outputs: None
- loadProfile(profileName)

    - Functionality: Each of the tests will be stored in a profile, in which upshifts and downshifts are defined by 1's and 0's in one array, and the time between shifts is defined in another array. The Arduino has limited SRAM, so the data for each of the testing profiles will be stored in flash memory. This means this data must be read in by the program, rather than immediately available from the SRAM.
    - Inputs: Name of the test that is going to be performed
    - Outputs: Testing profile data (shift sequence and timing)
- executeShiftSequence(profileShiftSequence, profileTiming)
    - Functionality: Utilizes that data loaded in from loadProfile(), and the functionality of controlSolenoid() to execute the test. It will read profileShiftSequence to determine which pin is the input pin to controlSolenoid(), and profileTiming to determine the duration parameter of controlSolenoid().
    - Inputs:
        - profileShiftSequence: An array of 1's and 0's, where 1 represents an upshift, and 0 represents a downshift
        - profileTiming: An array of floating-point numbers that represent, in milliseconds, the time between each shift
    - Outputs: None
- monitorSystemStatus()
    - Functionality: Ensure that the system is safe to operate by checking if the sensors are within the expected range. If the function returns False, the system will not be able to operate.
    - Inputs: None
    - Outputs: Boolean that indicates whether system is in operating range (True if yes, False if no)

Testing

To collect data on the prototype design, a testing apparatus will be designed and constructed to replicate the forces and motions endured in the real environment. Since the criteria for a successful shift are force and distance requirements, springs provide a simple and reliable method of testing shifts. The function of a spring can be defined by Hooke's Law rewritten as:

$$-k = \frac{F}{x}$$

where F is the spring's resultant force, x is the displacement of the spring, and k is the spring coefficient. As shown in the preliminary testing data, the criterion for a successful shift is roughly 90lbf applied at 0.4in. The required spring coefficient can be calculated as 225 lbf/in.

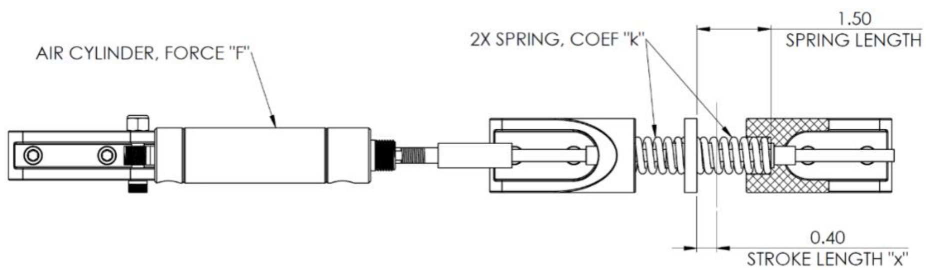


Figure 6 Testing Mechanism Diagram

The two gases will be performance tested for reliability, number of produced shifts and changes in temperature. The first test will be an endurance test in which a script will be written to produce up and downshifts until the system can no longer produce the required force to actuate the engine transmission. In addition, a script will be written to actuate 500 shifts within a 3-minute period (approximately 0.3 seconds per shift). Data will be collected with each shift and the temperature and pressure will be plotted against time. The output for carbon dioxide and nitrogen gas will be compared in order to recommend a final decision for the team.

Design

Electrical Integration

The figure below illustrates the power delivery as described in the *Electrical Components* subsection.

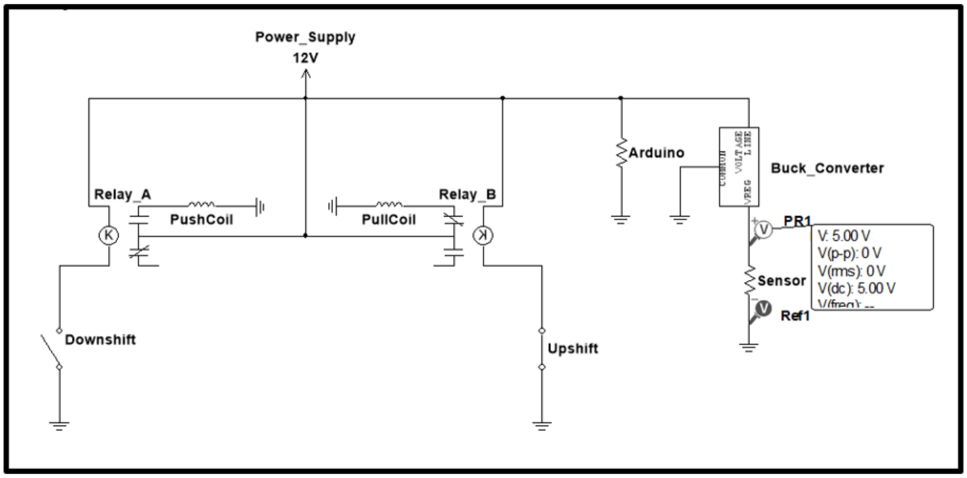


Figure 7. Electric Schematic

The remainder of the electrical system will consist of the components outlined above. Each of the components will connect to one of the pins on the Arduino and be configured as described in the *Software Development* sub-section.

Testing Apparatus

It is desired for a testing apparatus to be simple and adjustable so that multiple variations of actuation systems can be tested. There are two motions the apparatus must be able to replicate: up shift actuation and down shift actuation. Both actuations occur in the same linear path as the pneumatic cylinder, in opposite directions. Another important feature of the CBR600RR transmission is that the shifting linkage returns to the center position after each shift.

To accomplish these requirements, the pneumatic cylinder and springs will all be placed in the same axis. A support component will be design for each unique component. Because there is a high potential for iterating designs, the support components will be designed to connect to T-slot railing, for adjustability. In addition, the support components need only to withstand roughly 90lbf in one axis and whatever vibration is created from the testing device. According to the datasheet provided by Formlabs (9), Nylon 12 SLS printing material has an ultimate tensile strength of 7252 psi, which should be more than adequate for all mechanical supports.

The final testing mechanism design is comprised of the following components:

Item	**Description**
Spring	Provides resistive force to replicate transmission forces. Chosen based off calculations that match the force and distance criteria for successful shift.
Spring pusher	Connected to the pneumatic cylinder, this part pushes against the springs to compress them to the actuated state. Constructed from 6061 Aluminum.
Spring support	Supports springs in the operating position in alignment with the linear shaft and pneumatic cylinder. Printed out of Nylon 12.

Cylinder support	Attaches pneumatic cylinder to base of assembly and aligns it in the operating axis. Printed out of Nylon 12.
Linear shaft	Connects to the pneumatic cylinder shaft and spring pusher. This component translates linear force to compress each spring.
Linear bearings	Oil embedded sleeve bearings chosen to fit linear shaft and provide smooth operation. Pressed into spring supports.
Shaft coupler	Attaches linear shaft to pneumatic cylinder by threading into each component. Constructed from 6061 Aluminum.
Limit switches	Micro limit switches are used to detect when the shifting mechanism has completed a full stroke. The spring pusher presses against the trigger arm to toggle the switch.
T-slot framing	Standard 1.5x1.5in T-slot frame rails used for mounting components. T-slot hardware allows each component to be repositioned with ease to accommodate multiple design configurations.

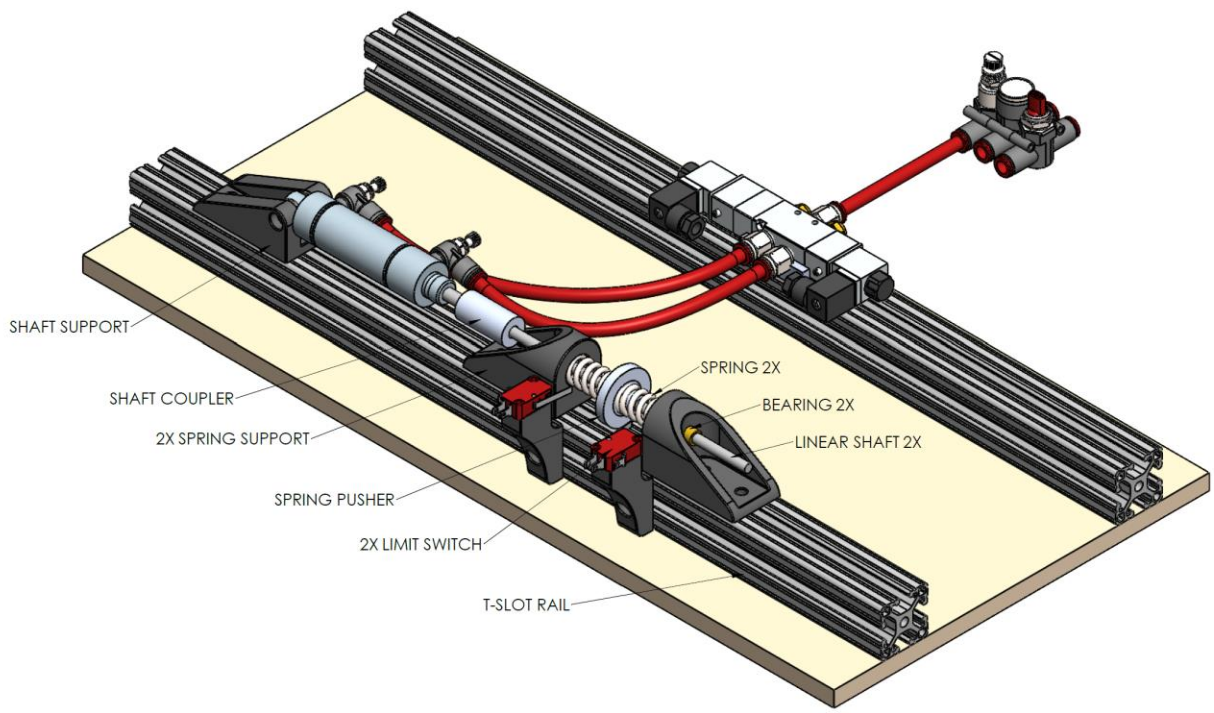


Figure 8. Testing Mechanism Itemized

The entire assembly was designed in Solidworks for rapid prototyping and running simulations on components before manufacturing. The main load bearing components were ran through Solidworks simulations and resulted in the following factors of safety:

Item	Minimum Factor of Safety
Spring pusher	60
Spring support	8.8
Cylinder support	8.9
Linear shaft	32.6
Shaft coupler	9.2

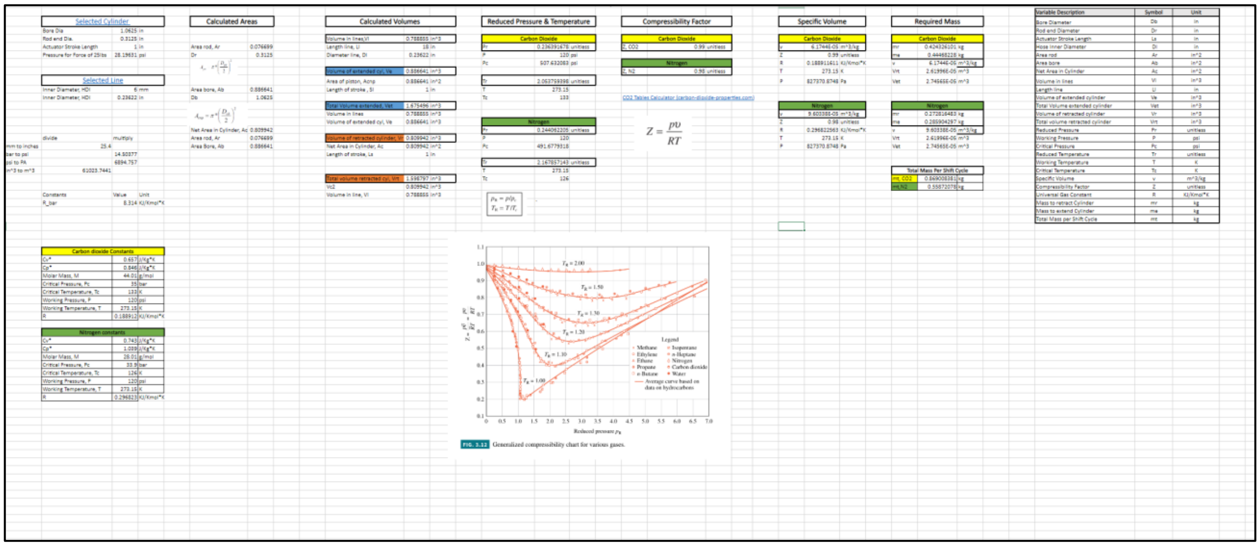
Appendix

Example Code

```
// Purpose: Controls activation of solenoid from a digital output pin of an arduino

void controlSolenoid(int solenoidPin, float duration) {

  // initializes limitSwitchPin variable

  int limitSwitchPin = 0;

  // This part of the code figures out which limit switch should be checked

  if (solenoidPin == upShiftPin) {

    limitSwitchPin = upShiftLimitSwitchPin;

    Serial.println("Upshift");

  } else {

    limitSwitchPin = downShiftLimitSwitchPin;

    Serial.println("Downshift");

  }

  // This makes the solenoid pin go high (opens valve)

  digitalWrite(solenoidPin, HIGH);

  // Starts a timer

  unsigned long startTime = millis();


  // Following loop terminates for either:

  // A: Limit Switch is pressed

  // B: Timer exceeds duration specified in function

  while(digitalRead(limitSwitchPin)==HIGH & millis()-startTime<duration){
```

```
      delay(5);
    }
    // Once the loop terminates, set the solenoid pin to low (close valve)
    digitalWrite(solenoidPin, LOW);
}
```

Gas Selection Code



Preliminary Shifting Torque Data

Trial	Engine OFF									
	Shifting Torque [ft-lbs]									
	1st - 2nd	2nd - 3rd	3rd - 4th	4th - 5th	5th - 6th	6th - 5th	5th - 4th	4th - 3rd	3rd - 2nd	2nd - 1st
1	4	5.6	6.3	8.1	6.6	5.8	6.8	8.3	8.6	6.7
2	6.5	7.5	7.8	7	7.9	6.5	6	8.6	8	5
3	11.3	16.5	14.5	16.8	12.8	11.3	11.9	12.2	14.9	8
4	15.1	13.5	18.4	16.7	13.9	15.1	11.9	20	17.4	13
5	19	19	17	14	10	11	10	11	11	7
	[in-lbs]									
1	48	67.2	75.6	97.2	79.2	69.6	81.6	99.6	103.2	80.4
2	78	90	93.6	84	94.8	78	72	103.2	96	60
3	135.6	198	174	201.6	153.6	135.6	142.8	146.4	178.8	96
4	181.2	162	220.8	200.4	166.8	181.2	142.8	240	208.8	156
5	228	228	204	168	120	132	120	132	132	84
AVG	132.4									
MEDIAN	132									

Required		
linkage	1.5	in
F	88.3	lbs
x	0.3945	in
k	223.8	lbs/in

McMaster check		
k	221	lbs/in
F	88.3	lbs
x	0.399493	in
	98.73%	

Solidworks Simulation FoS Plots

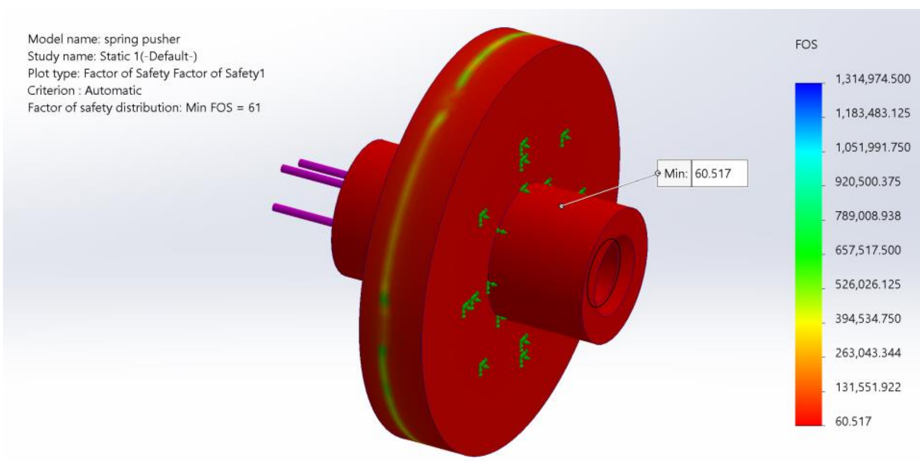


Figure 9. Spring pusher FoS plot

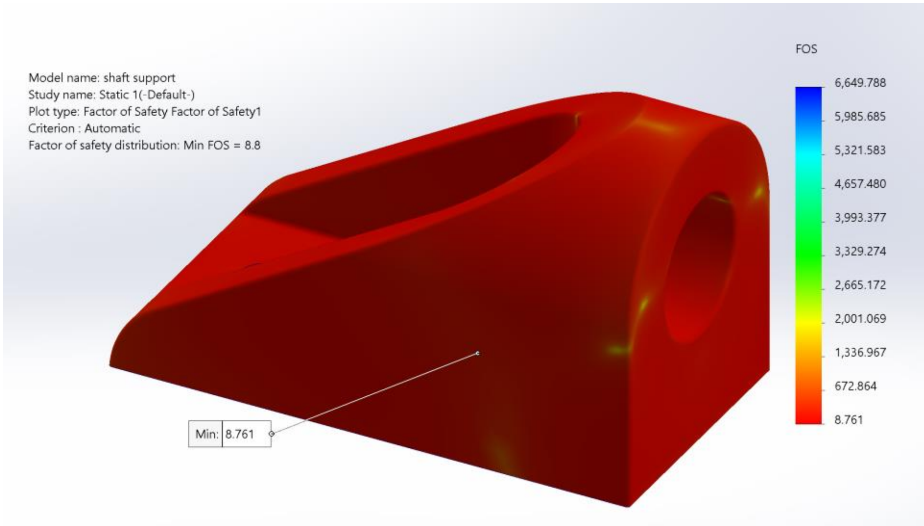


Figure 10. Spring support FoS plot

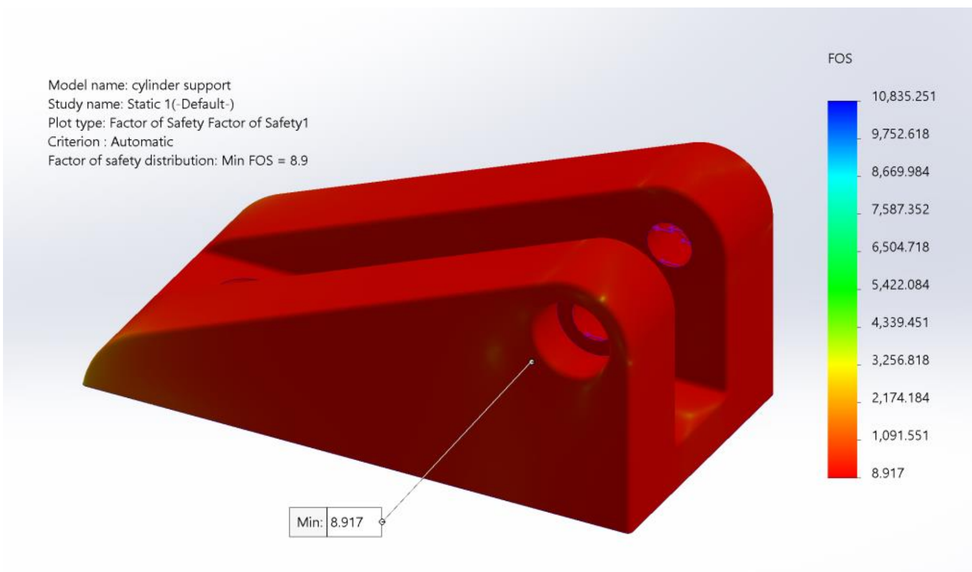


Figure 11. Cylinder support FoS plot

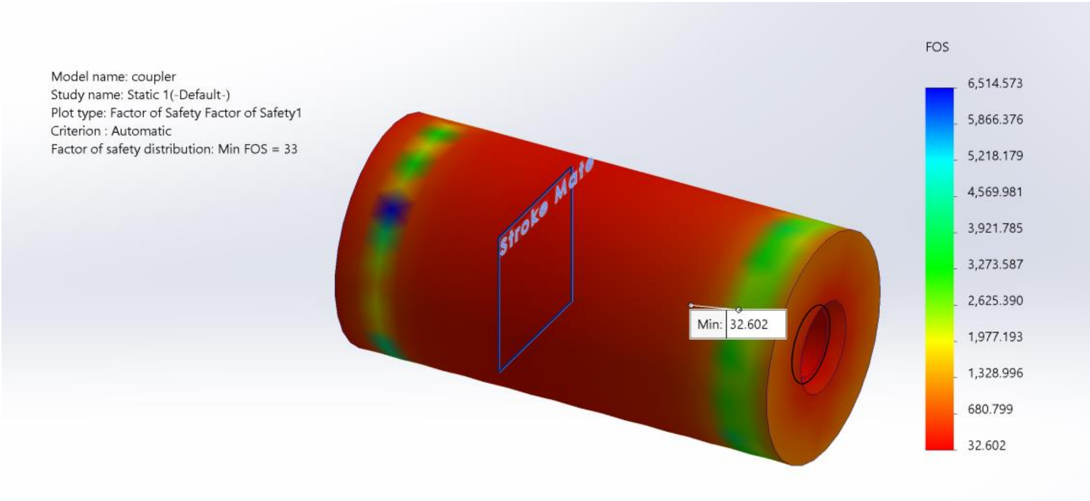


Figure 12. Shaft coupler FoS plot

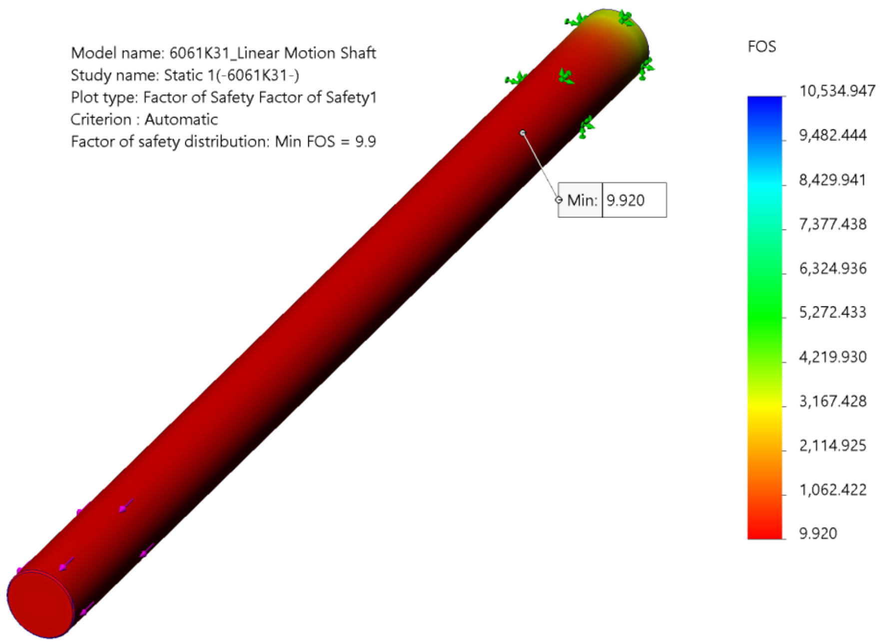


Figure 13. Linear shaft FoS plot

Citations

1. Chalmela, R. J. (2016). *Electro-Pneumatic shifting and servo control of a clutch for a FSAE racecar*.
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