Air Flow in Automotive Engines

Authors: Devin Guerrera, William Kelly, Joseph Scafidi, Peter Springer, Erik Wegge

Submitted to: Professor Selçuk Güçeri,

Submitted on: April 28, 2022

Table of Contents

Table of Figures

Table of Tables

Abstract

This project analyzed and optimized the flow of incoming air and outgoing exhaust through an automotive internal combustion engine to improve the engine power output reliably. The testing vehicle was a 1997 Chevrolet Corvette that started with the factory V8 engine. Engine build design choices were made through research and analysis to optimize airflow and to support the increased component stresses due to the increase in power. Computational fluid dynamics software was utilized to model fluid flow throughout both intake manifolds and further analyze changes that occurred between engine components. Horsepower output measurements were taken before and after modifications to determine power gains and evaluate build design choices.

Acknowledgments

The Air Flow in Automotive Engines team would like to thank several people and groups who were integral to our success and contributed greatly to our work:

- First, our sincere gratitude to Professor Selçuk Güçeri of WPI's Mechanical Engineering Department. Professor Güçeri advised our project and gave his personal time to keep us on track and provide supporting information. Each member of the group had enrolled in many of his classes beforehand, and it was special to be able to apply the information he taught us to a much more personal project. His efforts, experience, and knowledge of automotive engines and processes were critical to the completion of the group's work.
- Thank you to the Bowtie Shop in Billerica, Massachusetts who generously provided us a workspace and tools to work on the project. They helped us progress through any setbacks or issues that we encountered, and this project would not have been possible to complete without this space.
- Thank you to Paul Thompson for allowing us to use his dynamometer in our performance testing as well as aiding in the ECU tuning process. Our results would not have been achievable without his expertise.
- Lastly, thank you to Worcester Polytechnic Institute for funding a significant portion of the project. With the high costs of materials needed for this project, we were relieved to be provided with any financial help purchasing the numerous parts and components.

Executive Summary

This project investigated the optimization of airflow in a 1997 Chevrolet Corvette. An internal combustion engine combines air and fuel to develop mechanical power. Every component in the intake, engine, and exhaust system has an impact on developed power. The primary objective of this optimization was to increase the developed power of the engine safely and reliably which would not pose any risk to the vehicle or operator. In general, increasing the amount of air that enters the cylinder will allow an engine to produce more power. Reducing any restrictions that could slow the air down and increasing the displacement of the engine are the two primary methods of increasing airflow, and the team utilized both of these techniques successfully. The team's goal was to test the car on a dynamometer after each major modification to the intake system and engine to measure any performance gains.

These modifications to the car included both engine and supporting modifications. The first of which was a new engine block with 0.3 liters more displacement, fully machined and bored 0.0055 over stock. In the block, a set of new forged rods and pistons were installed, as well as ARP main cap studs and ARP rod bolts. Along with the new internals, a new camshaft and upgraded oil pump were introduced. New 243 cast cylinder heads along with new hydraulic roller lifters, stronger valve springs, and new rocker arms were installed. A higher flowing Trailblazer SS intake manifold was introduced, and the supercharger restrictor plate was removed. In the intake system, a methanol injection system sprays methanol to increase power and lower intake temperatures. Behind the engine, a twin-disc clutch, solid couplers in the torque tube, and polyurethane bushings in the control arms were installed.

Figure 1: *Modified Engine Internals*

Reliability and safety were important factors in the build process. Any damage to internal engine components often results in catastrophic failure as each part must work in sync with the others. It is also important to note that the cost of a project like this is quite expensive, so the team wanted to ensure accuracy in the build, as mistakes would have been extremely costly.

The project team also desired to predict where power gains came from before testing on the dynamometer. The team used ANSYS Fluent, a computational fluid dynamics (CFD) software package, to simulate the complex thermodynamic and fluid dynamic situation inside both intake manifolds. The LS6 and Trailblazer SS intake manifolds were made from glass-reinforced nylon but had different runner and plenum geometries. The team created solid models of the fluid volumes of both manifolds in Solidworks. The group then applied the material properties of the manifolds and their operating conditions in ANSYS Fluent and simulated airflow for six revolutions of the engine at 2000 RPM. The team found that there was no difference in the amount of air flowing through the manifolds at a specific mass flow rate, but that the way air accelerated in the runners of the Trailblazer SS manifold would impact torque development. Figure 2 shows the pressure plot of an open runner in the Trailblazer SS manifold.

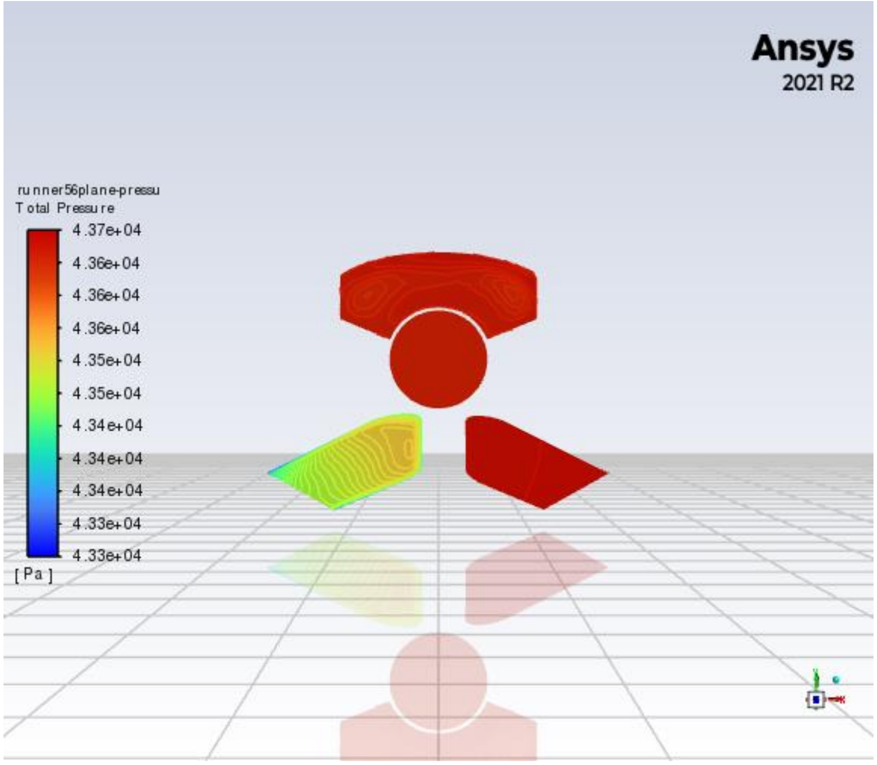


Figure 2: *Pressure Plot of Trailblazer SS Manifold Through Runner #6 at n=130*

A vehicle chassis dynamometer was used to most accurately measure the actual horsepower before and after modifications. The dynamometer also records all engine logistics from the sensors and has tools to cater to each run on the dynamometer based on the desired results. The data from these sensors were utilized in the CFD to simulate the airflow as accurately as possible. Below is an image that highlights results from a trial of the vehicle on the dynamometer after modifications.

Name	Value
AIR Pump	off
Base Advance	22.0 °
Coolant Advance	0.0 °
IAT Advance	0.0 °
Knock Retard	1.0 °
Burst Knock Retard	0.0 °
Dynamic Airflow	2,248.1 lb/h
Mass Airflow Sensor	10,550 Hz
Mass Airflow (SAE)	37.80 lb/min
Injector Pulse Width Avg...	11.8 ms
Injector Pulse Width Avg...	11.9 ms
Calculated Engine Load (...	100.0 %
Accelerator Pedal Position	99.0 %
Throttle Position (SAE)	99.6 %
Vehicle Speed (SAE)	60 mph
Short Term Fuel Trim Ban...	0.0 %
Long Term Fuel Trim Bank...	0.0 %
Short Term Fuel Trim Ban...	0.0 %
Long Term Fuel Trim Bank...	0.0 %
O2 Voltage B1S1 (SAE)	0.438 V
O2 Voltage B2S1 (SAE)	0.298 V
Equivalence Ratio Commanded	0.79 λ
MPVI2.1 -> Ballenger - A...	0.80 λ
Engine Oil Pressure	61.8 psi
Delivered Engine Torque	507 lb·ft
Idle Desired Airflow	73.7 lb/h
Idle Adapt (STIT)	0.00 lb/min
Idle Air Control Position	310
LTIT Gear/ACoff	-0.11 lb/min
LTIT PN/ACoff	0.00 lb/min
Accelerator Pedal Position	99.0 %
Throttle Position Sensor	0.00 V

ngine Speed (rpm) [Sensor] / 100

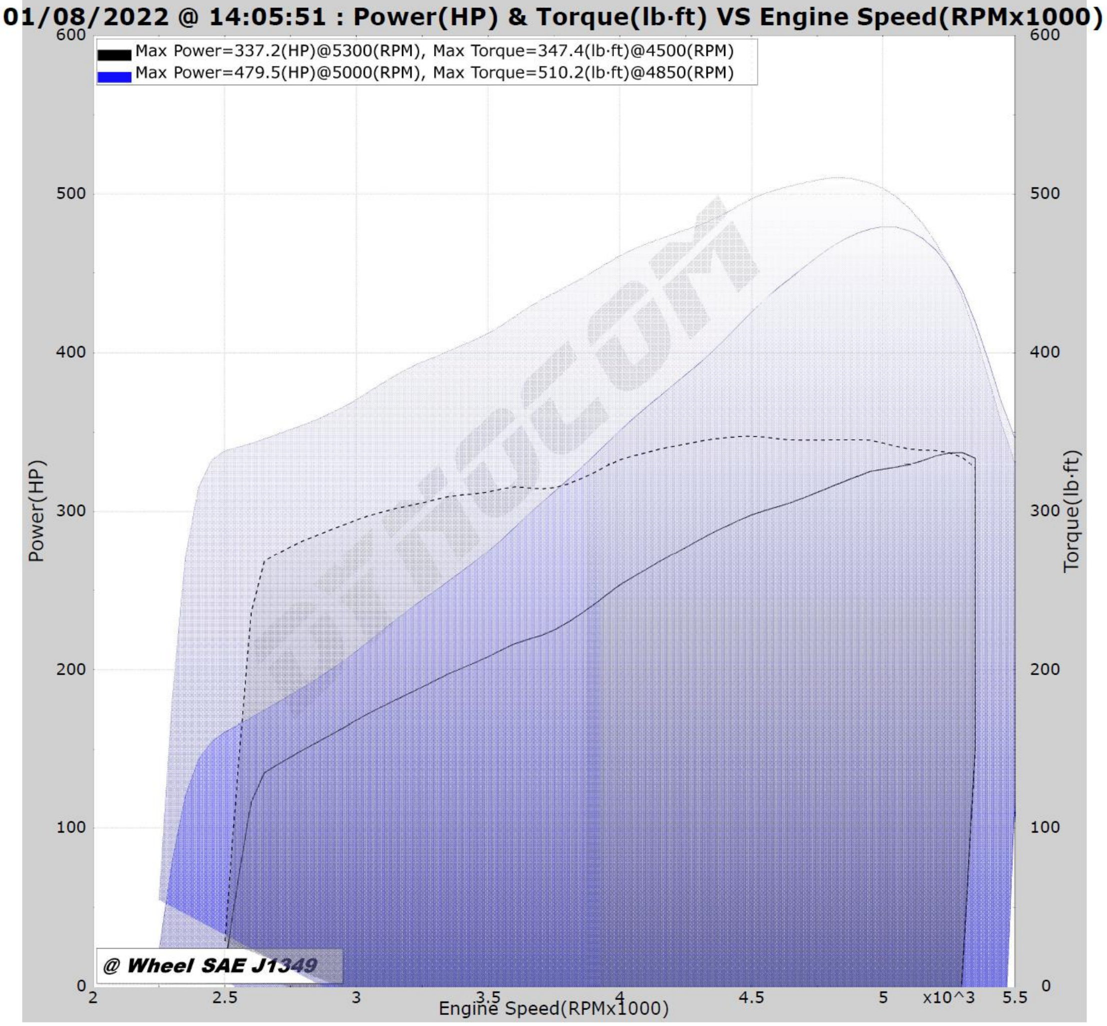
anifold Absolute Pressure (kPa) [Sensor

	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4
30			20	32	25	27				
35		17		37	26	35				
40	17	18		32	30	29	34			
45	17	16	25	33	33	30	37	34		
50	19	24	32	33	35		28	34	34	
55	21	25	31	32	37					34
60	6				38					
65					38					
70					38					
75					39					
80					37					
85					25					
90						25				
95						25	26			
100							26	25	23	
105									21	21

Created: 1/8/2022 6:51:25 PM Duration: 1m 51s Zoom: 2m Time: 06:52:55.338, 00:01:28.687

Figure 3: *Dynamometer Testing Data*

The group encountered numerous setbacks throughout the project, mostly supply chain/shipping issues and a very extended delay for machining work due to the ongoing COVID-19 pandemic and current economy. Other issues of damaged vehicle parts due to the previous owner became apparent after reassembly and added troubleshooting and repair labor that further delayed testing. However, the group was able to successfully gather data on the new engine build with the original LS6 intake manifold and the supercharger restrictor-plate intact. This data is shown below in Figure 4.



Color	Run	Title	Date	Time	Max HP	Eng HP	Avg HP	Gain	Max Torque	Eng Torque	Avg Torque	CF	Description
■	1	Run #1	1/8/22	18:44	337.2 HP	NA	194.1 HP	0.0%	347.4 lb·ft	NA	257.3 lb·ft	0.95	
🟦	2	Run #2	4/23/22	18:47	479.5 HP	NA	301.8 HP	42.2%	510.2 lb·ft	NA	396.6 lb·ft	0.97	

Figure 4: *Dyno Graph of Initial and Final Results*

This overlaid dyno graph shows initial data as Run #1, and final data after modifications as Run #2. The power was increased from 337.2 HP to 479.5 HP, and torque increased from 347.4 ft*lb to 510 ft*lb. This data shows promising results, even with the dyno run only reaching 5,500 RPM, 1,000 RPM less than the limit. The power curve can only improve once the intake manifold is changed, and the restrictor plate is removed to increase boost levels from 8 psi to ~12psi. After those modifications and more time for tuning and testing, the group is confident the engine build will be capable of reaching the goals proposed.

Introduction

The power produced by an internal combustion engine is directly related to the flow of air both into the engine through the intake as well as exiting through the exhaust passageway. Lack of air inside of an engine can lead to poor performance and even damage, which is catastrophic in many cases. By increasing and optimizing the free flow of air through the system, an engine is capable of generating more power while improving both performance and reliability.

The intake and exhaust systems of a car affect how freely air enters and exits an engine, respectively. By modifying these systems to allow for increased flow rates, a combustion engine can generate more power with each stroke (intake, compression, power, and exhaust). The amount of air passing through the engine contributes directly to how much fuel can be burned. However, the increase in flow and power also increases the forces on internal engine components and other parts of the vehicle. This requires supporting modifications to the engine and vehicle to safely and reliably withstand these elevated stresses.

The team developed a set of modifications which would achieve increased power and flow. These modifications are outlined in this report. In addition to just creating a set of modifications and performing the work to implement them, the team also tested which modifications created what power gain. The project team chose specific supporting modifications based on the power output goals, reliability, and cost to implement. These supporting modifications are also outlined in this report.

The team also sought to predict where these power gains came from. Computational fluid dynamics software is a viable option for simulating the flow of fluid and energy in an engine. Originally, the team wanted to simulate the entire intake system to accurately show how each modification increased power. But this task was too daunting to be completed with any amount of precision. So, the team chose to focus on modeling the two intake manifolds tested and measuring the differences between them. A computational fluid dynamics software package called ANSYS Fluent was used by the team to compare the flow qualities of both manifolds. An accurate simulation can predict the real-world interaction of fluid and geometry with ±10% accuracy. The team hoped to show that one manifold performed better than another.

After the group completed the major rebuild of the car, testing on a dynamometer could begin. A dynamometer measures the horsepower and torque developed at the wheels of a car. By running a car on a dynamometer and recording data from the car’s computer, the effects of the modifications that the team made could be quantified and displayed. Dynamometers can accurately represent the power contribution of each modification as well as provide insight into the performance of an engine. The team hoped to show that air was moving better within the engine by measuring the power gained on a dynamometer. These power gains could then be visualized and then compared to the predicted power gains from the ANSYS Fluent simulations.

Background

The 1997 Chevrolet Corvette

The specific vehicle used for this project was a 1997 C5 Chevrolet Corvette. Chevrolet is a General Motors Company (GM) and has been producing the Corvette since 1953. Corvettes are a commonly known “American Muscle” two-door luxury sports car that has come in a variety of different options and trim levels as it has developed over the past 70 years. “C5” refers to the specific generation of the Corvette used for testing through the course of this project. The Corvette model was released in 1953 with the “C1” generation, until the most recent current “C8” generation. Every 5-10 years when a major drivetrain or body style change is made, the generation changes to the next “Cx” number. C1 through C7 generations all had front-engine layouts, whereas the newest C8 generation has a mid-engine layout. This simply refers to where the engine is positioned along the length of the vehicle, affecting the drivetrain layout and weight distribution [1].

Figure 5: *The 1997 C5 Corvette Used for the Project Build*

The specific C5 generation Corvette for this project came from the factory with a 5.7 liter displacement "LS1". "LS" refers to a widespread family of small block V8 engines produced by General Motors (GM) from 1997 to the present. Small block V8 simply means that they are a smaller displacement than the "big block" version, and V8 refers to eight total cylinders in a "V" formation of four cylinders per side.

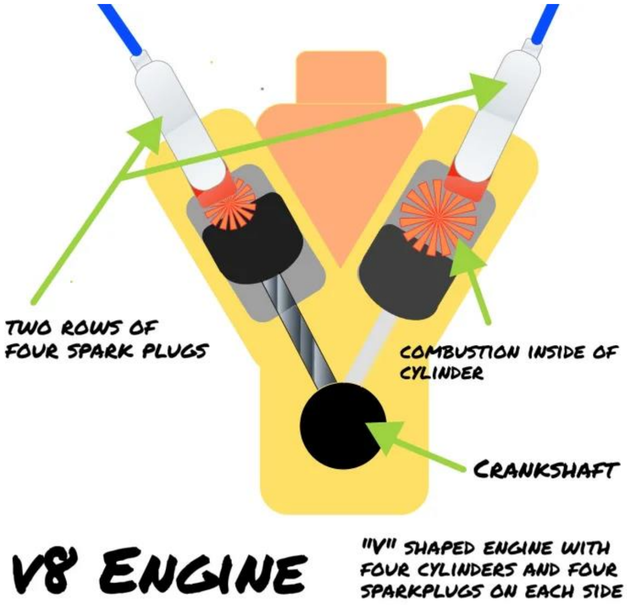


Figure 6: *V8 Engine Layout [2]*

Over the past 2 decades, various design changes and technological improvements have been made to increase power output, efficiency, and to be adapted to fit various vehicle models. When major design changes have been made to the engine, the engine code changes to "LS6", "LS2", "LS3" etc. The LS1 engine model comes from the 3rd generation Chevy small block. These came from the factory in GM vehicles such as 1997-2004 Corvettes, 1998-2002 Camaro, Firebird, Trans-Am, and various others. Additionally, in other vehicles, such as trucks and SUVs, engine blocks such as the LQ4/LQ9, LM4, and L33 were found. These blocks were identical to LS-style blocks, some being aluminum and some being cast iron. As time progressed, the 4th generation blocks were introduced. These were slightly reworked blocks with more features. Similarly, identical blocks could be found in trucks and SUVs.

Basic Internal Combustion Engine Operation

The basic function of a four-stroke combustion engine involves 4 main stages. First, is the intake stroke, which occurs after the opening of the cylinder valves, drawing in a specific mixture of air to fuel into the engine cylinder as the piston moves down the bore. On the second stroke, the piston reverses direction and begins compression. As the piston begins moving upwards, the valves are closed. During these first two strokes, the crankshaft makes one revolution. In the third stage, known as the "power-stroke", the air and fuel mixture ignites, causing a controlled explosion, forcing the piston to move down. Lastly, the piston moves in an upward direction as the exhaust valve opens, expelling the exhaust from the cylinder, thus completing two-full revolutions of the crankshaft [3].

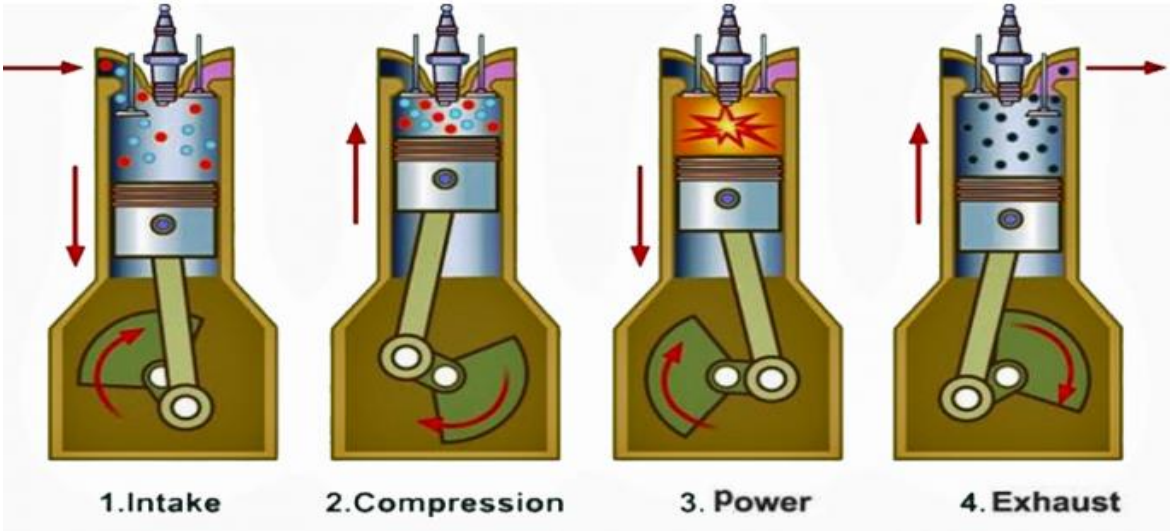


Figure 7: *Four Cycles of an Engine [4]*

The more air flowing into an engine, the more fuel that can be burned as a result. Airflow can be limited for a variety of reasons, including restrictions in both the intake and exhaust passages, as well as the closing and opening of valves to the cylinder. Air entering the engine enters at normal atmospheric pressure in a non-supercharged engine. The ratio of incoming air to fuel in most engines is 14.7:1 pounds per square inch. This ratio can change during wide-open throttle where maximum power can be achieved, where the air pressure may slightly decrease [5].

The Air Intake System

While the majority of power gains in an engine occur from the components listed above, any restrictions to the airflow upstream or downstream of these components will prevent the engine from obtaining maximum airflow and power gains. In many cases, this depends on aftermarket parts that increase the cross-sectional area of fluid passages and reduce restrictions throughout the system, as well as ways to manually increase flow. Technological advancements continue to find new and innovative ways to improve the process as well. When considering air intake, there are many ways to modify components before the air reaches the cylinders to greatly increase flow responsibly.

Air Intake Filter

The first functional component when considering engine airflow is the air intake filter itself. The main responsibility of this part is to filter out dirt and other foreign particles in the air or under the hood of a vehicle to prevent them from entering the engine. There are two main types of filters: an open pod filter and a drop-in filter. Where the open pod sacrifices lower filtration capabilities for better airflow. Modifications to intake passages may be necessary to allow fitment of open pod intakes, making drop-in filters desirable for those looking for a simple replacement [6]. The modifications in the passages may also allow for fewer bends in the piping, lowering the air pressure. Nevertheless, when considering ways to maximize airflow, the open pod is always desirable and can still provide adequate debris filtration. The diagram below elaborates how the two types of intakes vary and affect fluid flow.

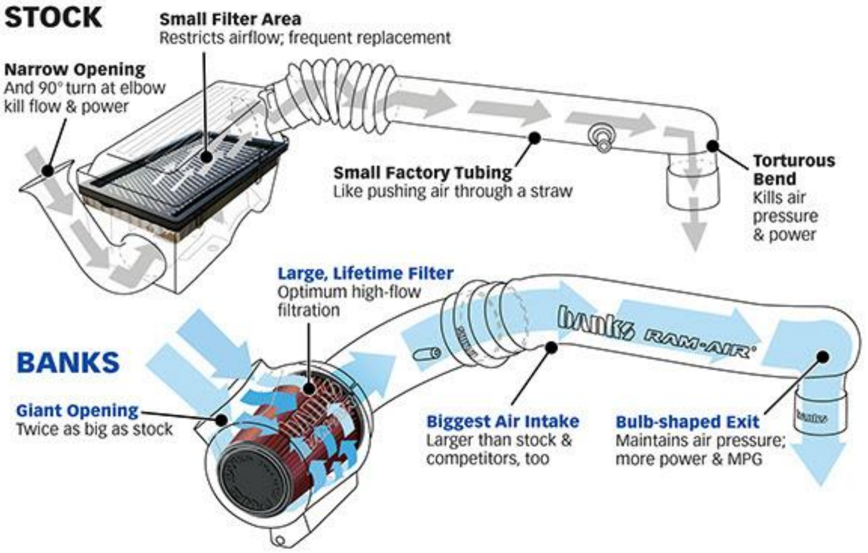


Figure 8: *Comparison of Drop-in vs. Open-Pod Air Intake Filters [7]*

Throttle Body

Following the entrance of air into the intake system, the volume of air then needs to be controlled. This occurs by the throttle adjustment. The throttle pedal, at the driver's right foot, is directly connected either via a physical cable, or a wire to the throttle body. The throttle body houses a plate that opens and closes as the throttle pedal is depressed. The farther the pedal is pushed, the more the throttle plate is opened. At idle, the throttle plate is partially cracked open, allowing some air to flow and keep the engine running at low RPMs [8].

Figure 9: *Throttle Body with Throttle Plate [9]*

Intake Manifold

Next in the intake system is the intake manifold. The intake manifold's purpose is to evenly distribute air to each of the cylinders in the engine. The intake manifold houses individual runners, which feed each cylinder the same volume of air. When the engine is running, only one runner has air flowing through it during each stroke. This is due to air only entering one cylinder at a time, as only one cylinder's intake valves are open. This causes vacuum in that runner as the air is pulled into the cylinder [10].

Figure 10: *LS6 Intake Manifold [11]*

Forced Induction

In forced induction engines, a compressor is used to force air into the engine to increase power. A compressor driven by a belt or gear drive is known as a supercharger, whereas a turbine-driven compressor driven by the exhaust system is known as a turbocharger. Some losses occur when driving these compressors, however, their integration results in significant power gains overall. A properly designed system will allow for higher boost pressures than exhaust pressures, essentially forcing exhaust gasses out while also cooling valves and filling the cylinder with air. Pressure relief mechanisms may be integrated into the system to prevent dangerous buildups of high-pressure air, helping avoid catastrophe within the engine.

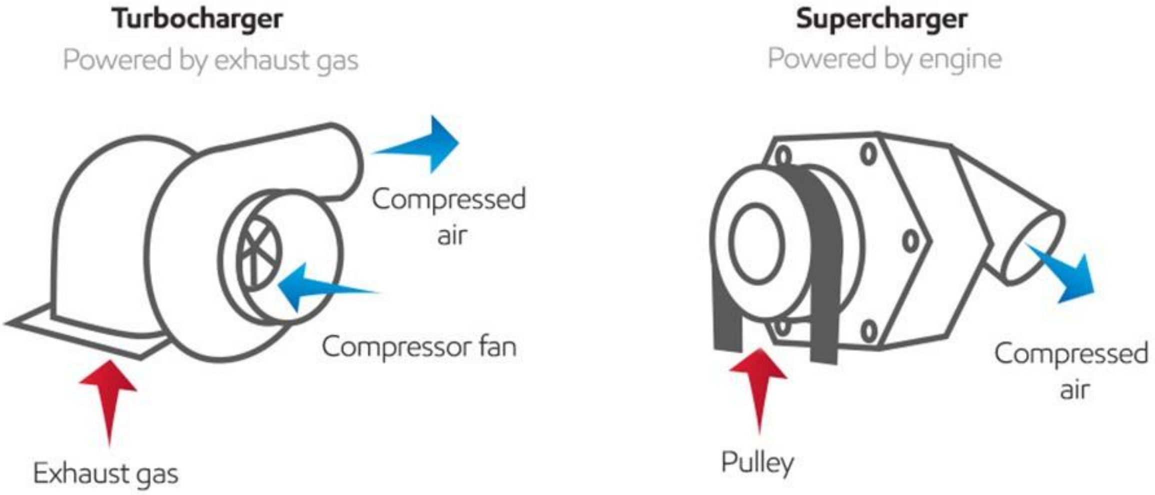


Figure 11: *Diagram Differentiating Turbocharger and Supercharger Function [12]*

Cylinder Heads

Cylinder heads are an integral part of any internal combustion engine, allowing for intake and exhaust gasses to flow into and out of the combustion chamber. The heads also seal the top of the combustion chamber, allowing for pressure to build as the piston travels upwards in the cylinder. Cylinder heads utilize valves controlled by one or more camshafts to control the flow of air in the engine. The number of intake and exhaust valves in the head varies depending on the specific engine, but the intake and exhaust valves are always separate as they have specific passages for air entering (intake) or exiting (exhaust) the combustion chamber. The valves in the heads can be controlled directly by a camshaft in the case of an overhead cam motor, or via a pushrod and rocker system controlled by a camshaft in a pushrod engine. A gasket sits between the mating surfaces of the head and the top of the cylinders on the engine block to create a good seal. Without a tight seal, pressure in the cylinder can escape between the head and block. The heads, gasket, and block all contain coolant passages that allow for coolant to flow through them to maintain optimal operating temperatures. Cylinder heads can be made from cast iron or aluminum, with the latter being more common due to better heat dissipation properties, lower density, and better machinability and weldability [13].

Camshaft

Camshafts are one of the most important parts of an internal combustion engine as they control the valve's opening and closing. When valves open, gasses can enter and exit the combustion chamber. Each cam lobe controls one individual valve. If an engine has 16 valves, there must be 16 cam lobes. At the cam lobe peak, the valve is completely open, and at the opposite end of the cam lobe, the base circle, the valve is completely sealed shut. Camshafts are typically made from either cast iron or billet steel. They are usually driven by a belt or chain, although some applications use gear-driven camshafts as well. Whichever method is used to rotate the camshaft(s), any camshaft found within an engine must rotate at the exact angular velocity of the crankshaft. This accounts for engine timing, as the valve must open and close at the correct moment to allow for optimal combustion at the stoichiometric ratio of air to fuel [14].

Figure 12: *Camshaft for V8 Pushrod Engine [15]*

Pushrod Style Engine

Pushrod style engines have their camshaft located within the engine block, right above the crankshaft. It utilizes pushrods which push on rocker arms to open and close valves. These engines, in V formation, are typically less wide, meaning they can fit in engine bays easier, with more room along the sides. Additionally, the designs are simpler and have been around for centuries. GM’s LS-series engine uses pushrods and is used in almost all larger GM vehicles, so it’s easily accessible.

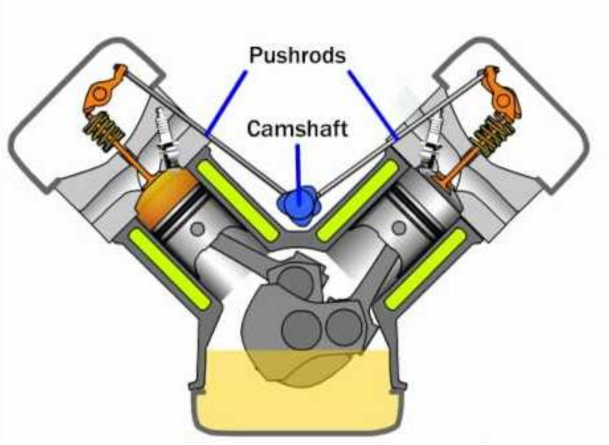


Figure 13: *Diagram Depicting Pushrod Style Orientation [16]*

Overhead Camshaft Style Engine

Overhead camshaft style engines have their camshaft(s) located in the cylinder head as opposed to inside the engine block. The camshaft pushes directly on the valve without the need for pushrods. There are both single overhead camshafts and dual overhead camshafts. Single overhead camshaft engines, similar to pushrod engines, use one camshaft to operate both intake and exhaust valves [17]. Dual overhead camshaft engines utilize an intake camshaft and exhaust camshaft, which operate their respective valves.

Figure 14: *Diagram and Image Depicting Overhead Style Orientation [18]*

Exhaust System

After the combustion occurs within the cylinders, the waste gasses must evacuate the engine. The purpose of the exhaust system is to evacuate these exhaust gasses efficiently by routing them underneath the vehicle (typically to the rear) through hollow metal piping. The exhaust system is also an important aspect of optimizing airflow because the air cannot be taken into the engine until the combustion gasses have left the engine. Other purposes of the exhaust system include housing oxygen sensors, converting some of the toxic pollutants into less harmful gasses, and reducing volume output [19].

Exhaust Manifolds

In a similar fashion to the intake manifold where the air is evenly distributed to each of the cylinders, exhaust gasses are collected from the cylinders and funneled out through a single opening in what is called the exhaust manifold. With that, increasing the size of the passages in the exhaust manifold will allow for increased fluid flow, similar to the intake system in that there are fewer restrictions to the flow [20]. These manifolds are generally cast-iron or stainless steel units as they must be able to handle the high heat of the exhaust gases as they exit the engine, whereas intake manifolds house much colder air and can be composed of plastics.

Catalytic Converters

After air flows through the exhaust manifold the second element of the exhaust system is the catalytic converter. This component is responsible for making toxic pollutants less toxic through catalyzing a redox reaction and converting them to less harmful pollutants such as carbon dioxide or water vapor. These parts can be very valuable as oftentimes precious metals are used as the catalyst and coat the inner-honeycomb structure of the converter. Airflow can be optimized through this part by simply integrating a high-flow performance catalytic converter into the exhaust system, which would possess a looser honeycomb structure allowing for less restricted flow.

Rear Piping

The final components of the exhaust include piping that runs from the catalytic converter to the rear end of the vehicle where the exhaust gases fully exit the system. Throughout this piping, there may be numerous silencing pieces known as mufflers and resonators to help control the noise output coming from inside the engine. These silencers are finely tuned to reflect sound waves produced from within the engine to cancel out the sound. The issue that may arise with these components when considering airflow is they may pose some restrictions to this flow. Once again, integrating high-flow components can help to reduce this issue or eliminate them completely, however in many states that option will not comply with emissions rules and regulations. However, the best flow will be achieved with solely exhaust piping from the catalytic converter back to the exit of the exhaust gases. A diagram of a typical exhaust system with many of the components mentioned in this section compared to a racing-style system where airflow is optimized can be found below.

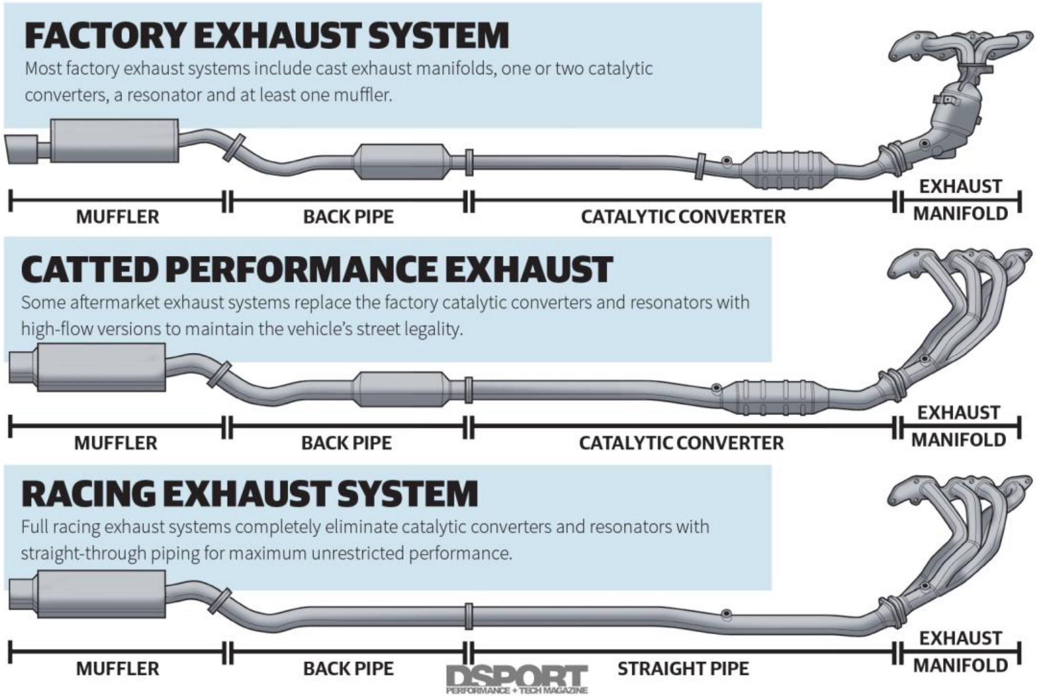


Figure 15: *Comparison of Factory vs. Performance and Racing-Style Exhaust Systems [21]*

Vehicle Drivetrain

Clutch

A clutch is a component found in vehicles with manual transmissions. With a manual transmission, the driver is responsible for changing the gear the vehicle drives in. This would not be possible without a clutch, which allows for the transmission of power through contact with the flywheel, while also enabling the driver to change gears and get the vehicle rolling from a stop. A manual transmission vehicle has three pedals rather than two, with the extra pedal controlling the engagement and disengagement of the clutch. When the pedal is depressed, the clutch disengages from the flywheel and releases the bond between the engine and transmission. The driver selects a new gear and then releases the clutch pedal to reunite the engine and transmission. A clutch assembly utilizes a throw-out bearing that slides along the input shaft of the transmission to engage and disengage the clutch disc from the flywheel upon user input [22]. A pressure plate surrounds the clutch disc to keep the flywheel and clutch mated together without slippage. Pressure plates typically utilize a diaphragm-type spring system to maintain clutch pressure on the flywheel, although coil springs can be used in some applications. The clutch disc is a thin steel plate covered in a frictional material that allows for the clutch to grab the flywheel as the pedal is let out [23]. Upgraded clutch assemblies may use different frictional materials, heavier springs, multiple clutch discs, or different disc designs to withstand higher engine power levels as well as different driving applications. Figure 16 shows the different components inside the clutch assembly.

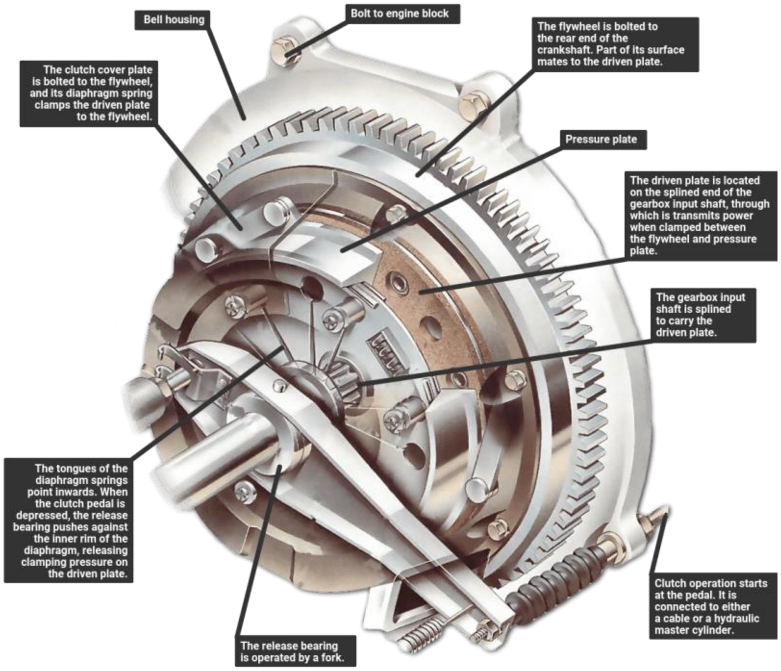


Figure 16: *Clutch Assembly Components [24]*

Torque Tube

Torque tubes are typically reserved for use in higher performance vehicles and are most commonly found in front-engine vehicles with rear-wheel drive [25]. Traditional rear-wheel-drive cars utilize a Hotchkiss style driveshaft with a U-joint at each end connecting the back of the transmission to the rear differential input. With performance cars such as the C5 Corvette, the engine is located at the front of the car and the transmission at the back for better weight distribution over the chassis. Connecting the two is a torque tube: a rigid driveshaft surrounded by a hollow tube. A torque tube is suitable for this application because the shaft connecting the engine and transmission is subjected to much higher angular velocities than a traditional driveshaft. This is because the shaft turns at engine speed rather than transmission output speed. Traditional driveshafts also suffer from torsional losses in the rear suspension components when the car accelerates. Using a torque tube design isolates the drivetrain from the rear suspension components, and causes the motor mounts to absorb these torsional loads instead. As a result, the torque tube aids power transmission between the engine and wheels and at the same time keeps the car moving straight under hard acceleration. The use of a torque tube design also allows for the rear suspension to be softer for better ride quality, as it is not responsible for absorbing torsional forces from the drivetrain. Figure 17 shows a torque tube in a 2017 Mercedes AMG GT R attached to the engine (lower right) and the transmission (upper left) of the drivetrain.

Figure 17: *Torque Tube Connecting Engine and Rear Transaxle [26]*

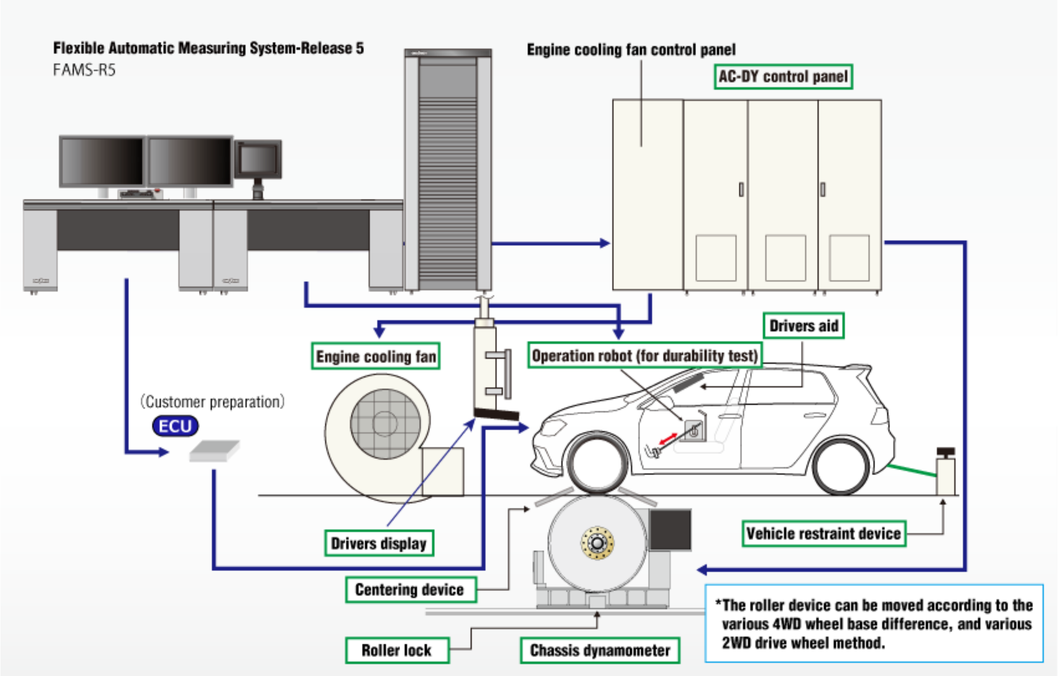
Dynamometers

A dynamometer, or dyno, is a measurement device used for calculating the moment of a force; or torque, as well as power outputs [27]. There are numerous applications for dynamometers, however, when being used in an automotive application, the power generated by an engine can be calculated using the torque and rotational speed of the engine. To derive power from the measured torque, the rotational speed in RPM of the engine is multiplied by the torque output in ft-lbs and divided by 5,252. The 5,252 constant is a result of the dimensional analysis converting between ft-lbs-RPM and hp which has more fundamental units of ft-lbf/s. Figure 18 shows the equation used to determine engine horsepower. Dynamometers can be used to get power measurements and sensor readings from the car, but they are more commonly used to aid engine tuning for peak performance, economy, or driveability.

$$Power\ [hp] = (Torque\ [ft - lb] \times Speed\ [RPM])/5252$$

Figure 18: *Horsepower Equation*

To test a vehicle using a chassis dynamometer, the vehicle is strapped down to designated anchoring points with the drive wheels of the vehicle on top of large rollers. The user accelerates to a certain engine speed with the drive wheels turning the rollers. Data is recorded during the entire run. Following the run, the data acquired from the dynamometer can be processed and analyzed on the commander. Figure 19 shows how the components of a chassis dyno work together to record data. Figure 20 shows a Corvette like the one the team used on a dyno.



*The roller device can be moved according to the various 4WD wheel base difference, and various 2WD drive wheel method.

Figure 19: *Diagram of Chassis Dynamometer [28]*

Figure 20: *A Corvette Strapped Down on a Dynamometer [29]*

The key feature of a dyno is that it can simulate normal street driving by providing resistance. Without this load provided by the dyno, the engine and drivetrain would not have any resistance while accelerating. The load simulates the forces an engine has to overcome while driving on the street including the force needed to propel a several thousand-pound object, the force of friction within the engine, drivetrain losses, losses due to the tires contacting the road, and air resistance that increases with speed. A dynamometer is capable of simulating larger loads than an engine would typically endure while driving on the street. A dyno can load down an engine more at a far lower engine speed, as its acceleration is not limited by spinning the tires, clutch slippage, or stalling a torque converter as it might while driving on the street. Much of the data was collected with a dynamometer; torque and horsepower output were the most important units of measurement gathered from the dyno, however, all engine parameters were measured.

The data is recorded by the dyno through a data acquisition system consisting of both a commander and workstation component. The commander is a computer that sends commands to the workstation. Throttle inputs are determined by the operator or user. The data is then collected and sent back to the commander where it can be processed, analyzed in the form of graphs or charts, and stored for future use. By providing the user with a graph of horsepower and torque output in addition to the instantaneous air/fuel ratio, intake air temperatures, and many other sensor readings, the user can adjust the tune in the ECU to achieve the desired goal. A dyno allows the user to visualize the parameters and outputs as well as test the car through the engine's rpm range to simulate driving on the street.

There are four different kinds of tests that a dyno can perform. Not all types of dynos can perform all kinds of tests. Acceleration tests involve accelerating the vehicle (typically at wide-open-throttle) to determine maximum torque and power output throughout the range of safe engine speeds. Step tests consist of holding the engine speed steady for a predetermined length of time, and slowly stepping up the engine speed. This type of test holds the engine speed constant in order to gather torque readings that are not influenced by inertia or the dynamometer. Sweep tests involve the dyno placing a resistive load on the rollers to limit the acceleration rate to a predetermined rate, such as 100 RPM per second. This helps to simulate real-world driving with steady acceleration. Finally, steady-state tests allow the user to make precise fuel and timing adjustments while varying throttle (in turn varying the engine load) while the dyno holds the engine speed constant [30].

Types of Dynamometers

Four types of dynos are typically used in the automotive industry. The most common type of dyno is the inertia dyno. Following this is the water-brake dyno which is the next most common dyno used. The next most common is the eddy brake dyno, which is more expensive but does have some advantages over the water-brake variety. Finally, the last type is an alternating current (AC) dyno. AC dynos are more expensive than the other types so they are reserved more for high-end programs such as Formula 1 racing teams.

Inertia Dynamometer

Inertia dynamometers are the most common type of dyno that are used, especially in an aftermarket setting. These dynamometers work by putting the vehicle’s driven wheels onto large, heavy rollers and accelerating at wide-open throttle. The dyno only measures the rate of change of acceleration, hence the name “inertia” dyno. The dyno software calculates the power based on the roller velocity and the time needed to achieve a certain rate of acceleration. These values are found using sophisticated accelerometers and computer software. Inertia dynos operate based on Newton’s Second Law, where the rate of acceleration is directly proportional to the power placed on the heavy rollers by the tires. Dynojet is a popular brand of dynamometers and is the most common pure inertia dyno used in the automotive industry.

Inertia dynos are objectively more simple than other types of dynos, however, there are some disadvantages to this design. First, these dynos cannot adjust the resistance of the rollers to accurately reflect the weight of the specific car on the rollers. Second, inertia dynos may not allow turbocharged engines to build boost as they normally would driving on the street. This is a big disadvantage when tuning turbocharged engines since they require the utmost precision with regards to fuel and timing in order to prevent engine failure. Finally, one of the most notable drawbacks of an inertia dyno is the limitations of tuning. Inertia dynos are used for wide-open throttle acceleration and cannot do load or step tests. With this limitation, it is harder to tune the engine under different loading conditions, such as street driving or holding a constant speed on the highway. Only being able to get results under wide-open throttle applications makes it difficult to optimize the timing and fuel curves of the engine for efficiency, power, and driveability.

Water-Brake Dynamometer

Water-brake dynos, or hydraulic dynos, differ from inertia dynos in that they use hydraulic fluid or water to provide the braking force on the dyno to more accurately load the engine in various scenarios. These dynos utilize a constant speed brake as well as a rotor. The rotor is coupled to the rollers that are being spun by the wheels. These store energy and provide an initial inertial mass that the engine must overcome. In addition to the initial force needed to overcome the roller inertia, the dyno software calculates the additional load needed at any point in time. The rotor generates the braking force needed to load the engine with hydraulic fluid or water. The braking force generated by the rotor aims to match the output of the powertrain on the dyno. To measure the torque, the dynamometer utilizes a strain gauge to determine the torque reaction between the rotor’s stationary and rotating elements. From this reading, an engine’s horsepower can be calculated by the dyno. Although hydraulic dynos are capable of simulating various driving or racing conditions, there are still limitations to the machine. The most notable drawback with a water-brake dyno is the delay between stepping on the throttle and the time needed for the impeller cavity to fill up with fluid. This causes a slight inaccuracy when snapping the throttle wide open until the mechanism and fluid stabilize.

Dynapack is a specific brand of hydraulic dyno that aims to eliminate some of these issues. The most notable difference between these dynos and other dynos is the lack of rollers. Rather than putting the drive wheels onto rollers for acceleration tests, Dynapack dynos bolt directly to the wheel hubs on the car. Figure 21 shows how a Dynapack dyno system attaches to a car. This eliminates the need for heavy rollers, a large dyno, and eliminates rolling resistance due to friction between the wheels and the rollers. When dealing with high-powered vehicles, sometimes the tires will slip on the rollers. By bolting to the wheel hubs, Dynapack dynos eliminate traction issues. Traction limits can skew data as the engine speed will rise more quickly when the tires slip. This also means that the rollers will not measure acceleration properly. Another issue that Dynapack seeks to address is the time it takes for the fluid to fill up the impeller cavity. They do this with an optional "start-point stabilize" feature, which holds the engine at a steady speed at the beginning of the test to stabilize the engine before releasing the resisting force and allowing the vehicle to accelerate [31]. Dynapack does not use a strain gauge to measure and calculate power; rather, they measure the hydraulic fluid power required to hold the engine at a constant speed. These dynos are also capable of controlling the rate of acceleration, specified by the user, which can be beneficial to tuners as it allows them to better isolate and optimize certain areas of the RPM range.

***Figure 21:** Dynapack Dynamometer [31]*

Eddy Current Dynamometer

An eddy current dyno (sometimes referred to as an eddy brake dyno) uses eddy currents to provide the necessary loading for the dyno as well as to measure dyno readings. An eddy current is a current induced in a conductor by a moving magnetic field. The magnitude of the eddy current depends on the conductor geometry, speed of the moving magnetic field, and strength of the magnetic field. These types of dynos have smaller energy losses, higher efficiency, and are more versatile than traditional mechanical dynamometers. The smaller losses are due to the absence of any physical contact between windings and excitations inside the eddy brake. The friction in these dynos is almost negligible compared to traditional dynos. Eddy current dynos are more precise than other dynos as they can hold an engine steady within 1-2 RPM, whereas hydraulic dynos have a range closer to 5-10 RPM. Another feature of eddy current dynamometers is that they can perform several different kinds of tests including acceleration, step, sweep, and steady-state tests [32].

AC Dynamometers

The least common type of dynamometer is an AC dyno. This is due to the complexity of the machine along with the cost. These dynos use a large AC motor to absorb the power generated by the engine at the flywheel. The AC dyno can perform a variety of functions, including holding a constant speed or torque, absorbing the engine power, and powering the engine. It can also be rotated either clockwise or counterclockwise. With such a versatile machine, AC dynos can simulate many driving conditions including coasting, shifting up or down, or even an entire race [34]. However, these machines are very expensive and are typically only used by professional racing programs like Formula 1. Additionally, these dynos are not commonly found in an automotive aftermarket setting since they measure power at the flywheel rather than a chassis dyno that measures power at the wheels. Figure 22 shows how an AC dyno connects to an engine to measure its power directly.

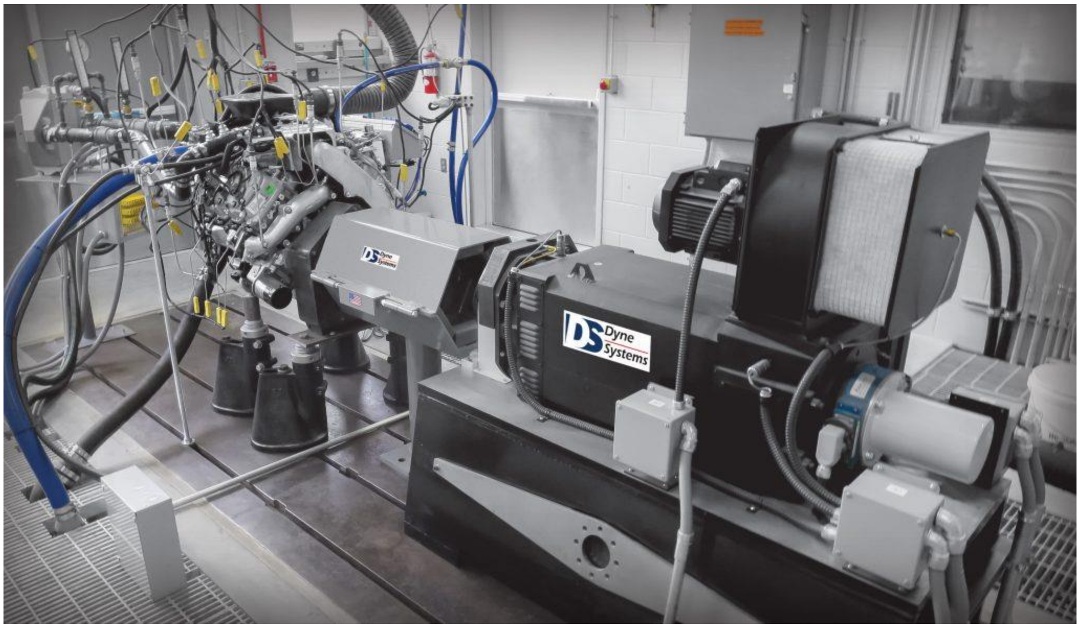


Figure 22: *AC Dynamometer [34]*

Simulation Software

Since the primary goal of this project was to find which upgrade has the greatest effect on power development, the team thought that it might be interesting to try to predict where the gains come from. Doing so is no easy task. Even with some approximations, the thermodynamic conditions surrounding an engine are complicated. The environment of the engine and the load it experiences are the two top-level variables that a model must simulate. Then the model must utilize material properties, component geometries, and turbulence characteristics that are all specific to the scenario. The complicated thermodynamic situation surrounding the engine cannot be easily resolved by hand to determine which upgrades will impact performance the most.

The Theory Behind Computational Fluid Dynamics

Currently, the best way to model fluid flow is with computational fluid dynamics (CFD) software. CFD software models the complex thermofluid situation inside or around a particular geometry [35]. All CFD software packages try to solve the partial differential equations known as the Navier-Stokes equations shown in their most general form in Figure 23. These equations model the conservation of mass, momentum, and energy of a control volume. A control volume is an infinitesimal volume that compliments the partial differential equations. The total volume of fluid being analyzed using the Navier-Stokes equations contains an infinite number of control volumes, thus making the domain of the analysis continuous.

$$
\begin{aligned}
\rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) &= \rho \frac{du}{dt} \\
\rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) &= \rho \frac{dv}{dt} \\
\rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) &= \rho \frac{dw}{dt}
\end{aligned}
$$

Figure 23: *The Most General Form of the Navier-Stokes Equations [36]*

In theory, this is an elegant way of conceptualizing the situation, but CFD software cannot analyze an infinite number of control volumes. So, a researcher applies a mesh to the geometry to discretize the domain [37]. The mesh creates small cells (discrete control volumes) that the solver uses to balance the Navier-Stokes equations based on the boundary and initial conditions. The accuracy of the solution is highly dependent on the quality of the mesh. A larger number of cells will yield more accurate results but increase the time it takes for the solver to converge to a solution. The shapes of the cells also impact the accuracy of the solution [37]. A good cell is regular in size and shape and is not stretched or thin. Complex fluid volume geometries can cause cells to become irregular and warped. CFD software usually includes a meshing tool to create a mesh with many parameters that can be tweaked to improve the mesh geometry.

CFD Modeling Conditions

Many theories have been developed to model fluid flow in all types of temperature, pressure, and velocity regimes. CFD software packages include ways to change the model type to fit the regime that is being tested. For this project, the team was primarily interested in the fluid flow interaction inside of a part. There is only one phase and one type of fluid, the flow is turbulent, and the material properties of the fluid are not constant. These are all parameters that CFD software packages have control over. For this model, the most interesting of the parameters is the viscous model type. The viscous model of the fluid determines how the solver handles turbulence. Turbulence is the small-scale change of the velocity of a fluid that is agitated, fluctuating, and seemingly random [38]. Whether a fluid is turbulent or laminar is related to the Reynolds number of a fluid [39]. The Reynolds number, a dimensionless quantity, is dependent on material properties (themselves a function of temperature and pressure), flow velocity, and geometry. The formula for calculating the Reynolds number is shown in Figure 24. Researchers have developed numerous turbulence models to fit a variety of operating and mesh conditions. Thus, the solver can tailor the model to the flow conditions inside these parts.

$$\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{V L}{\nu}$$

Figure 24: *Reynolds Number Formula*

CFD Modeling Benefits and Drawbacks

CFD modeling is an important way to conduct tests on parts in research or industry. Having a way to accurately model fluid flow in or over a part means that researchers or engineers do not have to create prototypes and expensive testing apparati [35]. Prototypes and test setups are expensive to create and are rigid in their purpose. If the prototype was made incorrectly or needed to be changed, then a new prototype would need to be made. Testing apparati may also need to be changed if a new prototype were developed. These processes take time and depending on the application this could be weeks or months of waiting. CFD has the distinct advantage of being quickly adaptable to new situations and parameters. The researcher or engineer only has to rerun the CFD model with the new conditions to produce a new test result.

Modeling this way implies, though, that the underlying relationships accurately portray the world in simulation [40]. This assumption is not valid. Much of what scientists and engineers know about thermodynamics and fluid flow is based on ideal theories and empirical relationships. These are usually bound within some range of temperature, flow type, flow material, pressure, etc. Nature ignores these boundaries and can transition a fluid between different models depending on the conditions. However, this flaw in CFD modeling should not detract from its value. CFD is useful for quick and varied models, especially in the initial stages of testing. CFD can be used to show scientists and engineers where to focus their efforts and which designs to eliminate without having to manufacture the prototypes and create the testing apparati.

Objectives

The team's primary objective was to reliably and safely increase the horsepower and torque of the vehicle as a direct result of increased airflow. With the engine's increased power output, it was important to increase power properly and avoid damaging the engine. Throughout the process, other ambitions of the team were established as additional goals to achieve. As modifications were introduced, the team hoped to measure how instrumental each change was towards increasing engine power, as well as find which modifications provided the largest and smallest power gains.

The group also discovered that instead of using the LS6 intake manifold, the Trailblazer SS manifold would also be an option for use. The latter of the two options had the possibility of producing a more favorable torque curve, so the group planned to test both and find which manifold would be the most desirable.

Lastly, the group wanted to conduct final performance testing of the vehicle on the dynamometer to accurately analyze results from before and after each modification. The power gain would correspond directly with the increased airflow, and while the group was able to make estimates and predictions on power, numerous variables could change the final power figures significantly.

Methodology

Engine and Internal Components

The group spent extensive time discussing project goals and what modifications were necessary to achieve them. Aside from simply increasing airflow to increase the power output, many other modifications were necessary to ensure the engine was able to withstand the increased forces caused by the increased power. These are commonly known in the automotive world as “supporting modifications” which allow the engine to not only make more power but to make that power reliably without failure. High-performance parts are more expensive due to various materials, processing, and engineering improvements, as will be discussed in detail for each component. As the group was working on a budget and spending a considerable amount of money out of pocket, the build components had to be selected carefully and strategically. The group had to analyze each component to balance both cost savings and reliability. Part failure was not an option, as the majority of these components would cause “catastrophic failure” to the engine. This means the engine would be unable to operate and further irreversible damage to many of the other components would result in thousands of dollars lost.

After extensive planning, parts purchasing, and initial testing on the stock engine to establish baseline power numbers, work began on the new engine build. In addition to assembling the components throughout the engine overhaul, machine work and balancing were necessary and were performed by ABT Machine Company in Holliston, MA.

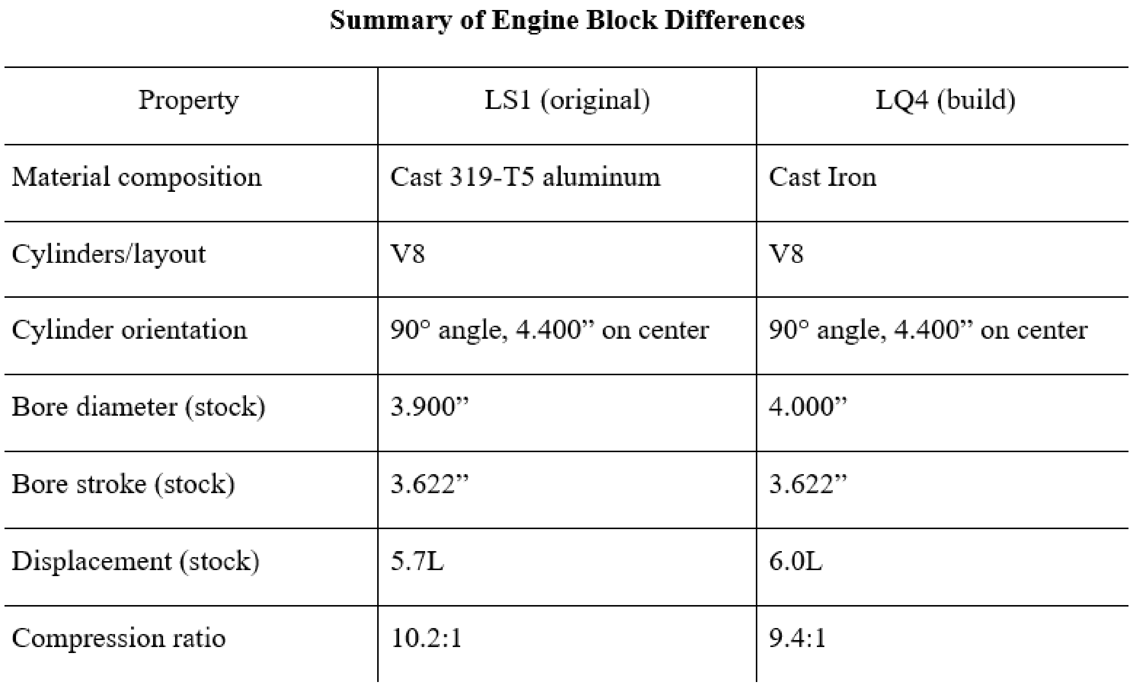
Engine Block

The LS1 engine block is made from cast 319-T5 aluminum and has eight cylinders at a 90° cylinder angle, and 5.7 liters of displacement with a compression ratio of 10.2:1. The 3.90” diameter bores are spaced 4.400” on the center with a stroke of 3.62”. [41]

The engine block that is being used for the project build is called an LQ4 engine block, sometimes also referred to as a Vortec 6000. LQ engines are also small-block V8s produced by

GM, however, these were used in GM trucks such as the Silverado, Suburban, Yukon, Sierra, and various others from 1999 to 2007.

The LQ4 engine block is made from cast iron, which is denser, stronger, and can handle higher temperatures than the stock LS1 cast aluminum block. Although the density of iron does mean this block is about 75-100 lbs heavier than the original block, its increased strength is necessary to reliably withstand the elevated forces and stress due to the increase of horsepower without risk of catastrophic damage. Since the LQ4 engine also has eight cylinders at a 90° angle and are spaced 4.400” on the center, it is compatible with many factory LS engine components and is a good candidate for building. The LQ4 engine has the same stroke length at 3.622”, but has larger pistons at 4.000” in diameter for a total displacement of 6.0 liters. [42] This 0.3 liters increase in displacement allows for more air and fuel to be drawn into the combustion chamber, leading to an increase in power output by the engine.



Summary of Engine Block Differences

Property	LS1 (original)	LQ4 (build)
Material composition	Cast 319-T5 aluminum	Cast Iron
Cylinders/layout	V8	V8
Cylinder orientation	90° angle, 4.400” on center	90° angle, 4.400” on center
Bore diameter (stock)	3.900”	4.000”
Bore stroke (stock)	3.622”	3.622”
Displacement (stock)	5.7L	6.0L
Compression ratio	10.2:1	9.4:1

Table 1: *Engine Block Comparisons*

Block Machining

After sourcing the LQ4 engine block, it was sent to ABT Machine Company to be prepared for assembly. This included thermal cleaning, magnafluxing, honing the cylinder bores to 4.0055” diameter, and decking the cylinder head mating surfaces to 9.225”. This work essentially prepares all the surfaces and features of a 20-year-old used engine to proper finish and size tolerances to be used in operation for the group’s build goals.

Figure 25: *Machined LQ4 Engine Block*

Crankshaft

The stock crankshaft in both the LS1 and the LQ4 engines are both nodular cast iron and capable of withstanding the forces of 900 wheel horsepower. [43] Aftermarket options such as forged 4340 steel crankshafts do exist to withstand even higher power, but are unnecessary and not cost-effective for the build goals. Therefore, the stock LQ4 crankshaft was reused after being cleaned and magnafluxed by ABT.

Figure 26: *Stock LS1 Crankshaft*

Main Caps and Bearings

The crankshaft is secured into place in the block by the main caps, or “mains” as they are commonly referred to. Main bearings are inserted into the block and the main caps, which clamp around the main journals of the crankshaft to secure it when the mains are tightened down. The stock LQ4 mains are made of ductile steel and capable of 1,000 hp, so upgrading to billet steel mains is unnecessary for the build intentions. The LQ4 engine has five “6 bolt mains". This means there are five total main caps, one on each end of the block and then one between every pair of cylinders, and each main is secured by six bolts. [42]

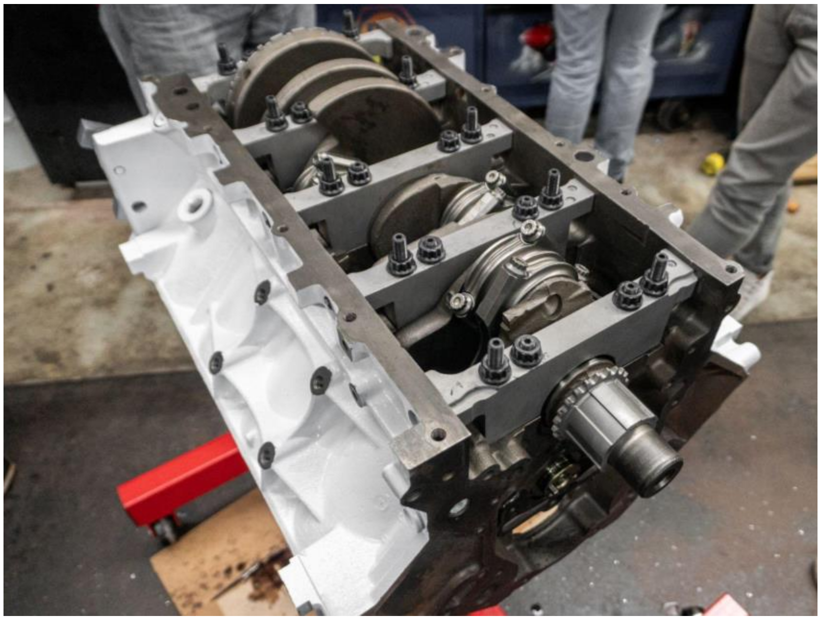


Figure 27: *Main Caps Assembled to Secure Crankshaft*

Main Bolts

Each main has four traditional bolts securing it from the top down, and then two additional bolts, one from each side. These main bolts were upgraded to ARP M10 main studs to better secure the main caps and prevent any unwanted movement from the crank under high power/RPM. Studs work in the same way as bolts, however, instead of having a head that is turned by force to rotate the entire bolt into the threaded hole, they are threaded in freely and then a nut is threaded on and tightened. Since the studs do not turn during the tightening, (only the nut is turning onto the stud) the stud is being torqued from a relaxed state. This means that the stud is only experiencing tensile stress and stretching in its longitudinal axis, rather than a bolt which is also subject to torsional stresses and under the twisting load. The result is a more reliable and consistent securing force due to a more equally distributed load and a more accurate torque value [44]. Additionally, ARP stands for “Automotive Racing Products” and is a company that specializes only in fastening hardware for automotive use. ARP uses their specially developed and patented 8740 chromoly steel alloy for these studs which has superior mechanical properties compared to the stock grade 8 bolts [45]. The main bearings allow the necessary free rotation of the crankshaft while still providing adequate support to keep the crankshaft in position. The stock main bearings are more than sufficient for the build intentions.

Figure 28: *ARP Main Stud, Nut, and Bolt*

Connecting Rod Assembly

The connecting rods, or “rods” are clamped around the crankpin journals on the crankshaft at the “big end” by two rod bolts, and attached to the pistons at the “small end” via the wrist pin. As discussed earlier, each combustion within a cylinder chamber is an explosion which forces the piston towards the center of the engine during the “power stroke”. The rods are responsible for connecting the piston to the crankshaft to transfer that linear motion in the cylinder to rotate the crankshaft. This means that as the power of the engine is increased, they must withstand higher and higher forces at elevated temperatures without deformation.

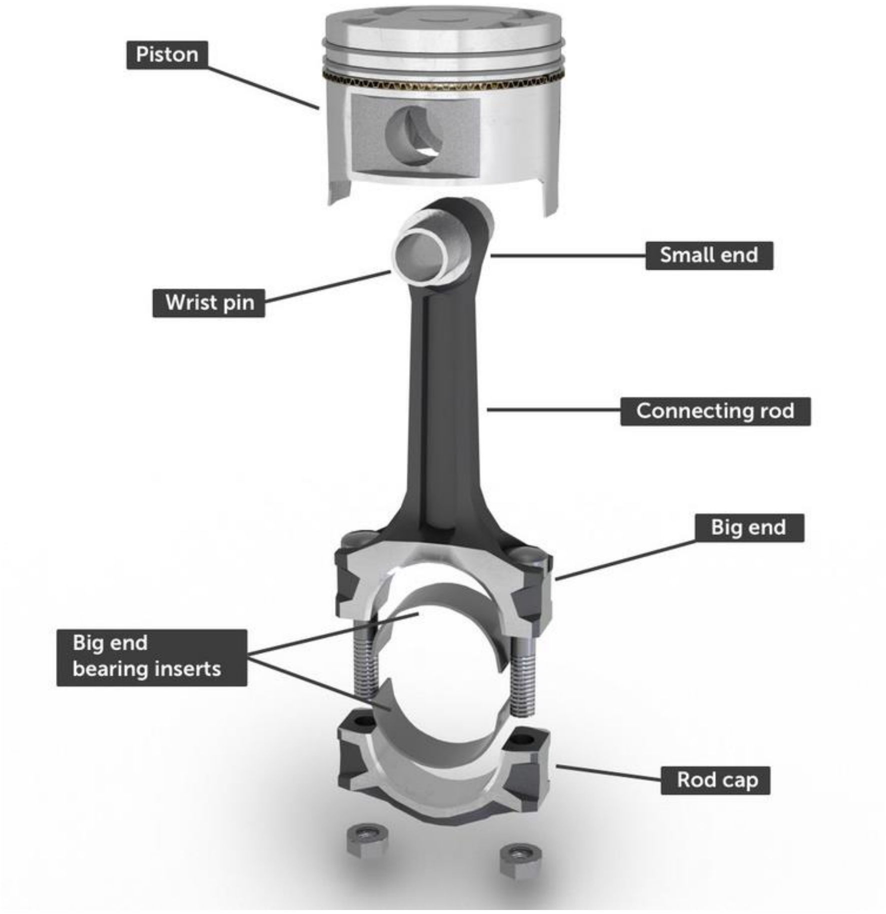


Figure 29: *Labeled Diagram of Connecting Rod Assembly (Piston Shown for Reference) [46]*

Connecting Rods

Both the LS1 and LQ4 engines use the same powdered metallurgy “I-beam” design connecting rods. Powder metallurgy is the process used to manufacture the shape, dimensions, etc. of the rods from their raw material. Specifically, this includes taking the powdered metal particles and any additives, compacting them to the desired shape, and applying heat or pressure (sintering) to create a solid part without heating it above the melting point. Secondary machining and finishing processes are often done for critical features that interface with other parts [47]. The “I-beam” design refers to the linear cross-sectional shape of the connecting rod, similar to a steel “I-beam” used in building construction.

Figure 30: *Diagram of Different Rod Designs [48]*

Due to power output goals when optimizing the airflow, it was necessary to upgrade the stock connecting rods to aftermarket ones to withstand the much higher forces and stresses. There are extensive aftermarket options for rods, and after research for an adequate balance between price and performance, the team decided to use Eagle Specialty Products H-Beam Connecting Rods. These are an H-beam design of forged 4340 steel with an advertised rating of up to 1,300 hp and 7,500 RPM, compared to the stock rods and bolts of about 500 hp and 6,500 RPM [49]. This substantial increase in capacity is due to the improvements in connecting rod material, design geometry, and rod bolt material.

Figure 31: *Eagle Specialty Products H-Beam Connecting Rods*

In addition to using a specialty high carbon steel with superior material properties, with the forging manufacturing process the grain flow of the material is able to be controlled to flow with the part shape, in this case, the connecting rod. This results in a more uniform and predictable grain structure to increase the directional strength, as well as reduce internal voids and offer a better response to heat treatment [50]. “After forging, the Eagle H Beams are multi-stage heat-treated, X-rayed, sonic-tested, magnafluxed, 100% machined, and shot-peened to stress-relieve the material” [49]. Through the forging, secondary processes, and elevated quality control by Eagle, these rods gain substantial mechanical properties for their application in an engine under higher horsepower.

The Eagle H-beams have an H-beam design rather than the stock I-beam design from GM. I-beam design connecting rods can perform better under compression forces, so they are a good choice when running very high amounts of boost, which greatly increases compression forces. However, the built engine will not be subject to very high amounts of boost (only ~12psi), and the H-beam design can save weight compared to the stock rods while still handling the power. Each of these Eagle H-beams is 620 grams compared to the stock rods at 650 grams, saving 30 grams per rod for a total of 240 grams. Since these rods are part of a rotating mass, weight savings become very significant to reduce the force needed to rotate the crank and produce power. Additionally, reducing weight in the rod and piston reduces the tensile forces the rod is subjected to. Finally, they are not tapered, which improves support at the wrist pin end.

Rod Bolts

These Eagle H-Beams also come standard with ARP 2000 rod bolts, used where each rod is clamped around the crank pin journal by the two rod bolts. These rod bolts are made from their specialty ARP 2000 alloy, which as discussed previously is far superior to the stock rod bolts and is rated up to 230,000 psi and helps withstand higher RPM.

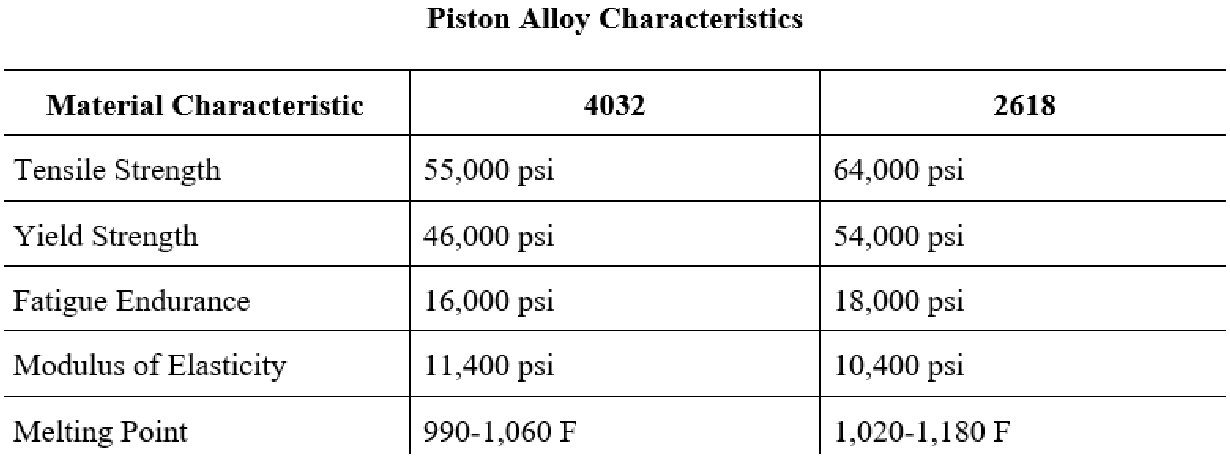
Figure 32: *ARP 2000 Rod Bolts (Mock Installation Without Crankshaft for Reference)*

Pistons

Pistons are especially crucial to an internal combustion engine build for many reasons. First, they are the closest component withstanding the elevated temperatures. They also must withstand any forces due to the combustion of fuel in the cylinder chamber and the pressure from combustion gasses. As previously discussed, increasing fuel and airflow contributes to increasing combustion forces, so the pistons in the build must be able to withstand this. The stock LQ4 engine comes with “dished” pistons made from M124 hypereutectic cast aluminum alloy [42]. Dished (as opposed to flat top) refers to a style of pistons where there is a “dished” indentation in the top face (combustion side) of the piston that allows for valve clearance. The dish also reduces the compression ratio, since it adds volume to the compression chamber compared to a flat top [51]. These pistons would not reliably withstand the forces of a boosted application, so they were upgraded to Summit Racing Pro LS Forged Pistons.

Figure 33: *Summit Racing Pro LS Forged Pistons*

These upgraded pistons are forged from premium 2618 aluminum alloy. The M124 alloy used in the stock pistons is a proprietary metal made by Mahle and composition/specifications are not available to the public. However, for comparison, 4032 is the other widely used alloy for forged piston applications (stronger than cast M124 alloy). The 2618 alloy used in the forged pistons selected by the group is a superior alloy mainly due to having a much lower (~12%) composition of silicon, which is replaced with a higher composition of aluminum, copper, magnesium, and a small amount of titanium [52]. This results in an improvement in mechanical properties that can be seen in the table below.



Piston Alloy Characteristics

Material Characteristic	4032	2618
Tensile Strength	55,000 psi	64,000 psi
Yield Strength	46,000 psi	54,000 psi
Fatigue Endurance	16,000 psi	18,000 psi
Modulus of Elasticity	11,400 psi	10,400 psi
Melting Point	990-1,060 F	1,020-1,180 F

Figure 34: *Forged Piston Alloy Characteristics [52]*

Additionally, as previously discussed, the forging manufacturing process produces much better mechanical properties as compared to a casting manufacturing process, since forging allows for better control over grain orientation.

Piston Rings

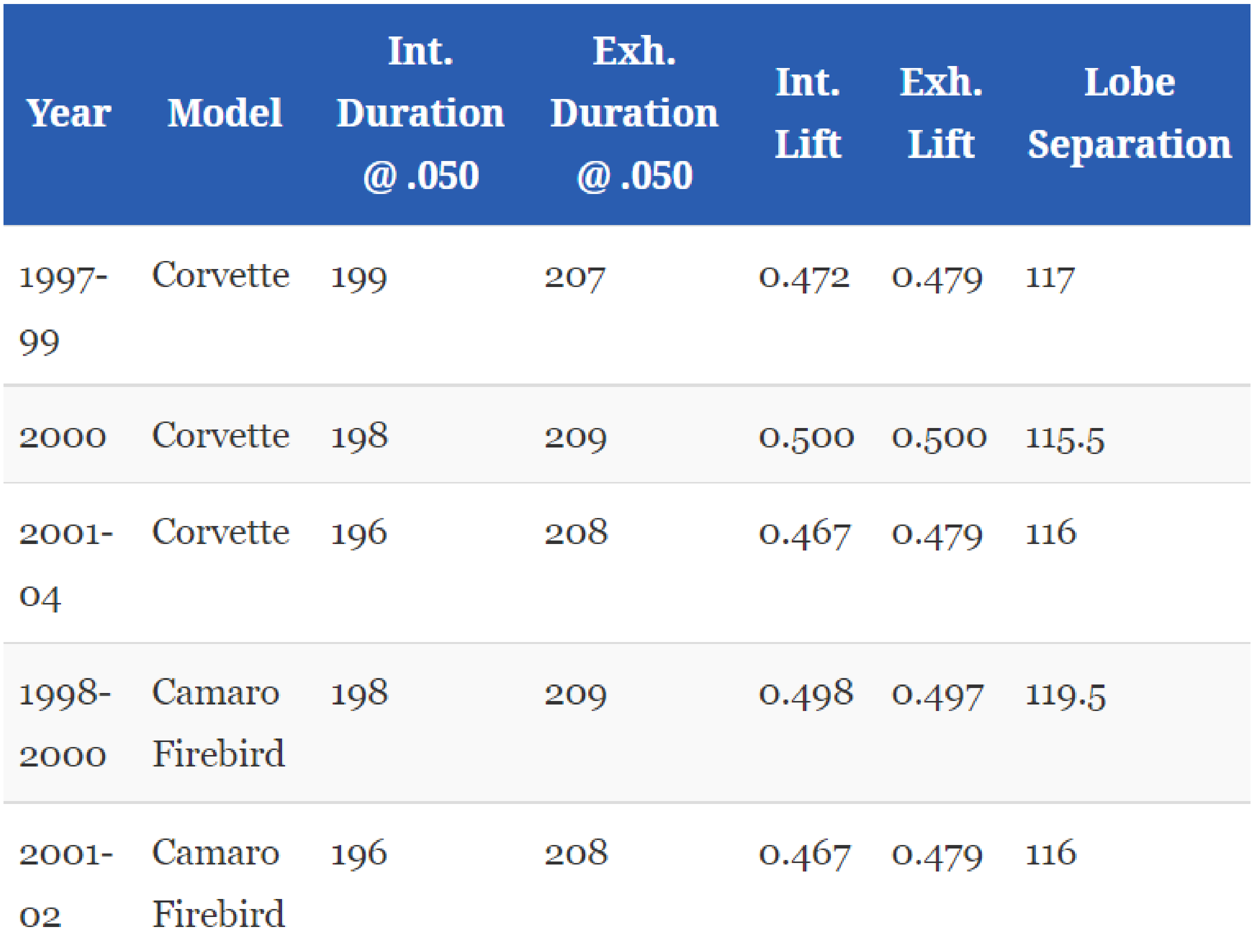
Pistons have metal rings around their outer diameter that contact the cylinder wall, rather than the piston itself. Most four-stroke engines use three rings, with the “top” (closest to the top face of the piston) two rings being responsible for forming the seal between the cylinder wall and the piston to maintain pressure in the combustion chamber. The “bottom” ring (closest to the crankcase) is responsible for maintaining an adequate thin film of oil on the cylinder walls, which is necessary for proper lubrication to reduce the friction that could otherwise damage the engine by wearing out the piston rings or scoring the cylinder walls. [53] The stock piston rings are plasma moly top rings and ductile iron 2nd rings. The group used Summit Pro LS rings that are made in conjunction with the Pro LS pistons. These rings are also plasma moly and ductile iron, respectively, but are thicker than factory rings with the ringlands of the pistons enlarged for their accommodation. The ring gaps were calculated using the accompanying equations given by Summit with the pistons and rings. The first set of rings were gapped to .024 inches. The equation is as follows: (Bore Size x .006”) = Ring Gap. For this particular engine, the equation was 4.0055” x .006”. The second set of rings were gapped to .022 inches. These ring gaps were calculated with the equation (Bore Size x 0055”) = Ring Gap. In this case, it was 4.0055” x .0055” [54].

Figure 35: *Piston Rings Installed on Forged Pistons*

Figure 36: *Engine Block after Installation of Crank, Camshaft, Piston, and Rod Assemblies*

Camshaft

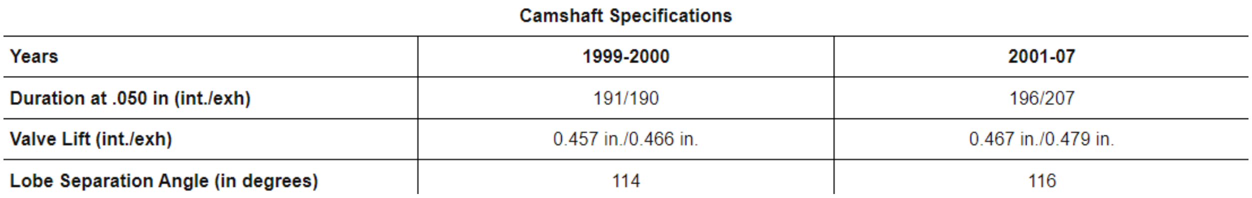
The original LS1, the new LQ4, and the aftermarket camshaft all have different specifications. These specifications allow the engine to perform better in different scenarios. The LS1 for example was only present in sports cars such as the Corvette, Camaro, Trans Am, GTO, and CTS-V [55]. Sports cars are designed for speed and performance. As such, the camshaft designated for these cars was more horsepower biased, as sports cars typically are used for high speeds and quick acceleration. The specifications for this camshaft, as seen below, accounted for such performance.



Year	Model	Int. Duration @ .050	Exh. Duration @ .050	Int. Lift	Exh. Lift	Lobe Separation
1997-99	Corvette	199	207	0.472	0.479	117
2000	Corvette	198	209	0.500	0.500	115.5
2001-04	Corvette	196	208	0.467	0.479	116
1998-2000	Camaro Firebird	198	209	0.498	0.497	119.5
2001-02	Camaro Firebird	196	208	0.467	0.479	116

Figure 37: *LS1 Camshaft Specifications [55]*

The LQ4 on the other hand, was created for truck and large vehicle applications [56]. These vehicles required an engine with a high torque value and power at lower RPM's, as that is where they are needed during normal operation for those vehicles. To deliver the performance needed from this camshaft, the specifications were as follows.

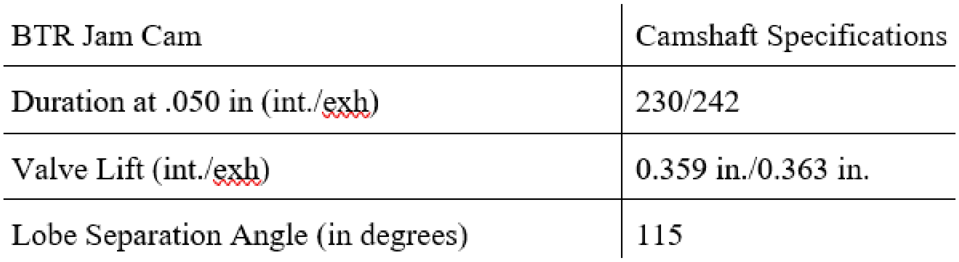


Camshaft Specifications

Years	1999-2000	2001-07
Duration at .050 in (int./exh)	191/190	196/207
Valve Lift (int./exh)	0.457 in./0.466 in.	0.467 in./0.479 in.
Lobe Separation Angle (in degrees)	114	116

Figure 38: *LQ4 Camshaft Specifications [56]*

Finally, the new aftermarket performance camshaft from Brian Tooley Racing has been created to improve the engine’s horsepower value, not only under naturally aspirated situations, but in forced induction applications as well [57]. This camshaft was created to take advantage of the nature of a forced-induction engine which increases boost as the RPMs increase. This camshaft’s specifications are as follows.



BTR Jam Cam	Camshaft Specifications
Duration at .050 in (int./exh)	230/242
Valve Lift (int./exh)	0.359 in./0.363 in.
Lobe Separation Angle (in degrees)	115

Figure 39: *BTR Jam Cam Specifications [57]*

Figure 40: *BTR Jam Cam [58]*

Cylinder Heads

For the LS/LQ line of engines, there are several options for cylinder heads that are a direct fit. Figure 41 shows the 243 heads that the team used in this project. 243 refers to the casting number of the part. The 243 heads are cast from aluminum and feature cathedral intake ports and D-shaped exhaust ports [59]. Cathedral ports have a narrower cross-section than rectangle-shaped intake ports [60]. This allows air to flow through them at a higher velocity for the same volumetric flow rate. As a result, the cathedral intake ports aid with throttle response and low to mid RPM range performance over the rectangular ports. The intake and exhaust valves are 2.00 inches and 1.55 inches in diameter, respectively. The intake side of the heads flows 260 CFM of air at 0.600 inches of lift, and the exhaust side flows 183 CFM at the same lift. 243 heads allow the engine to produce more power by increasing compression. Compared to the 317 heads that originally came on LQ4 engines, the 243 cylinder heads raise the compression ratio in the cylinder from 9.5:1 to 10.1:1 [61]. This is due to the 243 heads decreasing the combustion chamber volume by 2.22 cubic centimeters. For the project, the team utilized ARP head bolts to bolt the head to the block. Figure 42 shows the head bolt kit that the team used for the project. These head bolts are stronger than traditional torque-to-yield head bolts as they are made from ARP 2000 alloy. They provide additional strength, especially with the increased boost pressure that the engine will experience. Within the cylinder heads, the valve springs were swapped with stiffer ones. The car can accelerate to 7000 RPM rather than the 6000 RPM it can reach in stock form due to the higher spring rate. If the engine were to reach 7000 RPM on the stock valve springs, the valves may “float,” meaning the springs are not stiff enough to keep up with the camshaft profile at high RPM [62]. The stiffer valve springs also can withstand the additional pressure the cylinder and intake manifold experience due to the supercharger.

Figure 41: *243 Cylinder Heads [63]*

Figure 42: *ARP Cylinder Head Bolts [64]*

Methanol Injection System

In order to sustain higher power levels, extra precaution is needed in terms of the fuel being burned. Normally, performance vehicles require the use of a higher octane fuel, such as 91 or 93 octane. This can be found at nearly every gas station in the United States. This need for higher octane is due to higher compression values found in high-performance engines. As the compression is raised, an undesirable scenario known as “engine knock” can occur. Knocking is an uncontrolled explosion of the fuel in the combustion chamber, rather than burning uniformly at the correct time as initiated by the spark plug. This can be pre-ignition when the fuel explodes before the spark plug fires, or detonation when part of the fuel explodes before the controlled burn from the spark plug finishes. Both are extremely dangerous for an internal combustion engine as it creates a short, violent increase in cylinder pressure that can damage many parts such as the piston, piston rings, connecting rod, and cylinder wall.

To prevent detonation, one option is to install a methanol injection system. Methanol injection systems reduce the likelihood of detonation by introducing a mixture of methanol and water into the intake system. When combined with the 91 or 93 octane fuel the methanol boosts the octane rating of the fuel source, allowing the engine to run at more advanced timing to make more power. Despite water not being combustible, it is present in the mixture due to its innate ability to cool. Adding one part water to one part methanol allows for a cooler intake air temperature, as well as the previously mentioned octane benefits of methanol. Cooler air temperatures allow for increased timing and a more efficient burn inside the combustion chamber [65].

Figure 43: *Methanol Injection Kit Diagram [66]*

The methanol injection system used by the team is the Alkycontrol kit [67]. This kit is a tried and tested way of lowering intake air temperature, as well as boosting fuel octane. Many cars with supercharged applications have had great success running this system, as it introduces the mixture of methanol and water as it receives signals from the Manifold Absolute Pressure

(MAP) sensor. Therefore, when the sensor sees boost levels increasing, it sprays the mixture into the intake piping at an increasing rate.

Figure 44: *Alkycontrol Methanol Injection Kit (MAP) for C5 Corvette [67]*

Supporting Drivetrain Modifications

Clutch Assembly

The clutch chosen for the team's power goals was a McLeod twin-disc clutch, specifically their RST model. This clutch can transmit 800 wheel horsepower and 800-foot pounds of torque to the rear tires. It is an aggressive clutch, however, it still performs well on the street, unlike certain twin disc clutches which are too aggressive for day-to-day driving. The flywheel chosen is their steel option as choosing the aluminum option would mean better performance but would reduce drivability on the street. To fasten the flywheel to the crankshaft in the rear of the engine, special ARP flywheel bolts are used with ARP assembly lube as well as Red Loctite. These were torqued to 70 foot-pounds in a star formation for a more uniform flywheel seating procedure. To align both clutch discs with the pressure plate, a clutch alignment tool is used to hold them in place while the pressure plate is fastened to the flywheel [68].

Figure 45: *McLeod RST Twin Disc Clutch [68]*

Torque Tube

Inside the torque tube two couplers can be found. These couplers help fasten the driveshaft to the engine output shaft, as well as, the driveshaft to the transmission input socket. The old couplers that were removed were cracking and breaking apart. They were replaced with solid aluminum alloy 6061 couplers machined by a fellow WPI student. As the new couplers are solid, they allow the engine to transmit all the power to the rear wheels without any loss. While they may be less forgiving and create more vibration, the benefits of using solid couplers far outweigh the downfalls.

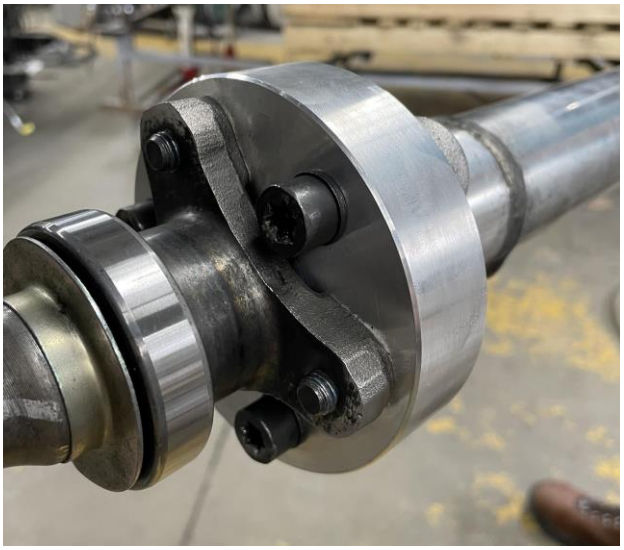


Figure 46: *Coupler Fastened*

Figure 47: *Bare Coupler*

Bushings

On all four corners of the C5 Corvette, a double wishbone suspension setup is used. This means there is an upper and lower A-shaped control arm, with two mounting points to the car for each arm. At each of those mounting points, the old rubber bushings were removed in favor of new polyurethane bushings. These increase firmness in the suspension system, allowing the car to corner faster and put the increased power down to the ground.

Figure 48: *Bushings Installed into Control Arm*

Dynamometers

This project utilized a Dynocom 7500 Series dynamometer with an eddy current brake [69]. Figure 49 shows a render of this dyno. The eddy current brake allows for extremely precise readings taken at higher sampling rates than most dynamometers. The roll speed sensors read 100 samples/RPM compared to other dynos at 20-60 samples/RPM. The Dynocom 7500 Series has a maximum rated speed of 225 miles per hour and a maximum rated torque of 7500 ft-lbs. Readings taken by this dynamometer feature timing accuracy within ±0.1 µs, drum speed accuracy within ±0.001 MPH, and engine speed accuracy within ±0.01 RPM. The increased sensitivity provides the user with the most detailed and accurate information possible. The Dynocom 7500 Series is also capable of simulating a ¼-mile drag strip or circle track laps, but these features will not be needed for this testing as the Corvette will be driven mostly on the street. This dyno was available to the team at the Bowtie Shop. If the team had wanted to use a different type or model of dyno, a formal arrangement with another shop would have been needed. This dyno, however, met the team's criteria for accuracy, versatility, and regular availability.

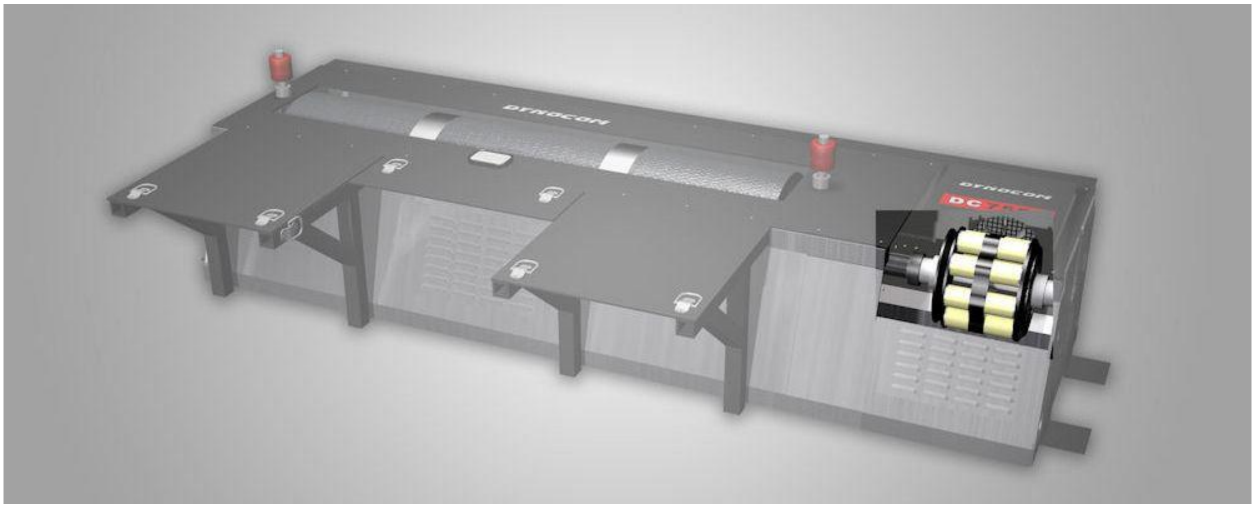


Figure 49: *Dynocom 7500 Series Dynamometer with Eddy Brake [70]*

Intake Manifold Flow Simulations

The original desire of the team was to simulate air flow through the entire intake system of the car. The team quickly realized that this task was too complicated to simulate with any accuracy. The intake air box, supercharger, intercooler, intake manifold, and cylinder heads together make a system that is incredibly dynamic and complicated. While it would be interesting to model this system, the project team would have to create a solid model of each part and then test them together. So instead, the group chose to focus its efforts on the simplest of the components: the intake manifolds. The team decided to model the flow of air through each manifold for two revolutions of the engine three times. Since two revolutions correspond to four strokes, the simulation would model how airflow changes inside the manifold as different cylinders accept air.

Choosing CFD Software and Steps for Solving

Before any work could be done on the simulation model, the project team had to choose the software platform through which to simulate flow. Several CFD software packages exist that could have worked for this project. Software packages include ANSYS Fluent, Solidworks Flow

Simulation, Autodesk CFD, OpenFOAM, and SimScale [71]. All of these are developed CFD programs that solve the Navier-Stokes equations for imported geometry using a mesh, material properties, and operating and initial conditions. The team chose to use ANSYS Fluent for these simulations for a few different reasons. First, ANSYS Fluent is specialized CFD software. It was built solely for CFD analysis, unlike Solidworks or Autodesk which originally were solid modeling software. Second, WPI already had a license for ANSYS and its related products and it could run on their computers uninterrupted and protected, unlike SimScale which is a cloud-based software. Third, it is developed by experts who can maintain a steady level of support, unlike the open-source OpenFOAM. And, like all of these software packages, solid modeling and meshing tools are included in the ANSYS suite of tools.

There are five top-level steps that every CFD simulation needs to complete before results can be visualized. The researcher must: define and import geometry, apply a mesh to the geometry taking into account the boundary layer regions, define material properties, define operating and initial conditions, and choose solver models and parameters. The project team made many choices here to try to simulate real-life inside the software.

Developing the Model Geometries

The team chose to use an LS6 intake manifold and a Trailblazer SS intake manifold with its engine. These manifolds have the same port size and fit onto the cylinder heads the same way. The geometry of the runners and plenum, though, are nowhere near similar. Initially, the group looked for existing solid models of the intake manifolds. While the manufacturing technique is not public information, by inspection it appeared that General Motors manufactured these parts using a molding technique due to the appearance of flash lines and cut gates. This did not imply that a solid model of the manifolds existed. The team asked aftermarket manifold manufacturers if they had existing models of either of the manifolds. The project team believed at the time that the aftermarket manufacturers based their manifolds on the OEM manifolds. However, the response from them was all the same: they had no models that they were willing to share. So, the next step was to ask General Motors directly. Unfortunately, after reaching out to their customer service department the group learned that the models were not available from them either. So, to get the simulation data, the team would have to develop the solid models from scratch.

For the simulations, the team needed to model the interior volume of the manifolds. The team developed two potential strategies to be able to recreate them. The first strategy was to use a 3D scanner to model either the manifold itself or the fluid volume inside. This would have created a dimensionally accurate model of the manifold as long as the tool to create the scan could see inside the manifold. However, the team was unsuccessful in finding a scanner to use at WPI or other nearby universities. The second strategy was to make the solid models by hand. This has the benefit of requiring no specialized equipment but would require the team to dimension both manifolds very carefully and then translate those drawings into a solid model. Without any other options, this is the method that the team was forced to use to generate solid models of the manifolds.

For the initial simulations, the team utilized a simplified model of an intake manifold for this engine. The model included eight runners that wrapped over the top of the plenum and had outlets at an angle. Figure 50 shows the simple geometry manifold that the team used initially. This simplified model did well to test different parameters within ANSYS since simulations converged quickly. By testing parameters this way in the solver, the team could tweak the CFD model while the development of the real solid models occurred in parallel.

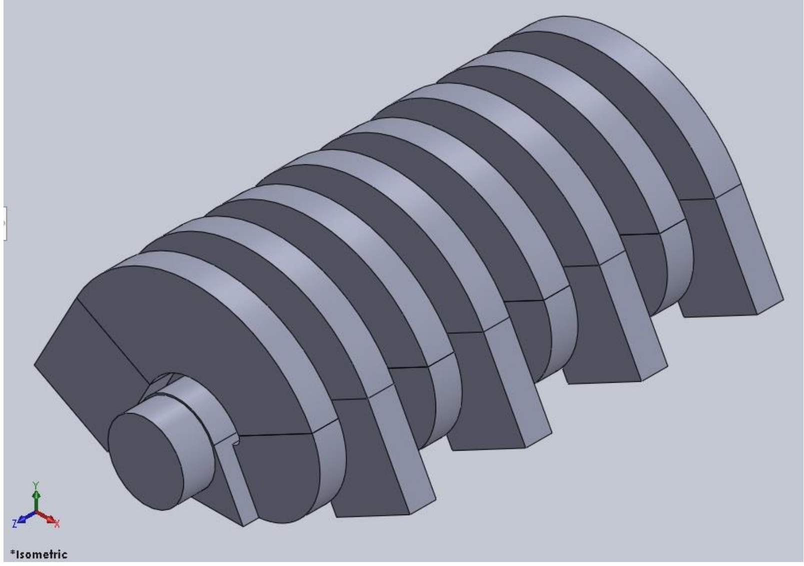


Figure 50: *Rapid Testing Manifold Geometry*

The team meticulously dimensioned each manifold so that they could be recreated within Solidworks. Certain features were ignored and smoothed to simplify the measurements and the solid model geometry. Since CFD modeling is not perfect, simplifying the geometry is an acceptable tradeoff and improves the convergence speed of the solver. The team created two versions of the LS6 manifold and two versions of the Trailblazer SS manifold before they were deemed accurate for the simulations. For the final version of the LS6 manifold, the team modeled the runner and an eighth of the plenum together and joined those parts together to create the whole model. For the Trailblazer SS manifold, the team modeled an individual runner, the lower plenum, and the upper plenum and joined those parts together. Ultimately, the method used to create the Trailblazer SS manifold solid model was simpler, but time constraints prevented the LS6 manifold solid model from getting the same treatment. Figures 51 and 52 show the final version of the manifolds that the team used in the simulation. Appendix A contains the figures showing all versions of each manifold variation in isometric, front, top, and side views.

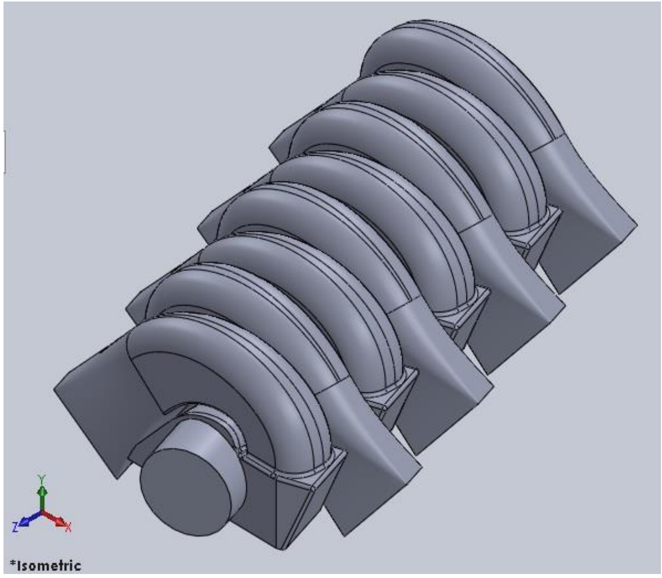


Figure 51: *LS6 Intake Manifold Interior Volume Solid Model*

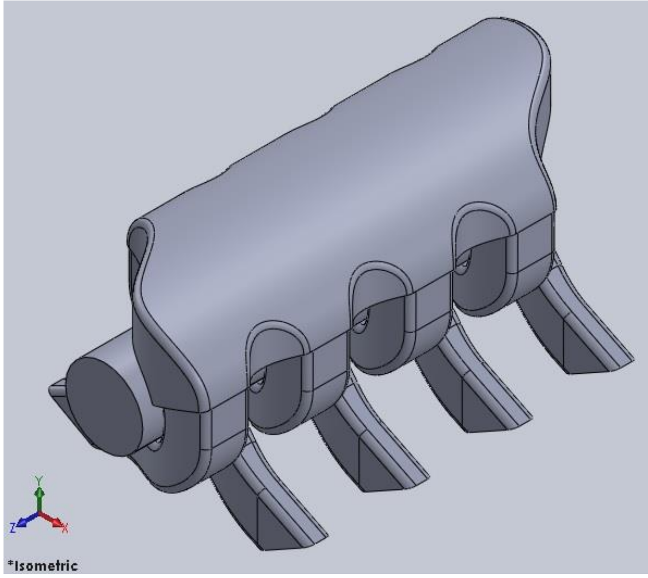


Figure 52: *Trailblazer SS Intake Manifold Interior Volume Solid Model*

ANSYS Interface

Figure 53 shows the main interface of ANSYS with Fluent ready to be used by the user. Different modules within ANSYS perform different functions. The only one that the team used directly was ANSYS Fluent. ANSYS provides a few different versions of CFD software. The project team chose Fluent specifically within ANSYS because Fluent works well with pipe flow. Fluent contains five cells that contain information about the geometry, mesh, setup, solution, and results of the CFD model. The geometry, mesh, and results in cells opening other tools within ANSYS, but the remaining cells use Fluent directly. The cells interface with each other, and any updates to a cell higher on the list are captured and require the user to rerun subsequent steps.

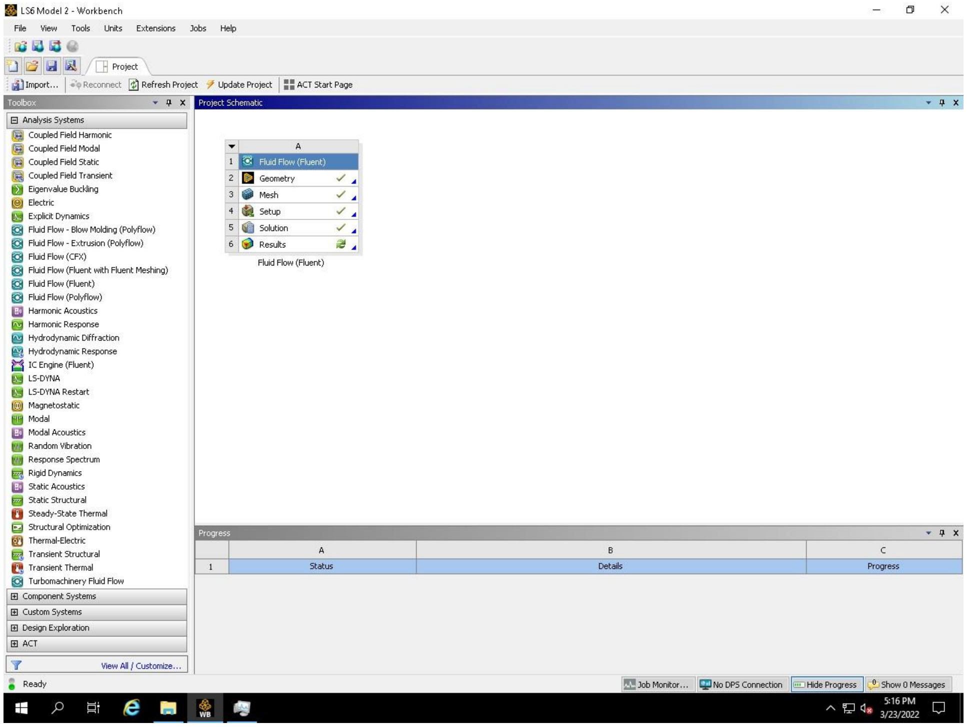
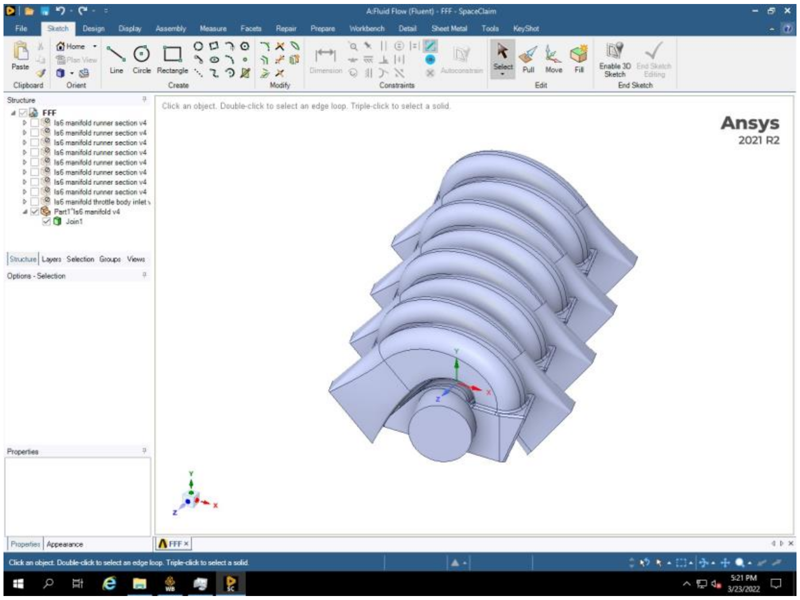


Figure 53: *ANSYS Workbench Main Interface*

ANSYS SpaceClaim

ANSYS could use any manifold geometry as long as the volume was continuous and contained no gaps. Since the team developed the runners and plenums of each manifold as separate part files and then joined them together within Solidworks, there was a risk of creating voids within the centers of each manifold. But, the team was creative in dimensioning the units and ensured that there were no voids in the final models. All manifold geometries were exported from Solidworks as a ".step" file so ANSYS SpaceClaim could read them. Figure 54 shows imported geometry within ANSYS SpaceClaim. In SpaceClaim, the separate parts of the manifold were suppressed to allow only the joined part to be interpreted by ANSYS Meshing and Fluent.



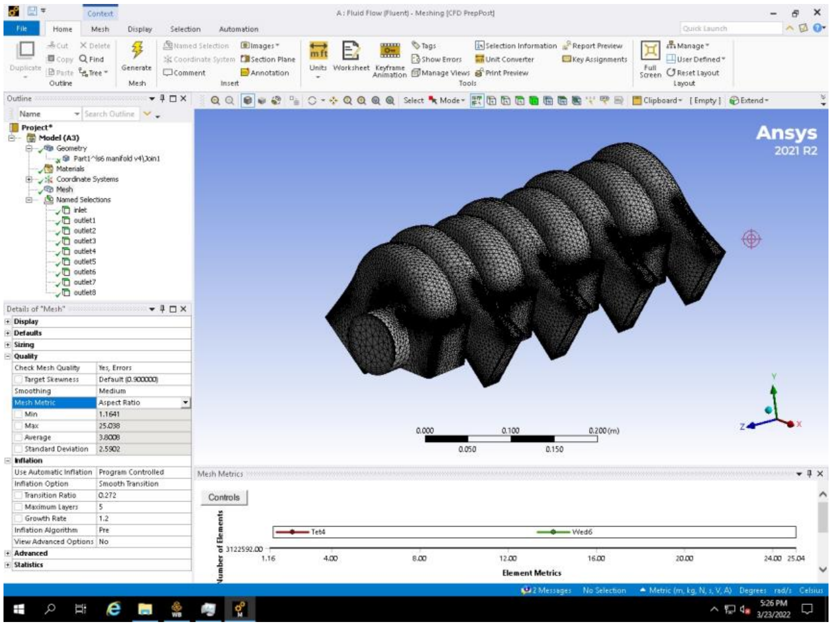
Click an object. Double-click to select an edge loop. Triple-click to select a solid.

Figure 54: ***Imported Geometry Inside ANSYS SpaceClaim***

ANSYS Meshing

The next step was to define the mesh in ANSYS Meshing, shown in Figure 55. The mesh is a discretization of the solid model geometry that the solver can understand. Conceptually, it is the same as the control volume used to define the Navier-Stokes equations, but these cells are finite. For a given geometry, the number of cells is greater than one million, but this number generally depends on meshing parameters. A larger number of cells means that the solution will be more accurate but it will take longer to converge [72]. Additionally, the shapes of the cells impact the accuracy of the solution. Regular cells tend to create solutions that converge more quickly and more accurately than those which are highly stretched. When the geometry of the part is not regular and includes sharp corners and tight spaces, the cells can become highly irregular. Tools within ANSYS Meshing can help alleviate these issues, but often the best solution is to simplify geometry where possible. This is why the team could simplify the solid models of the LS6 and Trailblazer SS manifolds without risking the integrity of the solution.

Quality tools inside ANSYS Meshing show the maximum aspect ratio, orthogonality, skewness, element quality, and more of the current mesh [73]. Additional parameters within this tool can be used to generate a higher-quality mesh. ANSYS Fluent also contains tools to check the quality of the mesh. Most importantly, Fluent contains a tool that checks the minimum volume of all cells in the mesh. If the minimum value were less than or equal to zero, the mesh would be invalid and would need to be regenerated. Meshing also is the stage in the process where the team defined the inlets and outlets of the model. They are defined at this stage because the mesh is generated using inflation [74]. Inflation changes the size of the cells at the walls of the fluid volume. These simulations assumed that the velocity of the fluid at the walls is zero. But, the fluid velocity changes very quickly from the wall to the freestream inside the manifolds. If the cells are large near the walls, the change is not captured correctly and the model is not accurate. By allowing inflation near the walls, the boundary layer is incorporated into the mesh. The mesh can then use larger cells in the freestream region away from the walls, making the solver faster and more accurate. By defining the inlet and outlets at this stage, the mesh can incorporate those openings into its generation algorithm and only generate inflated sections in the appropriate areas.



Details of "Mesh"

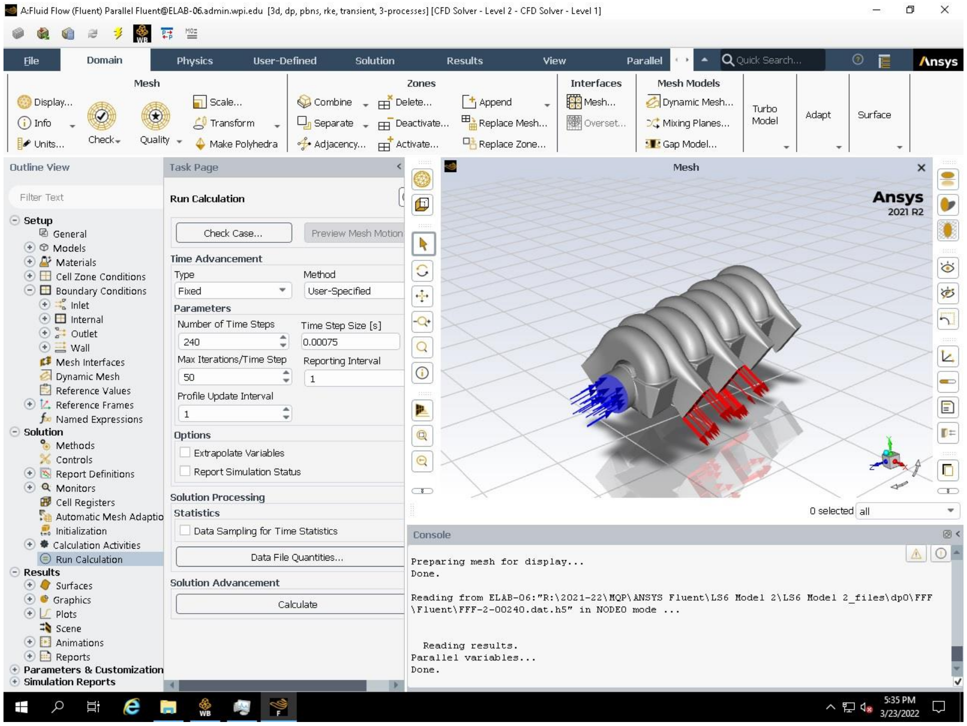
Display	
Defaults	
Sizing	
Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.900000)
Smoothing	Medium
Mesh Metric	Aspect Ratio
Min	1.1641
Max	25.038
Average	3.8008
Standard Deviation	2.5902
Inflation	
Use Automatic Inflation	Program Controlled
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Statistics	

Figure 55: *ANSYS Meshing Interface with Options*

ANSYS Fluent

After the team defined the geometry and mesh, the team could use Fluent to create a model. Figure 56 shows the interface for Fluent. The solver uses the imported geometry and mesh with other parameters to generate a solution. This solution can be steady-state or transient.

In either case, Fluent iterates the solver to try and balance the Navier-Stokes equations [75]. The difference between the left and right-hand sides of these equations is captured in the residuals [76]. The residuals of a model tend to shrink with more iterations and good modeling parameters. Fluent defines the convergence of a time-step in transient analysis or a solution in the steady-state analysis as the iteration where the residuals fall below preset values. Ideally, the scaled residuals of a converged solution would be zero, but due to round-off errors usually, the residuals of a model tend to some small value much less than 1. The team monitored the scaled residuals in real-time during the simulations to make sure that the solutions converged. While residuals are not the only quality of a model to watch, they are a good first indication of convergence.



Time Advancement

Type: Fixed

Method: User-Specified

Parameters

Number of Time Steps: 240

Time Step Size [s]: 0.00075

Max Iterations/Time Step: 50

Reporting Interval: 1

Profile Update Interval: 1

Options

☐ Extrapolate Variables

☐ Report Simulation Status

Solution Processing

Statistics

☐ Data Sampling for Time Statistics

Solution Advancement

0 selected: all

```
Preparing mesh for display...
Done.

Reading from ELAB-06:"R:\2021-22\MQP\ANSYS Fluent\LS6 Model 2\LS6 Model 2_files\dp0\FFF
\Fluent\FFF-2-00240.dat.h5" in NODE0 mode ...


  Reading results.
Parallel variables...
Done.
```

Figure 56: *ANSYS Fluent Interface*

To model the opening and closing of the runners, the team utilized a script that would change the boundary conditions at the outlets of the manifold. The project team assumed that the engine speed was constant and that only two runners were open at any one time. In combination with the firing order of the engine, the group could define a pattern of open and closed runners. But, Fluent is not capable of defining a pattern to change boundary conditions on its own. So, the team developed a boundary condition changing script which could automatically change which runners were open at the appropriate time step according to the firing order and engine speed [77]. This script was written in Scheme, a dialect of Lisp, and can be found in Appendix B.

The team defined the solid and fluid material properties of the manifold. Both manifolds only have air flowing through them. The air was defined as an ideal gas with the properties of specific heat, thermal conductivity, and viscosity defined as piecewise linear according to Table A.4 in Fundamentals of Heat and Mass Transfer by Bergman, Lavine, Incropera, and Dewitt [78]. The team approximated the temperature range to take this data over using realistic values that were later confirmed by the initial data. For these simulations, that range was 250-400K. The solid material was only the wall of the manifold. The manifolds are both made from glass-fiber-reinforced nylon [79]. Fluent can use the Granta MDS materials database to select more exotic materials within a model. From that database, the group chose to use nylon 6,6 containing 30-33% glass fibers for the manifold wall material.

The project team defined the initial boundary conditions for the model based on the initial data and some assumptions. First, the team assumed that the pressure inside the intake manifold is isobaric initially. Therefore, the MAP sensor reading could be used to directly define the gauge pressures at the inlets and outlets. Second, the team assumed that the wall temperature was at some value larger than ambient. Thus, the team added 20°F to the ambient air temperature value taken from the IAT sensor. Third, the team assumed that the backflow temperature from the outlets was at the engine coolant temperature. This value was 162°F. Fourth, the team assumed that the throttle was fully opened but the engine was not accelerating. This is not accurate to the real world. When a throttle is opened completely, the engine will continue to accelerate until it reaches its maximum speed. However, since the switching script cannot model that functionality, the team chose to model constant speed with a fully opened throttle. Finally, to simplify the pressure inputs, the operating pressure of the model was redefined as zero. By choosing this value, all the pressure values would be absolute pressure.

The team modeled the transient flow through each manifold for three four-stroke cycles. While only one full four-stroke cycle would be necessary for the analysis, the first cycle would contain garbage data as the model settled from the initial conditions. The energy equation for heat transfer between media was enabled. For the viscous model, the team chose to use the realizable k-epsilon model. This model was chosen on the advice of the ANSYS help documentation [80]. The realizable k-epsilon model is useful for most types of fully turbulent flow. Only runners 1 and 3 were open at the start of the simulation, all other runner outlets were modeled as walls. All solution methods were of the second-order variety for better accuracy. And lastly, the simulation was initialized from the inlet. Initializing the simulation is necessary to provide initial values for the solver to use. The inlet was chosen arbitrarily, all zones or an outlet could have also been chosen.

As few parameters as possible were modified within Fluent. There are hundreds of options inside Fluent that could change the way the solver computes the solution. Thus, only the most important options were modified. The team summarized the parameters that were changed within ANSYS Meshing and Fluent to generate these models in Appendix C. The team used these settings for both the LS6 and Trailblazer SS manifold simulations.

Analysis and Results

Dynamometer Testing

Baseline Data

To accurately analyze power gains as a direct result of optimized airflow through the engine, the group needed to gather preliminary data on the vehicle's performance before swapping the new engine into the car. To achieve this, the vehicle was placed on a dynamometer to gather the horsepower and torque performance values of the engine. The specific dyno model used was a Dynocom 7500 Series with Eddy Current.

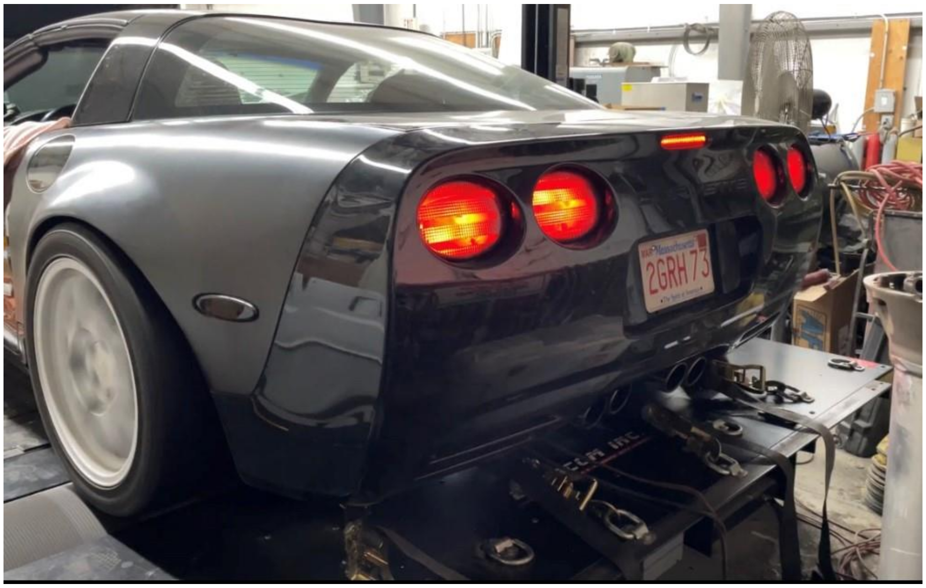
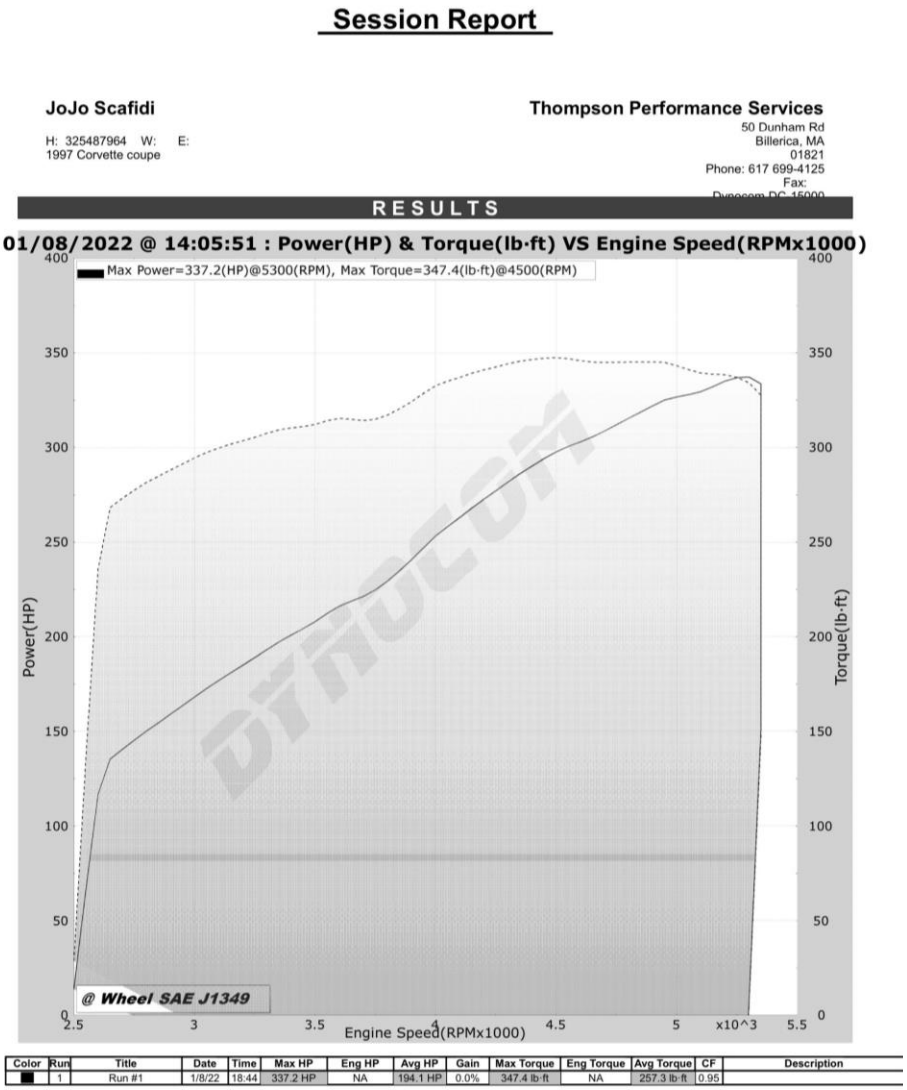


Figure 57: *Corvette Ready & Secured on the Dynamometer*

The group was able to put the vehicle on the dyno very early on in the project with the help of Paul Thompson. This allowed us to accurately judge the car's current engine airflow state in terms of the horsepower and torque values generated, and also provided us the opportunity to address any existing performance issues the vehicle may have had before work began. In the run the vehicle had on the dynamometer, the graphs displayed 337 horsepower and 347 foot-pounds of torque generated, which includes the minor losses through the vehicle's drivetrain. All power figures obtained from the dyno account for drivetrain losses, as the dyno measures torque produced at the wheels rather than at the flywheel. Shown below is the chart following the dyno run as well as the HP Tuners software used to read all engine sensor readings. All engine sensor readings taken during the initial dyno run can be found in the attached zip file.



Session Report

JoJo Scafidi
H: 325487964 W: E:
1997 Corvette coupe

Thompson Performance Services
50 Dunham Rd
Billerica, MA
01821
Phone: 617 699-4125
Fax:
Dynocom DC-15000

RESULTS

01/08/2022 @ 14:05:51 : Power(HP) & Torque(lb·ft) VS Engine Speed(RPMx1000)

Max Power=337.2(HP)@5300(RPM), Max Torque=347.4(lb·ft)@4500(RPM)

Color	Run	Title	Date	Time	Max HP	Eng HP	Avg HP	Gain	Max Torque	Eng Torque	Avg Torque	CF	Description
■	1	Run #1	1/8/22	18:44	337.2 HP	NA	194.1 HP	0.0%	347.4 lb·ft	NA	257.3 lb·ft	0.95	

Figure 58: *Preliminary Horsepower & Torque Value Graphs*

Name	Value
AIR Pump	off
Base Advance	22.0 °
Coolant Advance	0.0 °
IAT Advance	0.0 °
Knock Retard	1.0 °
Burst Knock Retard	0.0 °
Dynamic Airflow	2,248.1 lb/h
Mass Airflow Sensor	10,550 Hz
Mass Airflow (SAE)	37.80 lb/min
Injector Pulse Width Avg...	11.8 ms
Injector Pulse Width Avg...	11.9 ms
Calculated Engine Load (...	100.0 %
Accelerator Pedal Position	99.0 %
Throttle Position (SAE)	99.6 %
Vehicle Speed (SAE)	60 mph
Short Term Fuel Trim Ban...	0.0 %
Long Term Fuel Trim Bank...	0.0 %
Short Term Fuel Trim Ban...	0.0 %
Long Term Fuel Trim Bank...	0.0 %
O2 Voltage B1S1 (SAE)	0.438 V
O2 Voltage B2S1 (SAE)	0.298 V
Equivalence Ratio Commanded	0.79 λ
MPVI2.1 -> Ballenger - A...	0.80 λ
Engine Oil Pressure	61.8 psi
Delivered Engine Torque	507 lb·ft
Idle Desired Airflow	73.7 lb/h
Idle Adapt (STIT)	0.00 lb/min
Idle Air Control Position	310
LTIT Gear/ACoff	-0.11 lb/min
LTIT PN/ACoff	0.00 lb/min
Accelerator Pedal Position	99.0 %
Throttle Position Sensor	0.00 V

ngine Speed (rpm) [Sensor] / 100

anifold Absolute Pressure (kPa) [Sensor

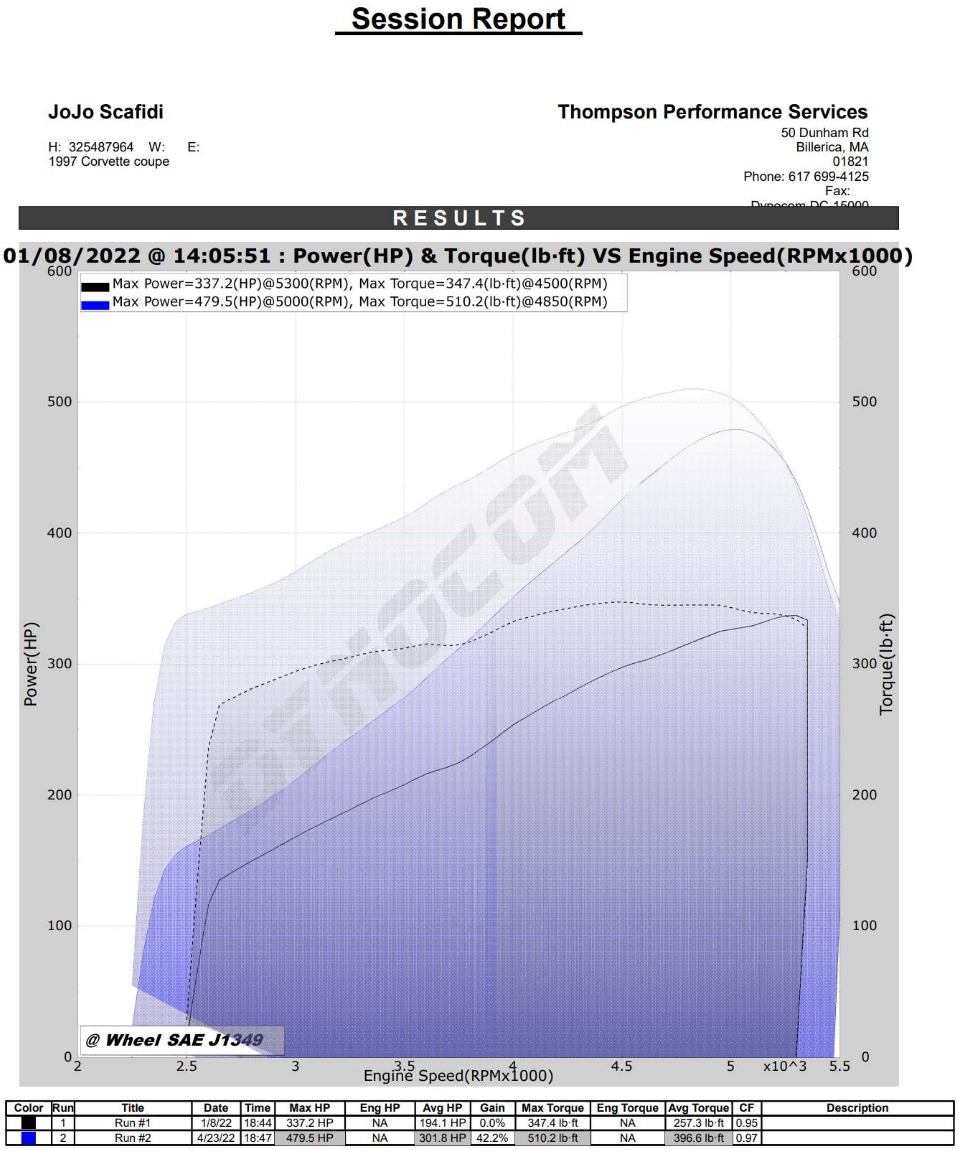
	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4
30			20	32	25	27				
35		17		37	26	35				
40	17	18		32	30	29	34			
45	17	16	25	33	33	30	37	34		
50	19	24	32	33	35		28	34	34	
55	21	25	31	32	37					34
60	6				38					
65					38					
70					38					
75					39					
80					37					
85					25					
90						25				
95						25	26			
100							26	25	23	
105									21	21

Figure 59: *Data Readings Taken from Dynamometer*

With the main goal of the project is to increase the power and torque of the engine, the dynamometer is the only way to accurately measure the increase from the previous engine to the new one. Additionally, the dyno reads all engine sensors to make sure everything is working properly under load. With this information, the group can see if any other improvements were made to the engine as a result of the changes. For example, the Intake Air Temperature readings can be compared between the two engines to see the benefit of using a methanol injection system to lower the intake air temperatures. The increase in the air flowing through the intake manifold can also be measured using the data taken from the Manifold Absolute Pressure (MAP) sensor, which is responsible for reading the air pressure within the intake manifold to derive the mass flow rate of air. This is then used to calculate the amount of fuel needed for ideal combustion.

Final Data

Due to issues experienced getting the upgraded engine to run correctly, the group was unable to collect data for a full wide-open acceleration on the dyno within the given timeline of the project. Data for which parts most effectively increased power was also unable to be obtained. Shown below in Figures 60 and 61 is data from the first partial acceleration on the dynamometer. The engine was only brought to just over 5000 RPM, as the engine had only been tuned for that part of the engine’s RPM range. During this test, the new engine produced 479.5 horsepower at 5000 RPM and 510.2 lb-ft of torque at 4850 RPM. These numbers are promising for the new engine to make the goal of about 700 horsepower, after the restrictor plate is removed and the Trailblazer SS intake manifold is installed.



Session Report

JoJo Scafidi

H: 325487964 W: E:
1997 Corvette coupe

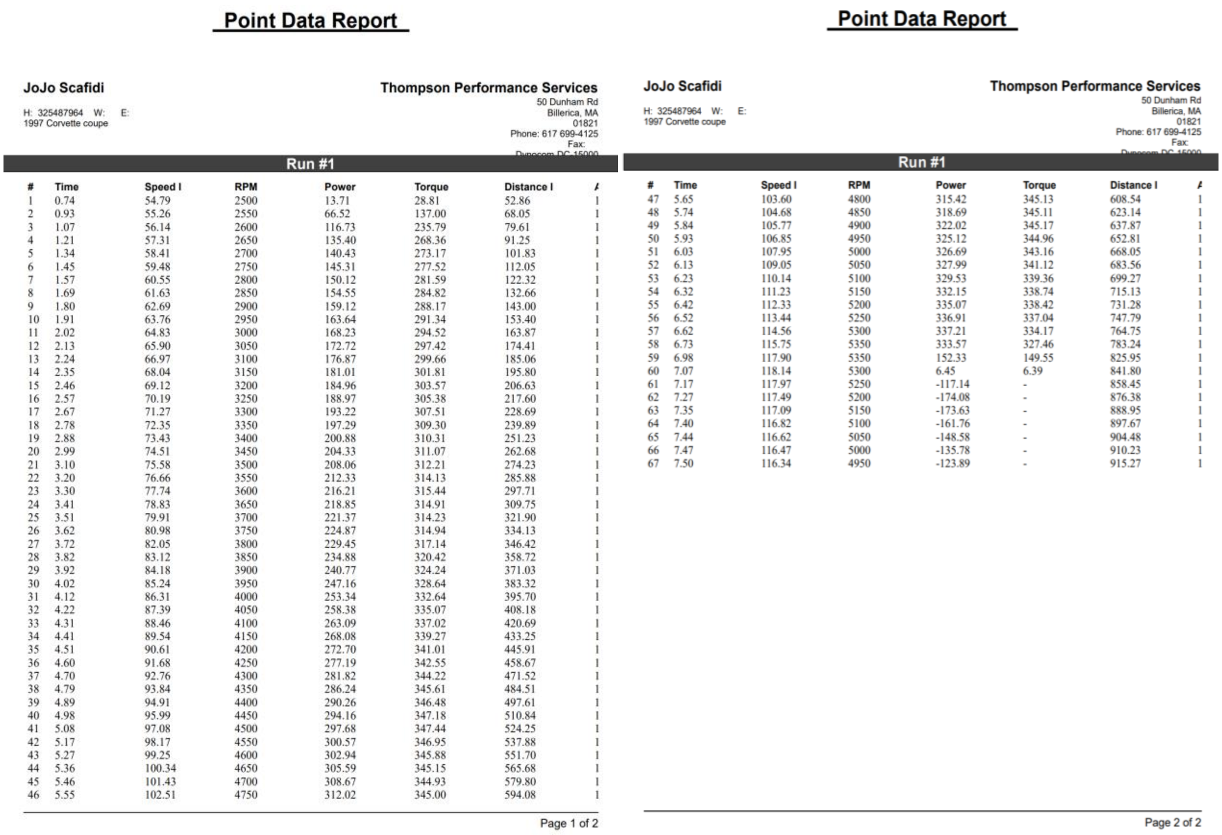
Thompson Performance Services
50 Dunham Rd
Billerica, MA
01821
Phone: 617 699-4125
Fax:
Dynocom DC-15000

RESULTS

01/08/2022 @ 14:05:51 : Power(HP) & Torque(lb·ft) VS Engine Speed(RPMx1000)

Color	Run	Title	Date	Time	Max HP	Eng HP	Avg HP	Gain	Max Torque	Eng Torque	Avg Torque	CF	Description
■	1	Run #1	1/8/22	18:44	337.2 HP	NA	194.1 HP	0.0%	347.4 lb·ft	NA	257.3 lb·ft	0.95	
🟦	2	Run #2	4/23/22	18:47	479.5 HP	NA	301.8 HP	42.2%	510.2 lb·ft	NA	396.6 lb·ft	0.97	

Figure 60: *Graph of Power Figures from Partial Acceleration on Upgraded Engine*



Point Data Report

JoJo Scafidi

H: 325487964 W: E:
1997 Corvette coupe

Thompson Performance Services
50 Dunham Rd
Billerica, MA
01821
Phone: 617 699-4125
Fax:
Dynocom DC-15000

Run #1

#	Time	Speed I	RPM	Power	Torque	Distance I	
1	0.74	54.79	2500	13.71	28.81	52.86	1
2	0.93	55.26	2550	66.52	137.00	68.05	1
3	1.07	56.14	2600	116.73	235.79	79.61	1
4	1.21	57.31	2650	135.40	268.36	91.25	1
5	1.34	58.41	2700	140.43	273.17	101.83	1
6	1.45	59.48	2750	145.31	277.52	112.05	1
7	1.57	60.55	2800	150.12	281.59	122.32	1
8	1.69	61.63	2850	154.55	284.82	132.66	1
9	1.80	62.69	2900	159.12	288.17	143.00	1
10	1.91	63.76	2950	163.64	291.34	153.40	1
11	2.02	64.83	3000	168.23	294.52	163.87	1
12	2.13	65.90	3050	172.72	297.42	174.41	1
13	2.24	66.97	3100	176.87	299.66	185.06	1
14	2.35	68.04	3150	181.01	301.81	195.80	1
15	2.46	69.12	3200	184.96	303.57	206.63	1
16	2.57	70.19	3250	188.97	305.38	217.60	1
17	2.67	71.27	3300	193.22	307.51	228.69	1
18	2.78	72.35	3350	197.29	309.30	239.89	1
19	2.88	73.43	3400	200.88	310.31	251.23	1
20	2.99	74.51	3450	204.33	311.07	262.68	1
21	3.10	75.58	3500	208.06	312.21	274.23	1
22	3.20	76.66	3550	212.33	314.13	285.88	1
23	3.30	77.74	3600	216.21	315.44	297.71	1
24	3.41	78.83	3650	218.85	314.91	309.75	1
25	3.51	79.91	3700	221.37	314.23	321.90	1
26	3.62	80.98	3750	224.87	314.94	334.13	1
27	3.72	82.05	3800	229.45	317.14	346.42	1
28	3.82	83.12	3850	234.88	320.42	358.72	1
29	3.92	84.18	3900	240.77	324.24	371.03	1
30	4.02	85.24	3950	247.16	328.64	383.32	1
31	4.12	86.31	4000	253.34	332.64	395.70	1
32	4.22	87.39	4050	258.38	335.07	408.18	1
33	4.31	88.46	4100	263.09	337.02	420.69	1
34	4.41	89.54	4150	268.08	339.27	433.25	1
35	4.51	90.61	4200	272.70	341.01	445.91	1
36	4.60	91.68	4250	277.19	342.55	458.67	1
37	4.70	92.76	4300	281.82	344.22	471.52	1
38	4.79	93.84	4350	286.24	345.61	484.51	1
39	4.89	94.91	4400	290.26	346.48	497.61	1
40	4.98	95.99	4450	294.16	347.18	510.84	1
41	5.08	97.08	4500	297.68	347.44	524.25	1
42	5.17	98.17	4550	300.57	346.95	537.88	1
43	5.27	99.25	4600	302.94	345.88	551.70	1
44	5.36	100.34	4650	305.59	345.15	565.68	1
45	5.46	101.43	4700	308.67	344.93	579.80	1
46	5.55	102.51	4750	312.02	345.00	594.08	1

Page 1 of 2

Point Data Report

JoJo Scafidi

H: 325487964 W: E:
1997 Corvette coupe

Thompson Performance Services
50 Dunham Rd
Billerica, MA
01821
Phone: 617 699-4125
Fax:
Dynocom DC-15000

Run #1

#	Time	Speed I	RPM	Power	Torque	Distance I	
47	5.65	103.60	4800	315.42	345.13	608.54	1
48	5.74	104.68	4850	318.69	345.11	623.14	1
49	5.84	105.77	4900	322.02	345.17	637.87	1
50	5.93	106.85	4950	325.12	344.96	652.81	1
51	6.03	107.95	5000	326.69	343.16	668.05	1
52	6.13	109.05	5050	327.99	341.12	683.56	1
53	6.23	110.14	5100	329.53	339.36	699.27	1
54	6.32	111.23	5150	332.15	338.74	715.13	1
55	6.42	112.33	5200	335.07	338.42	731.28	1
56	6.52	113.44	5250	336.91	337.04	747.79	1
57	6.62	114.56	5300	337.21	334.17	764.75	1
58	6.73	115.75	5350	333.57	327.46	783.24	1
59	6.98	117.90	5350	152.33	149.55	825.95	1
60	7.07	118.14	5300	6.45	6.39	841.80	1
61	7.17	117.97	5250	-117.14	-	858.45	1
62	7.27	117.49	5200	-174.08	-	876.38	1
63	7.35	117.09	5150	-173.63	-	888.95	1
64	7.40	116.82	5100	-161.76	-	897.67	1
65	7.44	116.62	5050	-148.58	-	904.48	1
66	7.47	116.47	5000	-135.78	-	910.23	1
67	7.50	116.34	4950	-123.89	-	915.27	1

Page 2 of 2

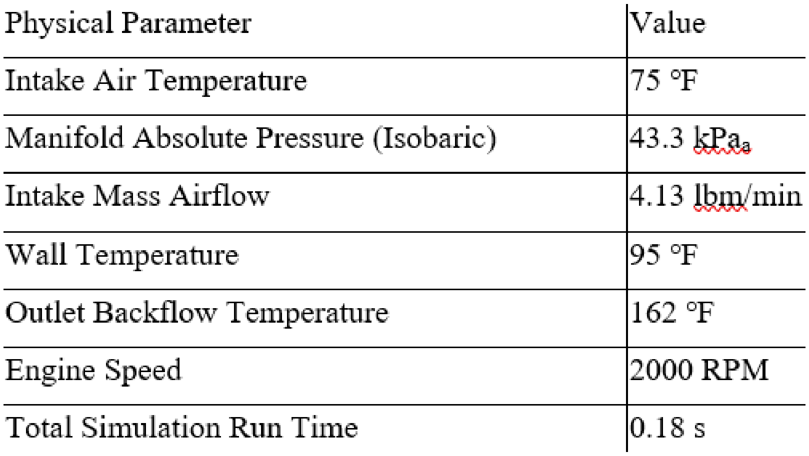
Figure 61: *Data from Dyno Acceleration on Upgraded Engine*

Intake Manifold Flow Simulation Results

The original purpose of these simulations was to determine if the project could model airflow through the intake system to predict power development. The team scaled this goal back to modeling the differences between each intake manifold. A manifold performs well if it can move air with little resistance. The manifold is designed by the manufacturer in such a way to facilitate filling the cylinders with air quickly. If more air can flow into a cylinder for a given engine speed, more power can be developed at the wheels of the car. So, a manifold that can flow more air should help an engine develop more power. This is not the only consideration related to manifold geometry for power, but it will be the one that this analysis tests.

The initial simulations utilized a simpler prototype manifold geometry to test the simulation parameters. The benefit of a simpler initial geometry is that simulations finish within a couple of hours rather than six, ten, or twenty-four hours. This means that different parameters can be tested and changed on geometry that has some similarities to the final models. The results on the simple geometry were not accurate, but it provided a nice testbed to check expected results and trial different graphics so that the simulations on the complex geometry could be run only once.

Airflow within the LS6 and Trailblazer SS intake manifolds was simulated in ANSYS Fluent. Table 2 summarizes the initial boundary conditions of the simulations as well as the duration of the model. Effectively, the environment that the team tried to recreate in Fluent was one where the engine was operating at a constant 2000 RPM at wide-open throttle. Parameters for temperature, flow, and pressure were taken from the initial dynamometer data with the LS1 engine and the LS6 intake manifold. The team then applied these conditions to both the LS6 and the Trailblazer SS manifolds. Therefore, engine speed and mass airflow were held constant between each manifold. ANSYS measured and recorded the difference in flow at the outlets each time step. The manifold that flowed the most volume of air for these conditions would be the better performing manifold according to simulation.

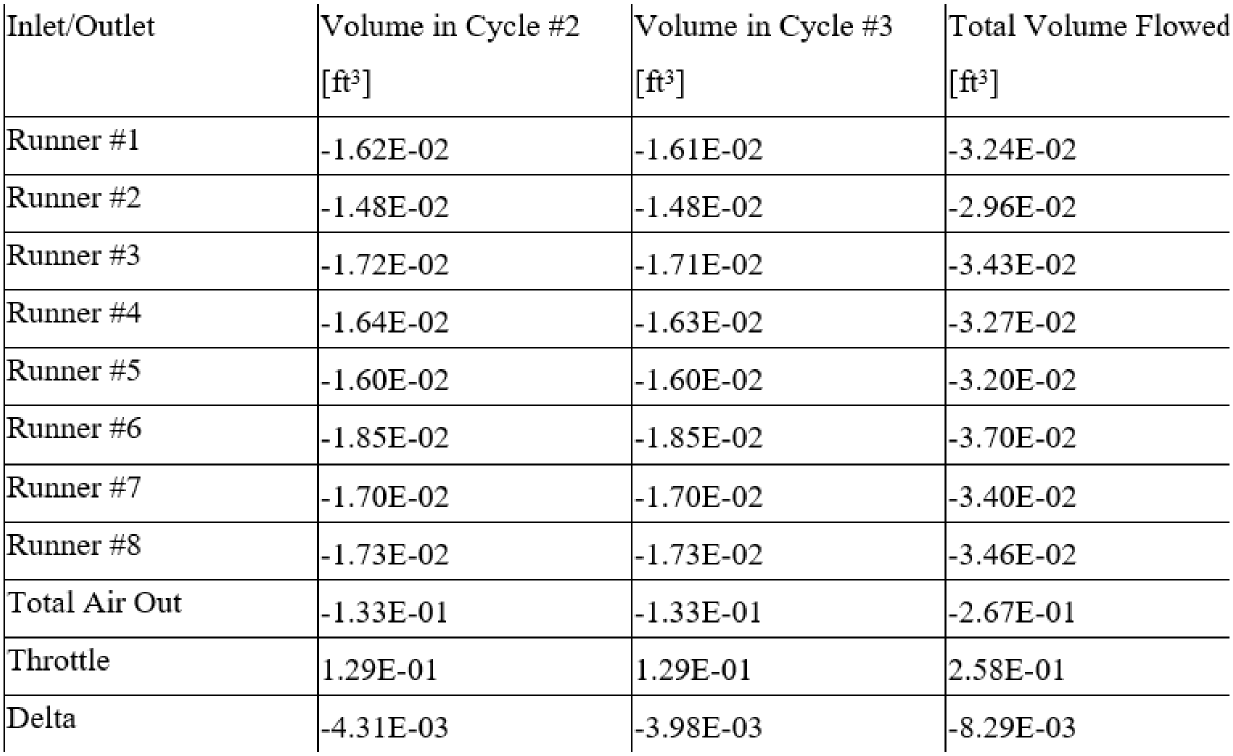


Physical Parameter	Value
Intake Air Temperature	75 °F
Manifold Absolute Pressure (Isobaric)	43.3 kPa$_a$
Intake Mass Airflow	4.13 lbm/min
Wall Temperature	95 °F
Outlet Backflow Temperature	162 °F
Engine Speed	2000 RPM
Total Simulation Run Time	0.18 s

Table 2: *Simulation Initial Boundary Conditions*

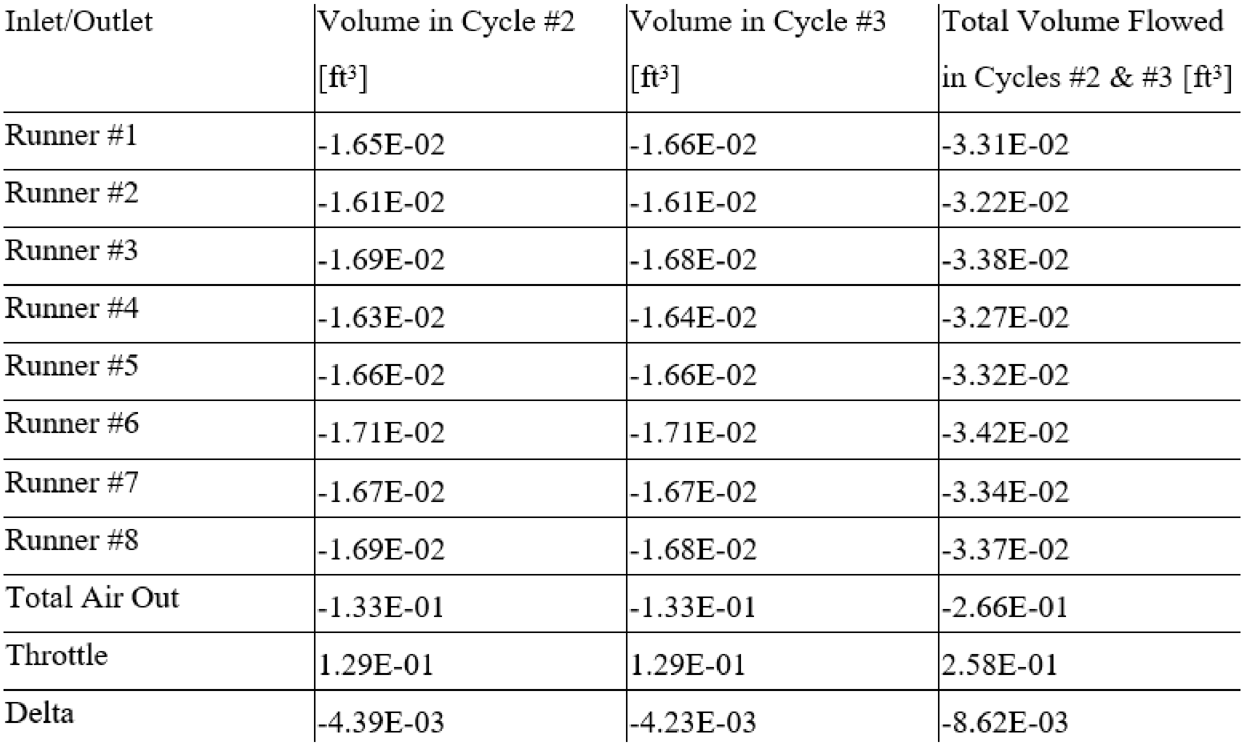
Fluent monitored the volumetric flow rate at the outlets of the runners for each time step. To calculate the total volume of air moved, the integral of the volumetric flow rate was taken with respect to time. The result was the amount of air moved in cubic feet by each runner. The simulation modeled three four-stroke cycles, but the data for the first of those cycles was muddied by the solver. Therefore, only the second and third cycles can be considered. Table 3 shows the volume of air flow by each open runner, the inlet, and the total volume flowed for the

LS6 manifold. Table 4 shows the same kind of data for the Trailblazer SS manifold. Appendix D contains the raw data used to summarize the flow data shown below. Appendix E contains all of the flow vs. time plots for each manifold.



Inlet/Outlet	Volume in Cycle #2 [ft³]	Volume in Cycle #3 [ft³]	Total Volume Flowed [ft³]
Runner #1	-1.62E-02	-1.61E-02	-3.24E-02
Runner #2	-1.48E-02	-1.48E-02	-2.96E-02
Runner #3	-1.72E-02	-1.71E-02	-3.43E-02
Runner #4	-1.64E-02	-1.63E-02	-3.27E-02
Runner #5	-1.60E-02	-1.60E-02	-3.20E-02
Runner #6	-1.85E-02	-1.85E-02	-3.70E-02
Runner #7	-1.70E-02	-1.70E-02	-3.40E-02
Runner #8	-1.73E-02	-1.73E-02	-3.46E-02
Total Air Out	-1.33E-01	-1.33E-01	-2.67E-01
Throttle	1.29E-01	1.29E-01	2.58E-01
Delta	-4.31E-03	-3.98E-03	-8.29E-03

Table 3: *LS6 Manifold Flow Data*



Inlet/Outlet	Volume in Cycle #2 [ft³]	Volume in Cycle #3 [ft³]	Total Volume Flowed in Cycles #2 & #3 [ft³]
Runner #1	-1.65E-02	-1.66E-02	-3.31E-02
Runner #2	-1.61E-02	-1.61E-02	-3.22E-02
Runner #3	-1.69E-02	-1.68E-02	-3.38E-02
Runner #4	-1.63E-02	-1.64E-02	-3.27E-02
Runner #5	-1.66E-02	-1.66E-02	-3.32E-02
Runner #6	-1.71E-02	-1.71E-02	-3.42E-02
Runner #7	-1.67E-02	-1.67E-02	-3.34E-02
Runner #8	-1.69E-02	-1.68E-02	-3.37E-02
Total Air Out	-1.33E-01	-1.33E-01	-2.66E-01
Throttle	1.29E-01	1.29E-01	2.58E-01
Delta	-4.39E-03	-4.23E-03	-8.62E-03

Table 4: *Trailblazer SS Manifold Flow Data*

The plots of volumetric flow vs. time for the runners all have a similar shape. Figure 62 shows a typical plot for volumetric flow over time at the outlet of a runner. The flow rate increases the longer the runner is open. This conclusion is valid from a physical perspective because it takes time for the air to accelerate through the runner. While the runner is closed, the air is not moving inside it. When the runner opens, the air is drawn through the runner from the plenum as the piston pulls air into the cylinder. This is modeled as a source of mass flow into the manifold. The velocity of the air continues to increase as the open runner duration increases. But, as this time passes, the pressure difference between the inlet and the outlet remains relatively constant at 400 Pa_a. Figures 63-66 show the pressure gradient in Runner #6 of the LS6 manifold over four separate time steps. Figures 67-70 show the pressure gradient in Runner #6 (left runner in image) of the Trailblazer SS manifold over the same four separate time steps.

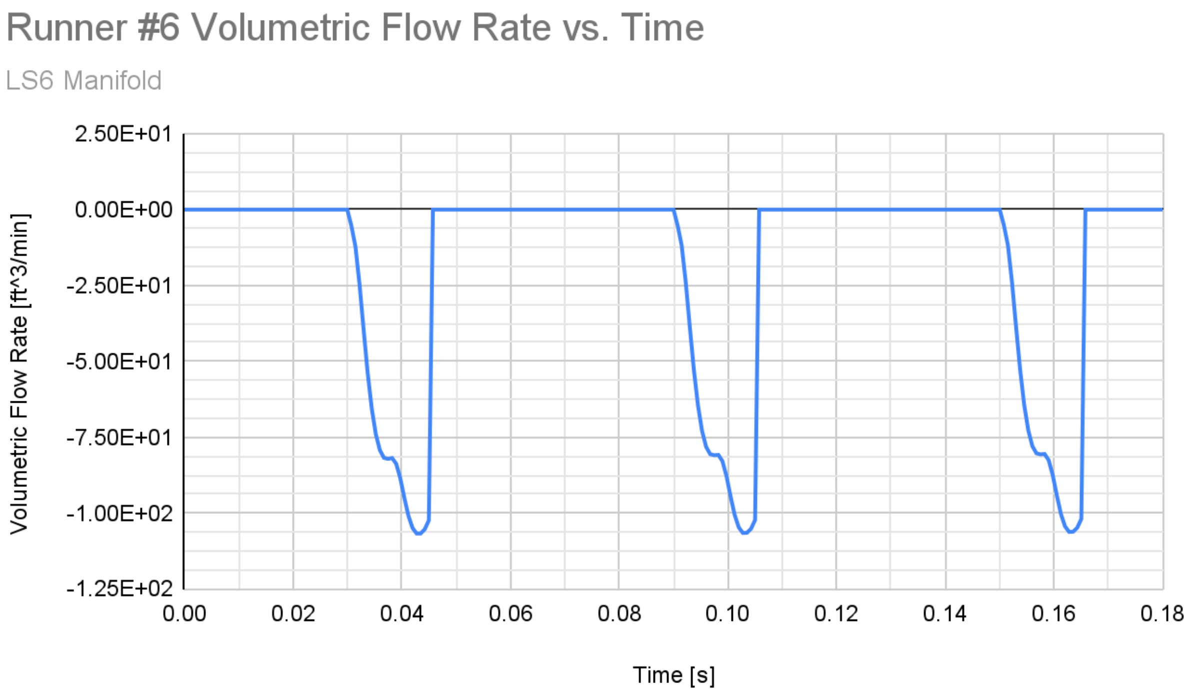


Figure 62: *Volumetric Flow vs Time for Runner #6 of LS6 Manifold*

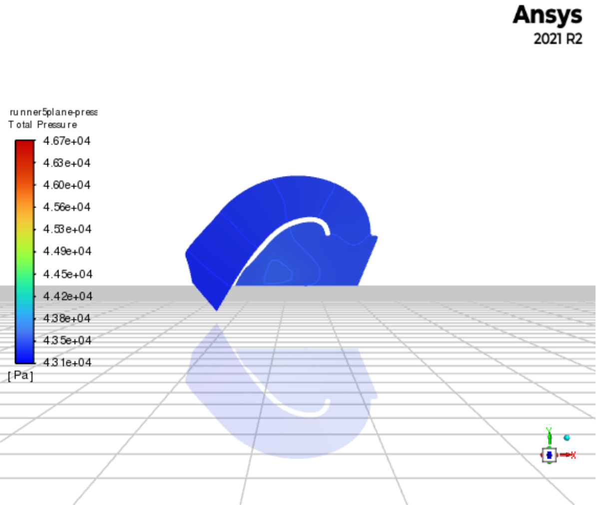


Figure 63: Pressure Plot of LS6 Manifold Through Runner #6 at n=121

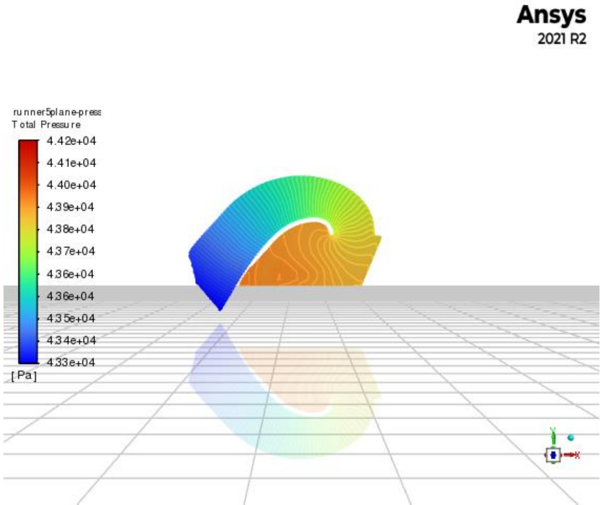


Figure 64: *Pressure Plot of LS6 Manifold Through Runner #6 at n=124*

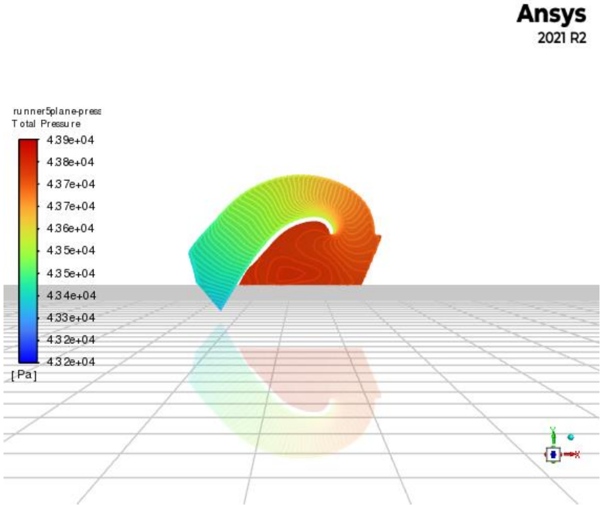


Figure 65: *Pressure Plot of LS6 Manifold Through Runner #6 at n=127*

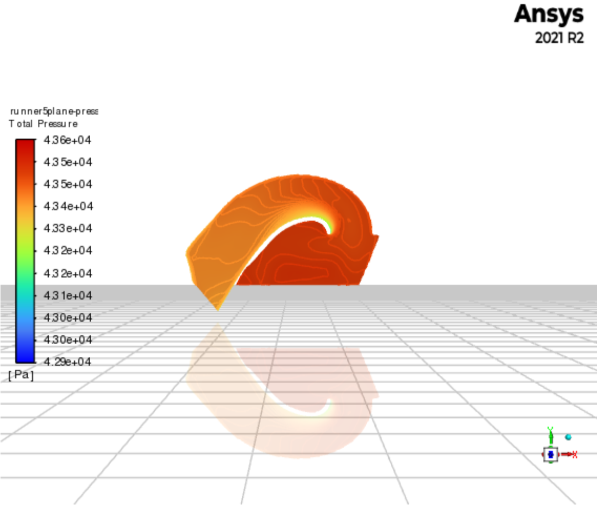


Figure 66: *Pressure Plot of LS6 Manifold Through Runner #6 at n=130*

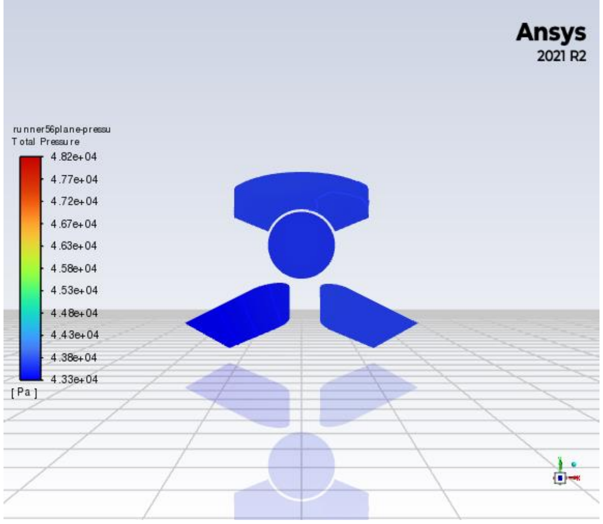


Figure 67: *Pressure Plot of Trailblazer SS Manifold Through Runner #6 at n=121*

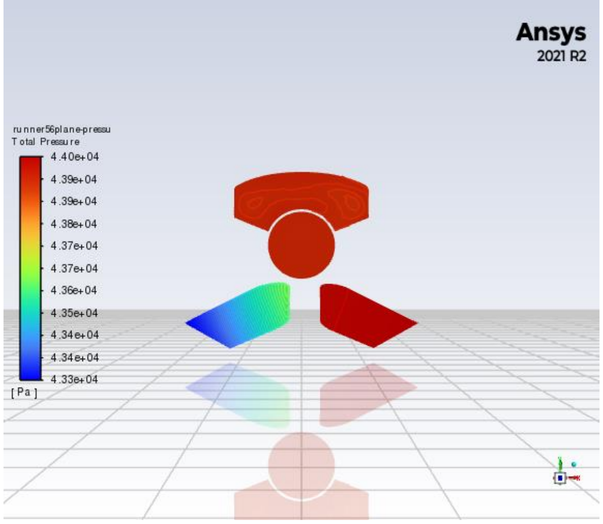


Figure 68: *Pressure Plot of Trailblazer SS Manifold Through Runner #6 at n=124*

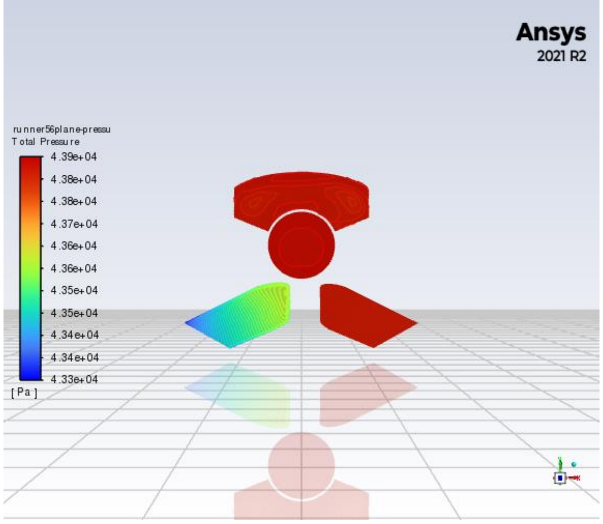


Figure 69: *Pressure Plot of Trailblazer SS Manifold Through Runner #6 at n=127*

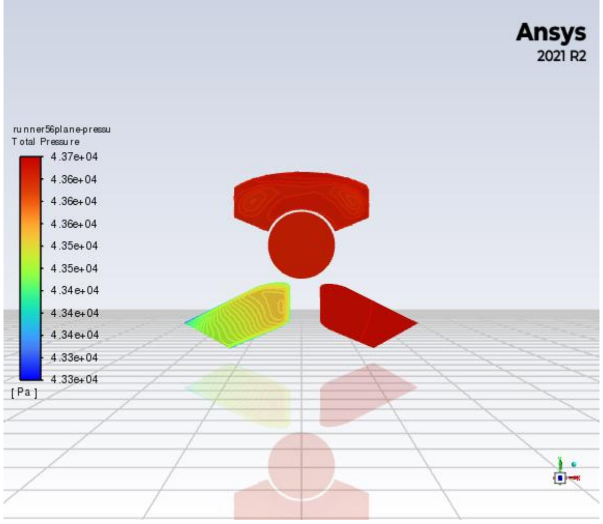


Figure 70: *Pressure Plot of Trailblazer SS Manifold Through Runner #6 at n=130*

According to the data in Tables 3 and 4, both manifolds flow a similar amount of air. This makes sense because all runners are open for the same amount of time with the same mass flow into the manifold. This is a critical limitation for this model. Since the simulations were performed using the same boundary conditions, it is possible that the same results may be obtained regardless of the difference in geometries. More simply, if the mass flow rates into the manifolds are the same, then the mass flow rates out of the manifolds must also be similar. Small variations in the outlet mass flow rates could be related to the temperature effects on the density of the fluid. These temperature effects can change the velocity of air in the runners to balance the mass flow. Figures 71-74 show the velocity magnitude of the fluid in Runner #6 of the LS6 manifold over four separate time steps. Figures 75-78 show the same data for the Trailblazer SS manifold.

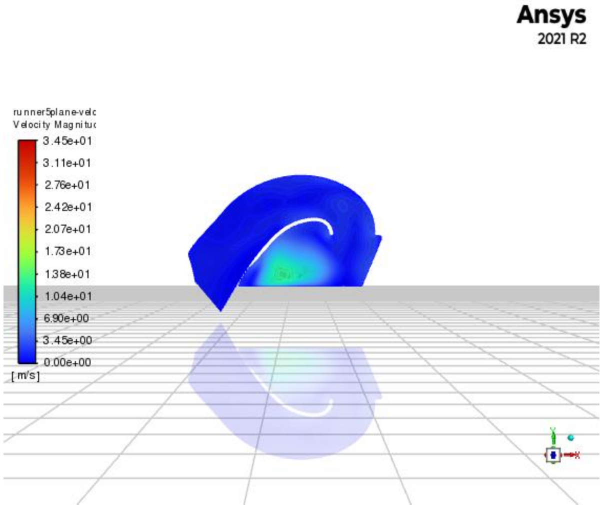


Figure 71: *Velocity of LS6 Manifold Through Runner #6 at n=121*

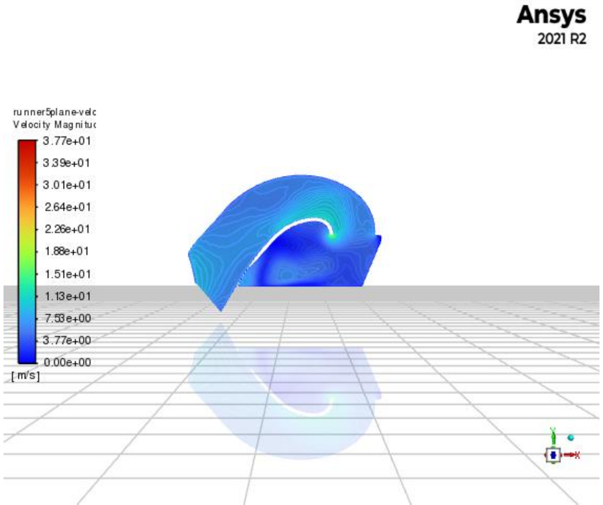


Figure 72: *Velocity of LS6 Manifold Through Runner #6 at n=121*

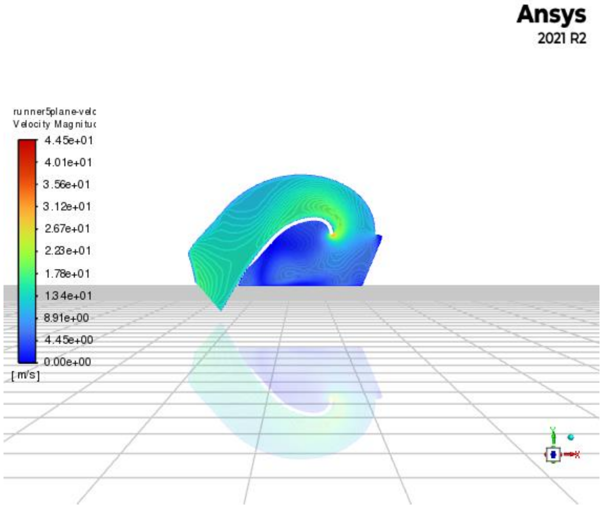


Figure 73: *Velocity of LS6 Manifold Through Runner #6 at n=127*

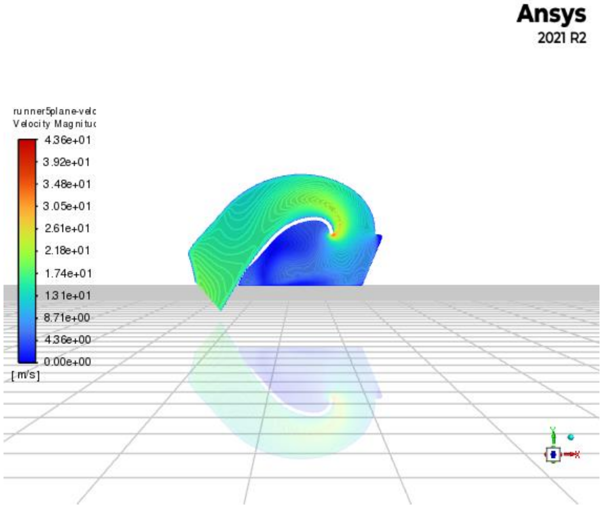


Figure 74: *Velocity of LS6 Manifold Through Runner #6 at n=130*

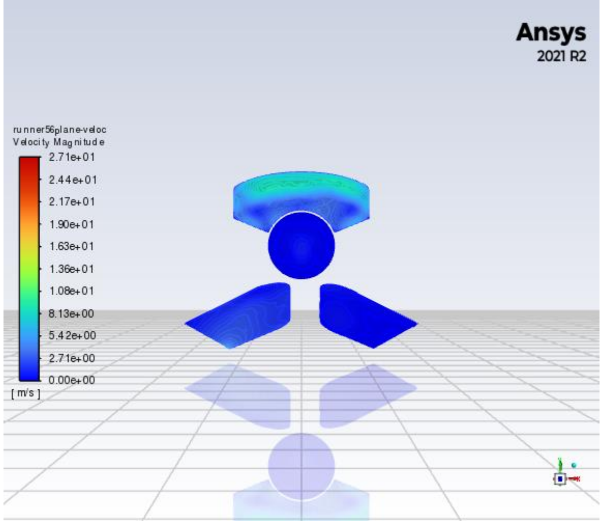


Figure 75: *Velocity Plot of Trailblazer SS Manifold Through Runner #6 at n=121*

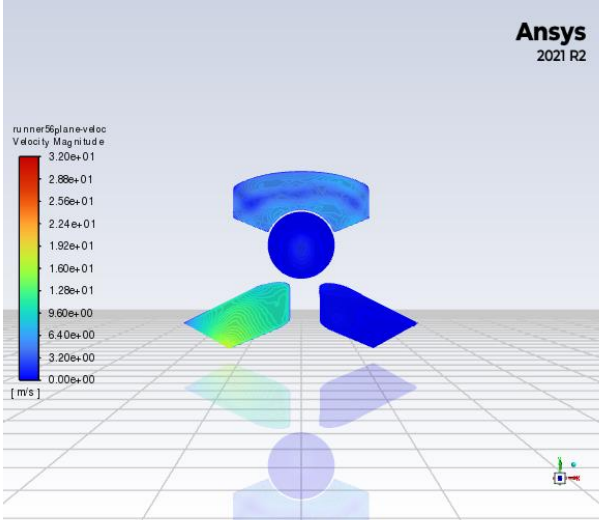


Figure 76: *Velocity Plot of Trailblazer SS Manifold Through Runner #6 at n=124*

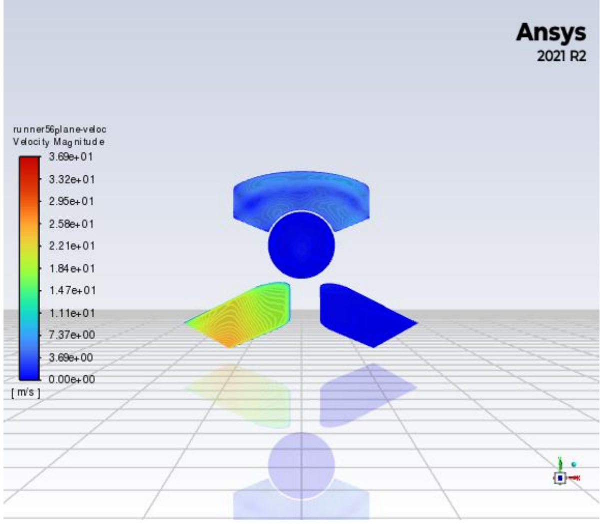


Figure 77: *Velocity Plot of Trailblazer SS Manifold Through Runner #6 at n=127*

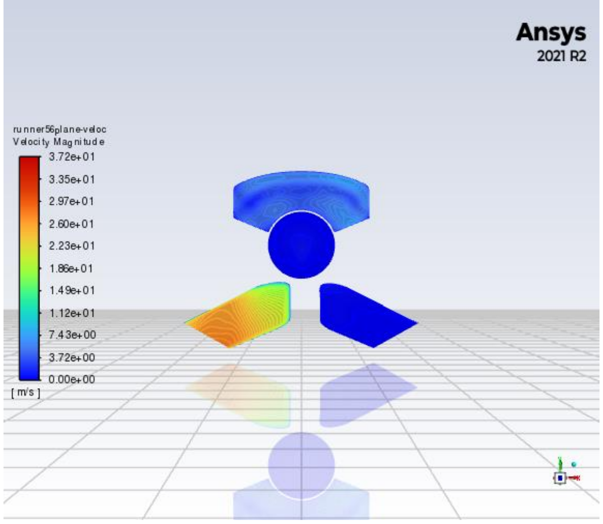


Figure 78: *Velocity Plot of Trailblazer SS Manifold Through Runner #6 at n=130*

In general, the velocity of the air in the runners of the Trailblazer SS manifold is initially higher than that of the LS6 manifold. The duration that these velocities were greater varied from runner to runner. This variation is probably due to the sequence of open runners. For approximately the first half of a corresponding runner's open period, the Trailblazer SS flowed air more quickly and therefore flowed more air. Additional evidence for this conclusion can be found by comparing the volumetric flow rates of corresponding runners in Tables D2-D9 and D12-D19. The runners in the LS6 manifold also have higher maximum volumetric flow rates than in the Trailblazer SS manifold. Therefore, the air in the LS6 manifold accelerates more quickly over its open period than the air in the same runner of the Trailblazer SS manifold even with a lower initial velocity.

An interesting observation of the data is that mass flow through the manifold is not net-zero at all instances in time. Figures 79 and 80 show the net mass flow through the LS6 and Trailblazer SS manifolds, respectively, throughout the simulation. These figures illustrate why roughly the first half of the first four-stroke cycle contains useless data: the mass flow through the manifold has not stabilized enough from the initial conditions. The fluctuation of the net mass flow rate does not tend to zero after that period, though. It continues to fluctuate between a maximum and minimum value. The variation for the LS6 manifold is +4/-3 lbm/min, while for the Trailblazer SS manifold it is +2/-1 lbm/min. The difference in this variation could be due to the more complex construction of the LS6 manifold solid model confusing the Fluent solver.

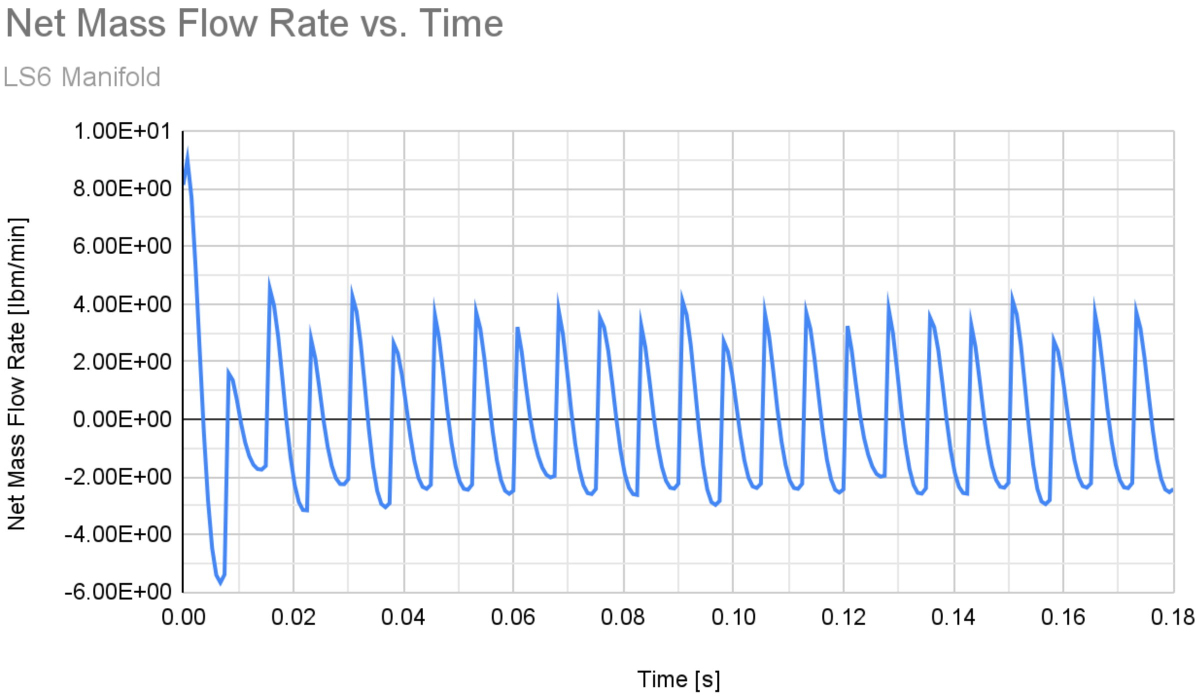


Figure 79: *Net Mass Flow in LS6 Manifold*

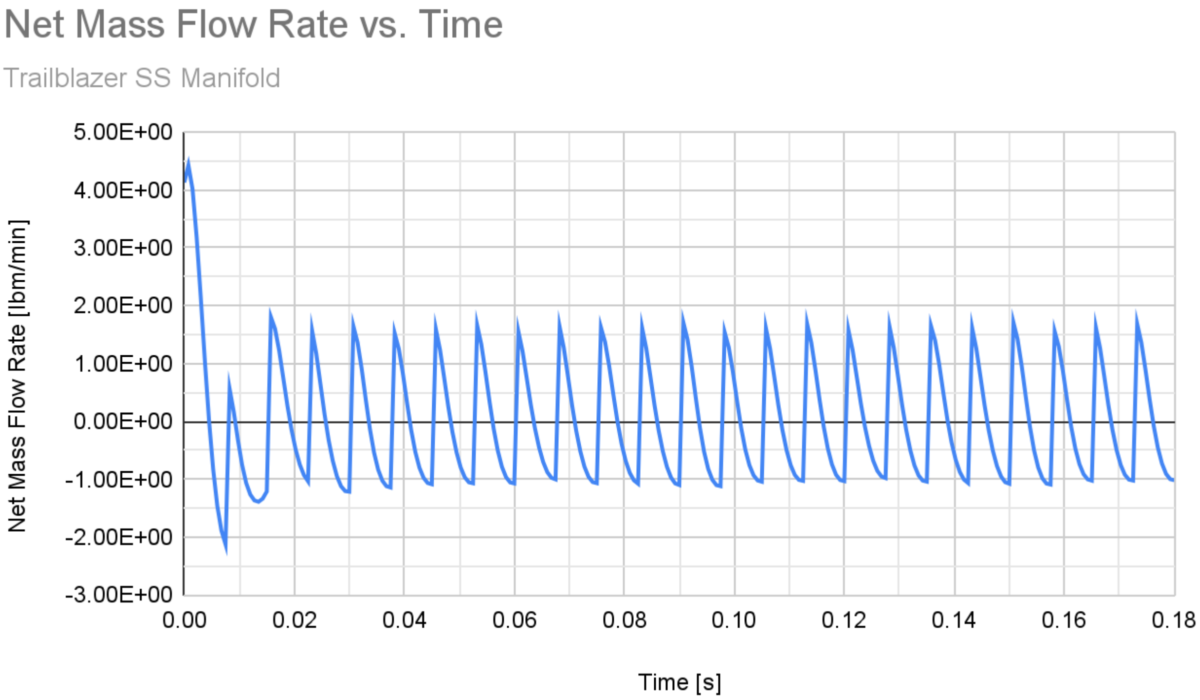


Figure 80: *Net Mass Flow in Trailblazer SS Manifold*

According to the flow rate plots Figures E1-E9 and E11-E19 in Appendix E, there is still flow into the inlet and out of the runners during the fluctuations for both manifolds, implying that the flow does not reverse. This implies that the nonzero net mass flow rate is not related to the operating conditions of the simulation. If the switching aspect of the model were ignored and the manifold was allowed to enter steady-state flow through just two runners, most likely the net mass flow quantity would tend to zero as time increased. Taking the integral of the second and third four-stroke cycles shows that the net change in mass is -5.16e-4 lbm inside the LS6 manifold, and -3.76e-5 lbm inside the Trailblazer SS, confirming the conclusion that the LS6 manifold has greater variation in net mass flow.

As a result, neither manifold performs better than the other under these simulation parameters. While the Trailblazer SS manifold had a more constant volumetric flow rate during the open duration, the LS6 manifold was able to accelerate air more quickly through the runners. This effectively negated the LS6 manifold’s poor initial velocity and allowed both manifolds to flow the same amount of air. The assumption that the manifold was isobaric also held since the difference between inlet and outlet pressure was less than 1 kPa$_a$.

This model suffered from a few crucial flaws. One, the Trailblazer SS model utilized LS6 manifold operating conditions. While the volume of air in the cylinder does not change between manifolds, it is possible that one manifold may have a different mass flow rate and manifold pressure than another due to the differences in plenum and runner geometry. Two, the flow was modeled as being forced into the manifold at the inlet rather than being drawn in at the outlets. While forced induction engines do utilize a compressor to push more air into the cylinders, ultimately air is drawn into the engine by the reciprocating action of the pistons in the block. This subtle difference is important because when the intake valve opens in the cylinder head and the piston descends, a pressure wave emanates from the valve and then again a short time later from the plenum [81]. This model does not include the effects of these pressure waves. Three, the geometry of the LS6 manifold solid model was computationally more complicated and affected the accuracy of those results. The Trailblazer SS manifold was created in fewer steps with simpler tools, and as a result, even though the model contained more components with more curves, Fluent could solve the Trailblazer SS model more quickly and with a better balance between inlet and outlet. Thus, there is no conclusion based on this simulation data showing that one manifold outperforms the other.

Conclusions and Areas for Further Improvement

The group saw tremendous success improving and optimizing airflow through the engine, as well as managing numerous moving parts and avoiding any major problems upon the reassembly of the engine and vehicle. The team utilized many modifications and performance parts to improve the flow of air through the engine and support the increased forces that resulted from the higher power output.

If the group were to continue with the project, the following additional modifications could be made to the car. First, an eight-rib belt pulley system could be incorporated; this system replaces all existing six-rib pulleys in favor of larger eight-rib ones. Upgrading the pulley system increases the surface area with which the supercharger belt can contact the pulley. With the six-rib belt, belt slippage can occur at higher engine speeds, reducing power transmission efficiency. This issue could be mitigated with a new pulley system. Second, an eight nozzle methanol injection system could be added, injecting the methanol into each cylinder rather than only into the intake tube. This would allow for a more even spray pattern. Third, a smaller diameter pulley could be installed onto the supercharger drive gear. This smaller pulley would allow the supercharger to make more boost, which in turn produces more power. Fourth, a larger diameter throttle body could be introduced, creating less air restriction and resulting in more power. Fifth, upgraded transmission and rear differential could be installed to account for the increase in power from the previous modifications, as the drivetrain is already reaching its limitations with the current modifications. And finally, an aftermarket engine control unit could be utilized for more precise control over engine parameters.

Bibliography

[1] R. Jurnecka, “Chevrolet corvette: History, buying tips, auctions, and more,” MotorTrend, 04-Apr-2020. [Online]. Available: https://www.motortrend.com/news/chevrolet-corvette-history-buying-tips-auctions/. [Accessed: 27-Apr-2022].

[2] Joanna, “What's under the hood of your car?,” *AxleAddict*, 29-Jun-2019. [Online]. Available: https://axleaddict.com/auto-repair/Ladies-Whats-Under-Your-Hood. [Accessed: 28-Apr-2022].

[3] “Internal Combustion Engines,” *Internal Combustion Engines - an overview | ScienceDirect Topics*. [Online]. Available: https://www.sciencedirect.com/topics/engineering/internal-combustion-engines. [Accessed: 27-Apr-2022].

[4] Joanna, “What's under the hood of your car?,” *AxleAddict*, 29-Jun-2019. [Online]. Available: https://axleaddict.com/auto-repair/Ladies-Whats-Under-Your-Hood. [Accessed: 28-Apr-2022].

[5] “Looking for can you run a combustion engine on hydrogen,” *Trending Topics, Stories and News - TrendChirp.com*. [Online]. Available: https://www.trendchirp.com/can-you-run-a-combustion-engine-on-hydrogen. [Accessed: 27-Apr-2022].

[6] W. J. Chai, “Performance air filter vs cold air intake: Pros & Cons,” Car Performance Boss, 27-Aug-2021. [Online]. Available: https://carperformanceboss.com/performance-air-filter-vs-cold-air-intake-pros-cons/. [Accessed: 27-Apr-2022].

[7] sgCarMart, “Understanding a car air intake system,” *sgCarMart.com*. [Online]. Available: https://www.sgcarmart.com/news/writeup.php?AID=127. [Accessed: 27-Apr-2022].

[8] P. Novak, “What is the purpose of the throttle body?,” It Still Runs, 10-Jan-2019. [Online]. Available: https://itstillruns.com/purpose-throttle-body-6528238.html. [Accessed: 27-Apr-2022].

[9] “General Motors 12605109, fuel injection throttle body ...,” Amazon, 16-Dec-2016. [Online]. Available: https://www.amazon.ca/General-Motors-12605109-Injection-Throttle/dp/B00M38UGPQ. [Accessed: 28-Apr-2022].

[10] C. Stevenson, “How does a car engine create a vacuum?,” It Still Runs, 10-Jan-2019. [Online]. Available: https://itstillruns.com/car-engine-create-vacuum-12193724.html. [Accessed: 27-Apr-2022].

[11] “SA203P_FULLBOOK_GMLSENGINES_PAGE_121_IMAGE_0004 • LS Engine DIY,” LS Engine DIY, 04-Jun-2017. [Online]. Available: https://www.lsenginediy.com/induction-guide-for-building-big-inch-ls-engines/sa203p_fullbook_gmlsengines_page_121_image_0004/. [Accessed: 27-Apr-2022].

[12] A. Ajmal, “This is the difference between a turbocharged and supercharged engine,” Wonderful Engineering, 17-Feb-2018. [Online]. Available: https://wonderfulengineering.com/turbocharged-vs-supercharged-difference/. [Accessed: 27-Apr-2022].

[13] Lewis, C., 2022. *What’s Better Cast Iron or Aluminum Cylinder Heads?*. [online] MicroGreenFilter. Available at: <https://www.microgreenfilter.com/cast-iron-or-aluminum-cylinder-heads/> [Accessed 24 April 2022].

[14] D. C. | M. 10, “Tech Tidbit: Why an ‘obsolete’ pushrod engine design is better than modern overhead cams,” designnews.com, 10-May-2021. [Online]. Available: https://www.designnews.com/automotive-engineering/tech-tidbit-why-%E2%80%9Cobsolete%E2%80%9D-pushrod-engine-design-better-modern-overhead-cams. [Accessed: 27-Apr-2022].

[15] “LS Camshaft,” Pinterest, 13-May-2020. [Online]. Available: https://www.pinterest.com/pin/455637687301992166/. [Accessed: 27-Apr-2022].

[16] Y. Dubey, “How motorcycle pushrod engines work?,” Motorcycle Pushrod Engine Working, Overhead Valve (OHV) Engines " BikesMedia.in, 10-Jan-2018. [Online]. Available: https://www.bikesmedia.in/reviews/how-motorcycle-pushrod-engines-work.html. [Accessed: 27-Apr-2022].

[17] “What are dual overhead cams?,” HowStuffWorks, 31-Jan-2001. [Online]. Available: https://auto.howstuffworks.com/question562.htm. [Accessed: 27-Apr-2022].

[18] S. Magazin, “SOHC and DOHC engine head configurations working principle 3D animation,” Sia Magazin, 27-Sep-2020. [Online]. Available: https://siamagazin.com/sohc-and-dohc-engine head-configurations-working-principle-3d-animation/. [Accessed: 27-Apr-2022].

[19] “Exhaust systems 101 - car exhaust systems explained,” Sun Devil Auto, 17-Aug-2021. [Online]. Available: https://www.sundevilauto.com/exhaust-systems-101/#:~:text=The%20exhaust%20system%20is%20made,vehicle%20and%20making%20occupants%20sick. [Accessed: 27-Apr-2022].

[20] “How does my exhaust system work?,” Kwik Fit. [Online]. Available: https://www.kwik-fit.com/exhausts/information/how-exhausts-work#:~:text=Exhaust%20gases%20are%20collected%20from,engine%20by%20an%20exhaust%20manifold.&text=These%20exhaust%20gases%20then%20travel,through%20a%20silencer%20or%20muffler. [Accessed: 27-Apr-2022].

[21] S. S. Sharaf, “Exhaust systems - uncorking your engine's potential: Bolt-on Basics,” DSPORT Magazine, 30-Sep-2016. [Online]. Available: https://dsportmag.com/the-tech/bolt-basics-exhaust-systems/. [Accessed: 27-Apr-2022].

[22] Mead, S., 2009. *When Fact Meets Friction: The Basics of Clutch Operation*. [online] edmunds. Available at: <https://www.edmunds.com/car-technology/when-fact-meets-friction-the-basics-of-clutch-operation.html> [Accessed 24 April 2022].

[23] Explained, E., 2015. *Engineering Explained: Clutch Basics And Performance Clutches*. [online] Car Throttle. Available at: <https://www.carthrottle.com/post/engineering-explained-clutch-basics-and-performance-clutches/> [Accessed 24 April 2022].

[24] “How a car clutch works,” *How a Car Works*. [Online]. Available: https://www.howacarworks.com/basics/how-a-car-clutch-works#:~:text=Some%20cars%20have%20a%20hydraulically,to%20the%20clutch%20release%20arm. [Accessed: 27-Apr-2022].

[25] Motor Car History. n.d. *Torque tube explained*. [online] Available at: <https://motor-car.net/innovation/drivetrain/item/14762-torque-tube> [Accessed 24 April 2022].

[26] “2017 Mercedes-AMG GT R,” *CARICOS*. [Online]. Available: https://www.caricos.com/cars/m/mercedes-benz/2017_mercedes-amg_gt_r/. [Accessed: 27-Apr-2022].

[27] Kim, S., 2007. *Learn About Dyno Testing - How Dynos Work - Chevy High Performance Magazine*. [online] MotorTrend. Available at: <https://www.motortrend.com/how-to/0710ch-how-dynos-work/> [Accessed 19 April 2022].

[28] Davis, M., 2004. *Chassis Dyno Guide - Frequently Asked Questions About Dyno Tests - Hot Rod Magazine*. [online] MotorTrend. Available at: <https://www.motortrend.com/how-to/hrdp-0405-chassis-dyno-guide/> [Accessed 19 April 2022].

[29] "Corvette dyno tune with Magnuson Supercharger," *STILLEN Garage*, 20-Sep-2013. [Online]. Available: https://blog.stillen.com/2013/09/corvette-dyno-tune/. [Accessed: 27-Apr-2022].

[30]High Performance Academy. 2022. *129 | Steady State vs Ramp Run - Understanding Dyno Modes*. [online] Available at: <https://www.hpacademy.com/previous-webinars/129-steady-state-vs-ramp-run-understanding-dyno-modes/> [Accessed 19 April 2022].

[31] Dynapack.com. 2022. *Software Features | Dynapack*. [online] Available at: <https://dynapack.com/software-features/> [Accessed 19 April 2022].

[32] Iqsdirectory.com. n.d. *Dynamometer: What Is It? How Does It Work? Types, Uses*. [online] Available at: <https://www.iqsdirectory.com/articles/dynamometers.html> [Accessed 19 April 2022].

[33] DynoEquip. n.d. *AC dynamometer working principle, AC dyno | DynoEquip*. [online] Available at: <https://www.dynoequip.com/ac-dynamometer-en/> [Accessed 19 April 2022].

[34] "AC Engine Dynamometers," *Taylor Dynamometer*. [Online]. Available: https://www.taylordyno.com/products/engine-dynamometers/ac-engine/. [Accessed: 27-Apr-2022].

[35] S. N. Pachpute, "An Introduction to Computational Fluid Dynamics (CFD)," *Basics of CFD modeling for Beginners*, 09-Feb-2022. [Online]. Available: https://cfdflowengineering.com/basics-of-cfd-modeling-for-beginners/. [Accessed: 15-Mar-2022].

[36] F. M. White, "Differential Relations for Fluid Flow," in *Fluid mechanics*, 8th ed., New York, NY: McGraw-Hill Education, 2016, p. 234.

[37] "All there is to know about different mesh types in CFD!," *manchestercfd*, 01-Jun-2016. [Online]. Available: https://www.manchestercfd.co.uk/post/all-there-is-to-know-about-different-mesh-types-in-cfd. [Accessed: 07-Apr-2022].

[38] F. M. White, "Viscous Flow in Ducts," in *Fluid mechanics*, 8th ed., New York, NY: McGraw-Hill Education, 2016, p. 339.

[39] F. M. White, “Introduction,” in *Fluid mechanics*, 8th ed., New York, NY: McGraw-Hill Education, 2016, pp. 25-26.

[40] J. W. Slater, “Overview of CFD verification & validation,” *NPARC Alliance CFD Verification and Validation Web Site*, 10-Feb-2021. [Online]. Available: https://www.grc.nasa.gov/www/wind/valid/tutorial/overview.html. [Accessed: 15-Mar-2022].

[41] O. A. C. Staff, “LS1 engine specs,” On All Cylinders, 12-Oct-2017. [Online]. Available: https://www.onallcylinders.com/2017/10/12/ls1-engine-specs-performance-bore-stroke-cylinder-heads-cam-specs/. [Accessed: 27-Apr-2022].

[42] O. A. C. Staff, “Lq4 6.0L LS engine specs,” On All Cylinders, 01-Feb-2018. [Online]. Available: https://www.onallcylinders.com/2018/02/01/lq4-engine-specs-performance-bore-stroke-cylinder-heads-cam-specs/. [Accessed: 27-Apr-2022].

[43] S. R. Staff, “Upgrading the LS1 and LS6 engines,” Upgrading the LS1 and LS6 Engines, 13-Sep-2018. [Online]. Available: https://help.summitracing.com/app/answers/detail/a_id/4814/~/upgrading-the-ls1-and-ls6-engines#:~:text=The%20stock%20crankshaft%20can%20handle,will%20also%20add%20extra%20displacement. [Accessed: 27-Apr-2022].

[44] M. Mavrigian, “Engine studs: Understanding the advantages of using studs vs. bolts,” *Auto Service Professional*, 20-Dec-2011. [Online]. Available: https://www.autoserviceprofessional.com/articles/2492-engine-studs-understanding-the-advantages-of-using-studs-vs-bolts-and-tips-on-achieving-proper-clamping-loads#:~:text=Studs%20provide%20the%20ability%20to,even%20and%20accurate%20clamping%20forces. [Accessed: 27-Apr-2022].

[45] A. R. P. Staff, “The official ARP web site: Technical information,” *ARP Bolts*. [Online]. Available: https://arp-bolts.com/p/technical.php. [Accessed: 27-Apr-2022].

[46] A. Muir, “Engine pistons and connecting rods,” *How a Car Works*. [Online]. Available: https://www.howacarworks.com/pistons. [Accessed: 28-Apr-2022].

[47] J. Sabhadiya, “What is powder metallurgy?,” *Engineering Choice*, 03-Mar-2022. [Online]. Available: https://www.engineeringchoice.com/powder-metallurgy/. [Accessed: 27-Apr-2022].

[48] Yujiannet, “Mopar 4340 forged I beam connecting rods,” *Engine Components*

Performance Conrod, Piston and Crankshaft Manufacturer in China. [Online]. Available: https://www.hurricanerods.com/products/Forged-Connecting-Rods-for-Chrysler-440-6.760-Center-Length.html#.YmoZYdrMKUk. [Accessed: 28-Apr-2022].

[49] S. R. Staff, “Eagle Specialty Products CRS6125O3D2000 Overview,” *Summitracing.com*. [Online]. Available: https://www.summitracing.com/parts/esp-6125o3d2000. [Accessed: 27-Apr-2022].

[50] C. Cooksey, “Forged versus cast pistons: What's the difference?,” *JE Automotive,* 27-Dec-2017. [Online]. Available: https://auto.jepistons.com/blog/forged-versus-cast-pistons-whats-the-difference. [Accessed: 27-Apr-2022].

[51] M. Magda, “Dish, Dome, Flat Top - What's the Difference?,” *JE Automotive,* 13-Sep-2017. [Online]. Available: https://auto.jepistons.com/blog/dish-dome-flat-top-whats-the-difference. [Accessed: 27-Apr-2022].

[52] J. Smith, “2618 vs. 4032 Piston Material Differences,” JE Automotive, 12-Oct-2017. [Online]. Available: https://auto.jepistons.com/blog/2618-vs.-4032-material-differences. [Accessed: 27-Apr-2022].

[53] J. Sabhadiya, “What is Piston Ring?- function, types, and uses,” *Engineering Choice*, 28-Feb-2022. [Online]. Available: https://www.engineeringchoice.com/piston-ring/. [Accessed: 27-Apr-2022].

[54] “Ring installation guidelines - summit racing equipment,” *Ring Installation Guidelines*. [Online]. Available: https://static.summitracing.com/global/images/instructions/sum-136sm8531005.pdf. [Accessed: 28-Apr-2022].

[55] OnAllCylinders Staff, “LS1 engine specs: Performance, bore & stroke, cylinder heads, Cam Specs & More,” OnAllCylinders, 12-Oct-2017. [Online]. Available: https://www.onallcylinders.com/2017/10/12/ls1-engine-specs-performance-bore-stroke-cylinder-heads-cam-specs/. [Accessed: 27-Apr-2022].

[56] “Chevy Lq4 Engine specs,” Chevy LQ4 Engine Specs, 01-Jun-2017. [Online]. Available: https://help.summitracing.com/app/answers/detail/a_id/4809/~/chevy-lq4-engine-specs. [Accessed: 27-Apr-2022].

[57] “Brian Tooley BTR CCP jam cam supercharged LS1 LS2 LS6 5.7 6.0 5.3 Camshaft Kit,” Michigan Motorsports. [Online]. Available: https://www.michiganmotorsports.com/camshafts-brian-tooley-btr/brian-tooley-btr-ccp-jam-cam-supercharged-ls1-ls2-ls6-5-7-6-0-5-3-camshaft-kit/. [Accessed: 27-Apr-2022].

[58] “BTR 32631134R1 Stage 2 camshaft, turbocharged, LS,” Speedway Motors. [Online]. Available: https://www.speedwaymotors.com/BTR-32631134R1-Stage-2-Camshaft-Turbocharged-LS,487670.html?sku=36983263&utm_medium=CSEGoogle&utm_source=CSE&utm_campaign=CSEGOOGLE&gclid=Cj0KCQjw06OTBhC_ARIsAAU1yOV4zX0HEtamczei7QLvP-xjDdAMw6BQXxMW0KjISESEasb7BsRe9ysaAmWbEALw_wcB. [Accessed: 27-Apr-2022].

[59] Solomon, O., 2022. *243 Heads - What is So Special?*. [online] RXMechanic. Available at: <https://rxmechanic.com/243-heads/> [Accessed 24 April 2022].

[60] DiY, L., 2015. *Ultimate LS Cathedral Port Cylinder Heads Guide*. [online] LS Engine DIY. Available at: <https://www.lsenginediy.com/ultimate-ls-cathedral-port-cylinder-heads-guide/> [Accessed 24 April 2022].

[61] Zick, “Lq4 with 243 heads whats the compression ratio?,” *PerformanceTrucks.net Forums*, Jan-2007. [Online]. Available: https://www.performancetrucks.net/forums/gm-engine-exhaust-performance-21/lq4-243-heads-whats-compression-ratio-417395/. [Accessed: 27-Apr-2022].

[62] M. Davis, “What You Need To Know About Valvesprings - All About Valvesprings - How To Do It,” *MotorTrend*, 01-Nov-2010. [Online]. Available: https://www.motortrend.com/how-to/hrdp-1011-what-you-need-to-know-about-valvesprings/. [Accessed: 27-Apr-2022].

[63] “GM LS1 243 CNC ported heads,” *GM LS1 LS6 243 Cathedral Port Heads*. [Online]. Available: https://latemodelengines.com/gm-ls1-heads-group.html. [Accessed: 27-Apr-2022].

[64] “Arp, head bolt kit, chev LS1/6 Gen III, hex, 4.8, 5.3, 6.0L,” *ARP, Head Bolt Kit, Chev LS1/6 Gen III, Hex, 4.8, 5.3, 6.0L - Competition Products*. [Online]. Available: https://www.competitionproducts.com/ARP-Head-Bolt-Kit-Chev-LS1_6-Gen-III-Hex-48-53-60L/productinfo/ARP134-3609/#.YmmQcNrMJEY. [Accessed: 27-Apr-2022].

[65] S. Tsuneishi, “Water / methanol injection - tech-knowledge,” *MotorTrend*, 09-Aug-2014. [Online]. Available: https://www.motortrend.com/how-to/impp-1101-water-methanol-injection/#:~:text=Water%2Fmethanol%20injection%20systems%20deliver,propensity%20for%20detonation%20is%20decreased. [Accessed: 27-Apr-2022].

[66] “Marken Performance and Restoration Inc,” *Marken Performance and Restoration*. [Online]. Available: https://markenperformance.com/n-6821-aem-water-methanol-injection-for-gas-diesel.html. [Accessed: 27-Apr-2022].

[67] “Corvette C5 map kit,” *Corvette C5 MAP Kit*. [Online]. Available: https://www.alkycontrol.com/shop/corvette-c5-map-kit. [Accessed: 27-Apr-2022].

[68] “RST,” Mcleodracing. [Online]. Available: https://www.mcleodracing.com/rst/p31. [Accessed: 27-Apr-2022].

[69] “DYNOCOM Industries Inc. 7500 Series,” *Dynocom 7500 Series*. [Online]. Available: https://www.dynocom.net/Brochures/7500Series.pdf. [Accessed: 27-Apr-2022].

[70] “1-866-436-DYNO(3966),” *Dynocom, Inc. Automotive Software & Hardware Data Systems*. [Online]. Available: https://www.dynocom.net/catalog/detail.asp?iPro=165. [Accessed: 27-Apr-2022].

[71] A. Pathak, “10 best CFD Analysis Software for Advanced Product Development,” 14-Sep-2021. [Online]. Available: https://geekflare.com/best-cfd-analysis-software/. [Accessed: 17-Mar-2022].

[72] “6.1.3 Choosing the Appropriate Mesh Type,” *Ansys Fluent 12.0 user's guide*, 29-Jan-2009. [Online]. Available: https://www.afs.enea.it/project/neptunius/docs/fluent/html/ug/node164.htm. [Accessed: 09-Dec-2021].

[73] “6.2.2 Mesh Quality,” *Ansys Fluent 12.0 user's Guide*, 29-Jan-2009. [Online]. Available: https://www.afs.enea.it/project/neptunius/docs/fluent/html/ug/node167.htm. [Accessed: 09-Dec-2021].

[74] LEAP CFD Team, “Tips & Tricks: Inflation layer meshing in Ansys,” *Computational Fluid Dynamics CFD Blog*, 06-Jan-2012. [Online]. Available: https://www.computationalfluiddynamics.com.au/tips-tricks-inflation-layer-meshing-in-ansys/. [Accessed: 07-Apr-2022].

[75] “26.1 overview of using the solver,” *Ansys Fluent 12.0 user's guide*, 29-Jan-2009. [Online]. Available: https://www.afs.enea.it/project/neptunius/docs/fluent/html/ug/node776.htm. [Accessed: 05-Dec-2021].

[76] “26.13.1 Monitoring Residuals,” *Ansys Fluent 12.0 user's Guide*, 29-Jan-2009. [Online]. Available: https://www.afs.enea.it/project/neptunius/docs/fluent/html/ug/node812.htm. [Accessed: 22-Mar-2022].

[77] “3. text user interface (TUI),” *Ansys Fluent 12.0 user's guide*, 29-Jan-2009. [Online]. Available: https://www.afs.enea.it/project/neptunius/docs/fluent/html/ug/node47.htm. [Accessed: 01-Feb-2022].

[78] T. L. Bergman, F. P. Incropera, A. S. Lavine, and D. P. Dewitt, “Thermophysical Properties of Matter,” in *Fundamentals of Heat and Mass Transfer*, 7th ed., Hoboken, NJ: Wiley, 2011, p. 995.

[79] Cheatin' Chad, “LS1 intake manifold, what is it actually made of?,” *LS1TECH - camaro and Firebird Forum discussion*, 16-May-2004. [Online]. Available: https://ls1tech.com/forums/generation-iii-external-engine/172326-ls1-intake-manifold-what-actually-made.html. [Accessed: 28-Nov-2021].

[80] “33.3.3 viscous model dialog box,” *Ansys Fluent 12.0 user's Guide*, 29-Jan-2009. [Online]. Available: https://www.afs.enea.it/project/neptunius/docs/fluent/html/ug/node1022.htm. [Accessed: 09-Nov-2021].

[81] R. Holdener, “Dyno Testing Fast's new adjustable intake runner system,” *MotorTrend*, 29-Jul-2016. [Online]. Available: https://www.motortrend.com/how-to/1607-dyno-testing-fasts-new-adjustable-intake-runner-system/. [Accessed: 25-Mar-2022].

Appendix A

These are the isometric, top, front, and side views of each model during development. They are broken into three categories: simplified geometry, LS6 manifold, and Trailblazer SS manifold. The final versions of the LS6 and Trailblazer SS manifolds are included with the supporting material of this project.

Simplified Geometry Models

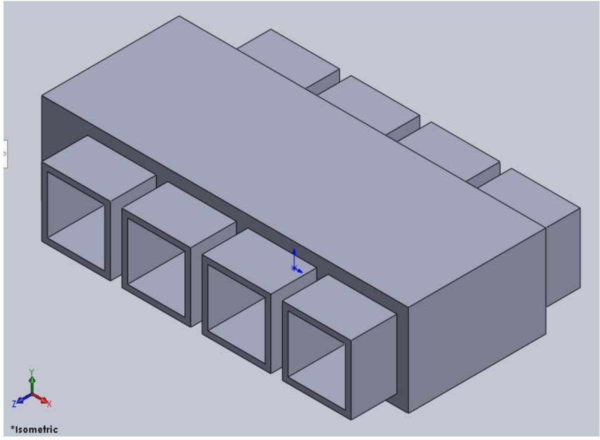


Figure A1: First Prototype Isometric View

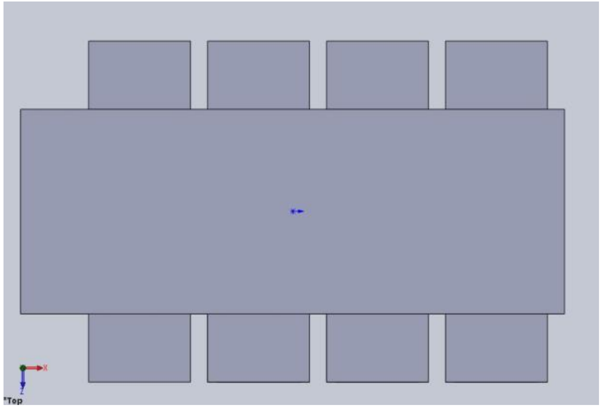


Figure A2: First Prototype Top View

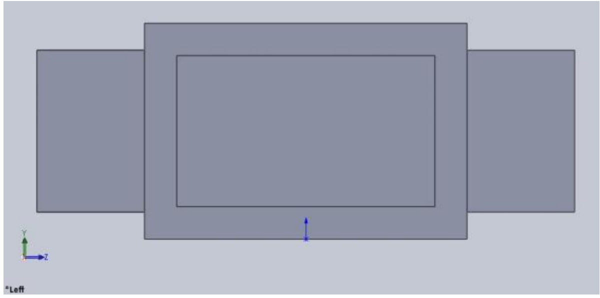


Figure A3: First Prototype Front View

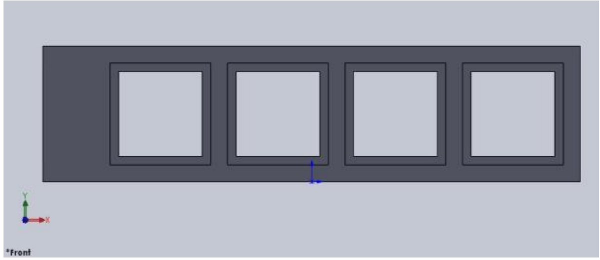


Figure A4: First Prototype Side View

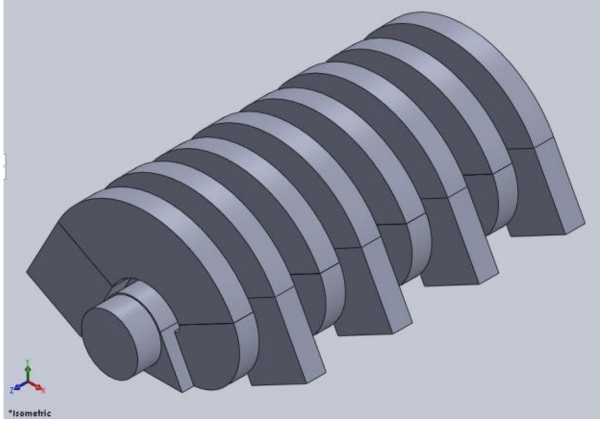


Figure A5: Second Prototype Isometric View

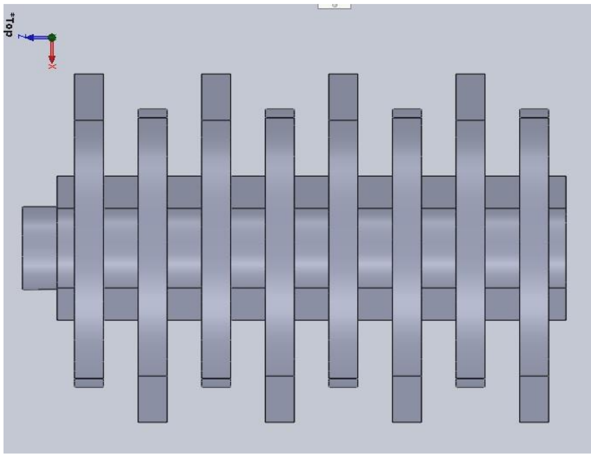


Figure A6: Second Prototype Top View

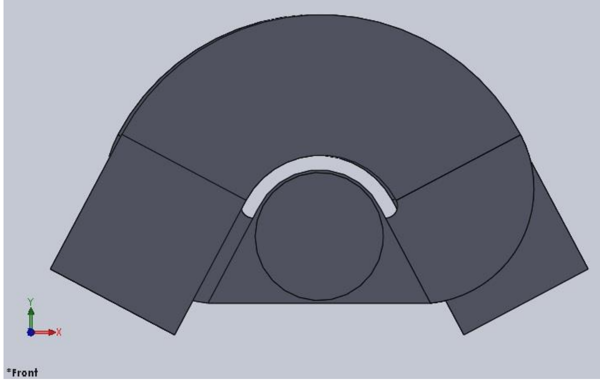


Figure A7: Second Prototype Front View

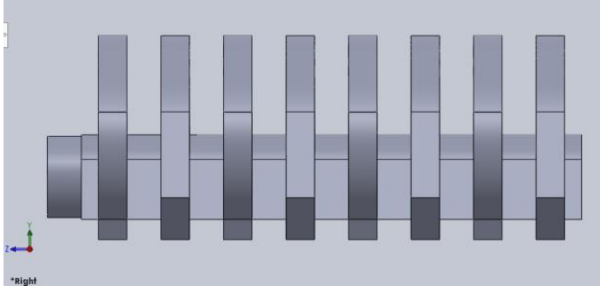


Figure A8: Second Prototype Side View

LS6 Manifold Models

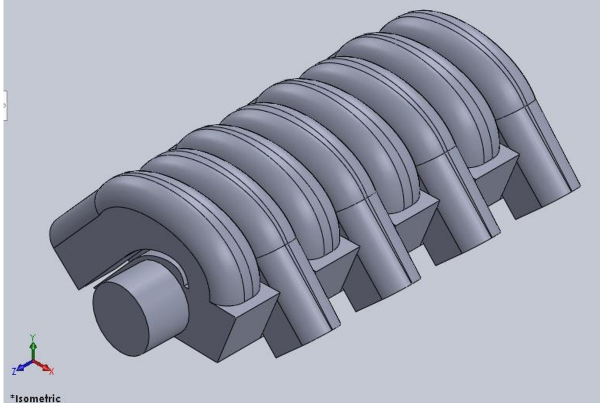


Figure A9: LS6 Mark 1 Isometric View

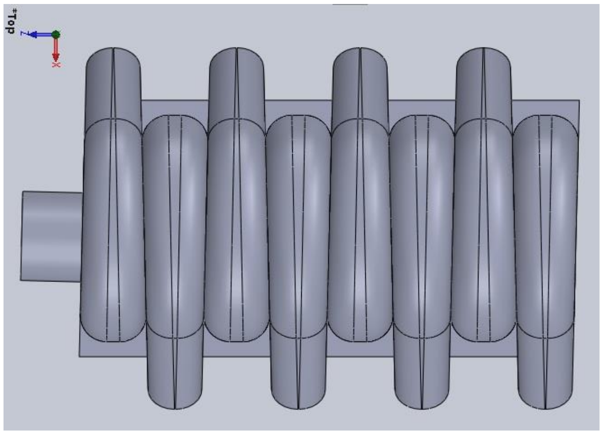


Figure A10: LS6 Mark 1 Top View

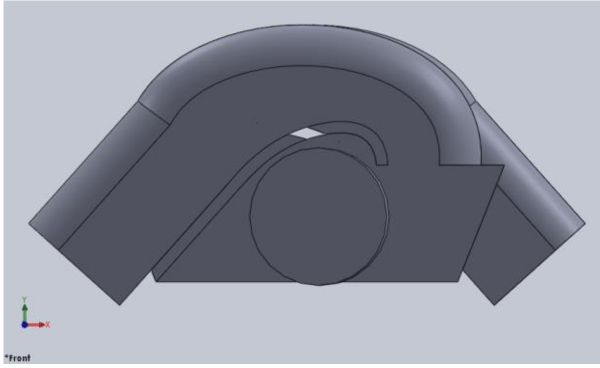


Figure A11: LS6 Mark 1 Front View

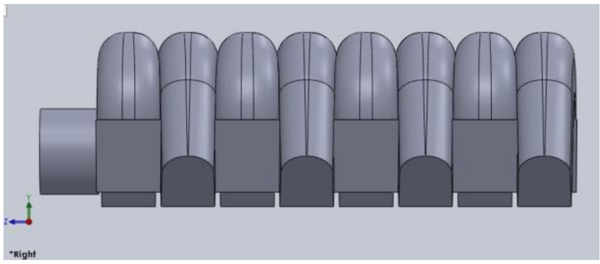
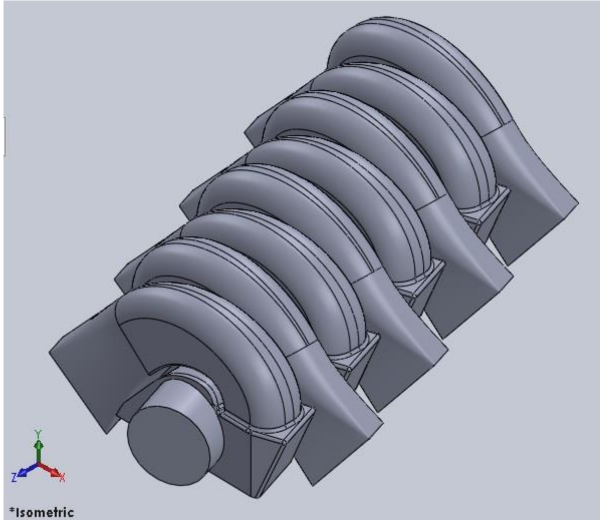


Figure A12: LS6 Mark 1 Side View



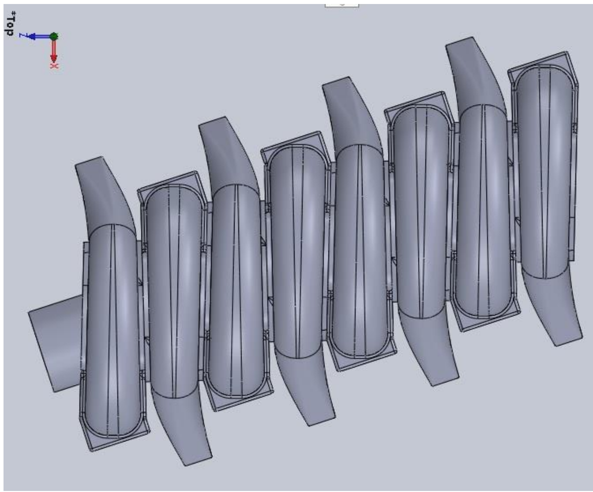


Figure A13: LS6 Mark 2 Isometric View

Figure A14: LS6 Mark 2 Top View

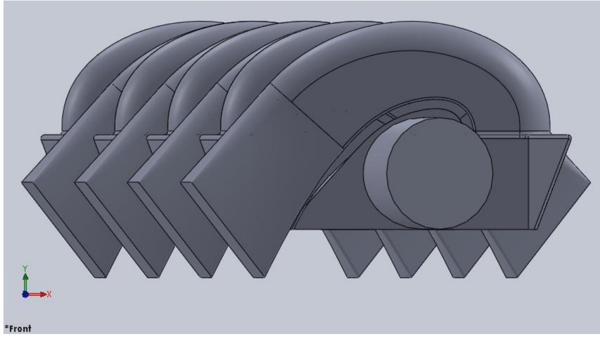


Figure A15: LS6 Mark 2 Front View

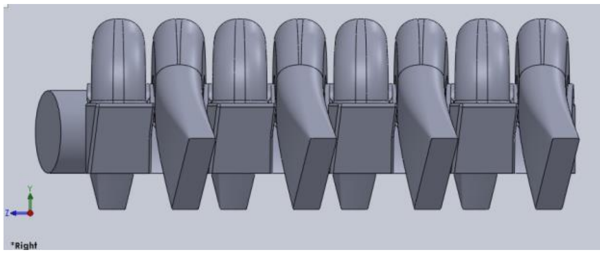


Figure A16: LS6 Mark 2 Side View

Trailblazer SS Manifold Models

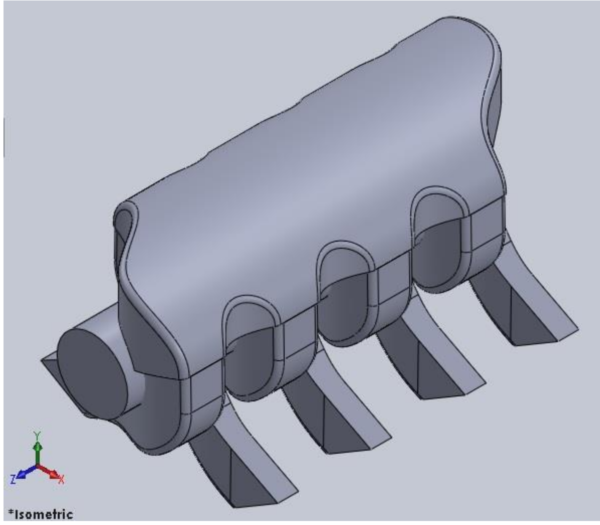


Figure A17: Trailblazer SS Mark 1 Isometric View

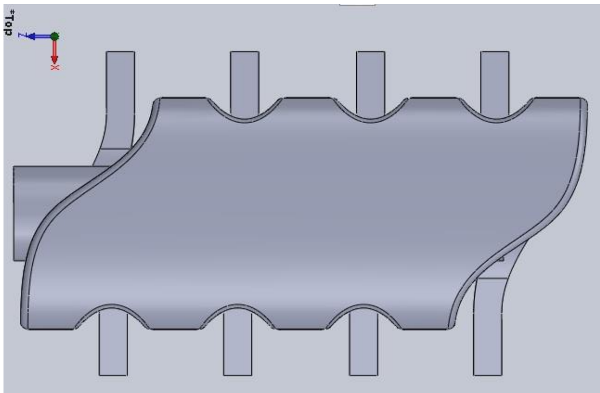


Figure A18: Trailblazer SS Mark 1 Top View

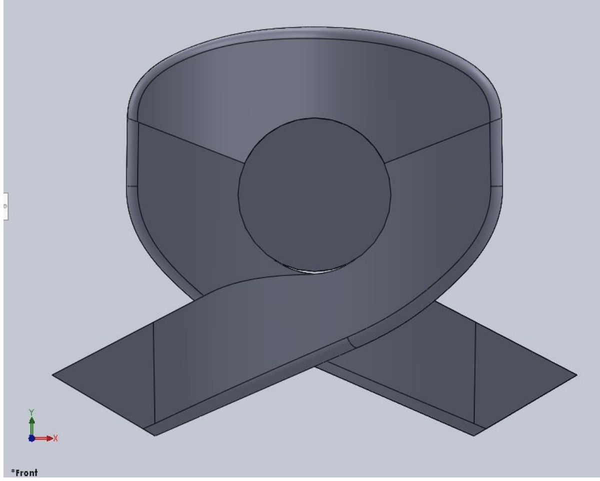


Figure A19: Trailblazer SS Mark 1 Front View

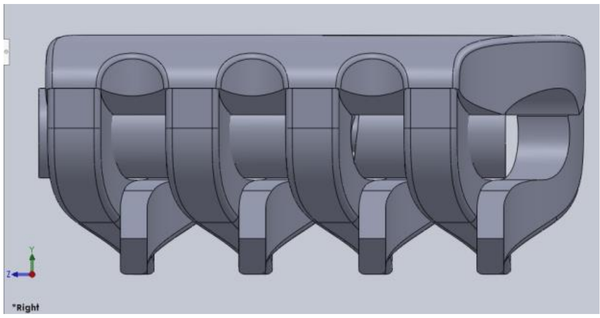


Figure A20: Trailblazer SS Mark 1 Side View

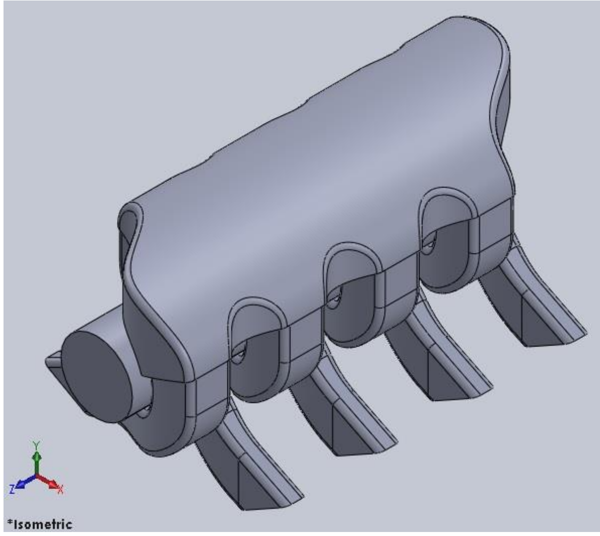


Figure A21: Trailblazer SS Mark 2 Isometric View

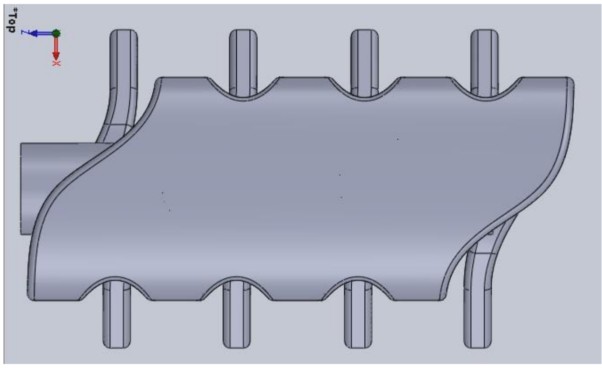


Figure A22: Trailblazer SS Mark 2 Top View

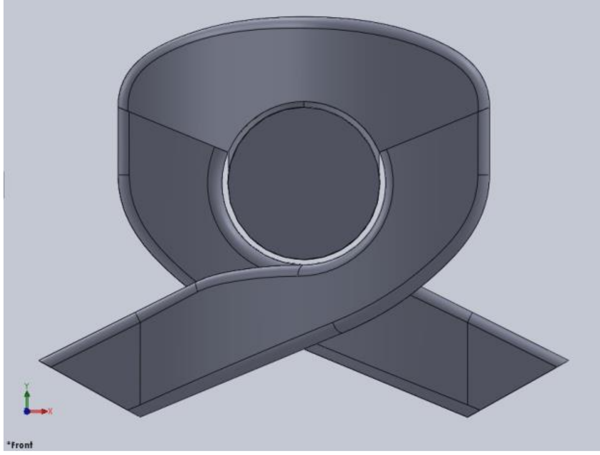


Figure A23: Trailblazer SS Mark 2 Front View

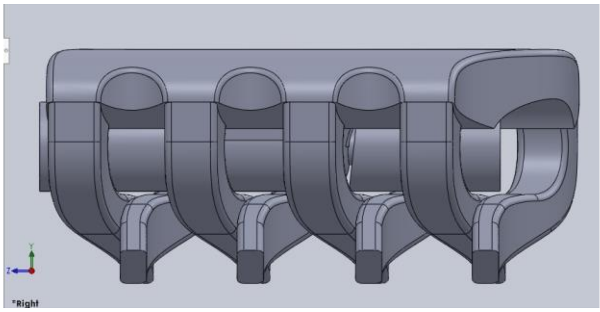
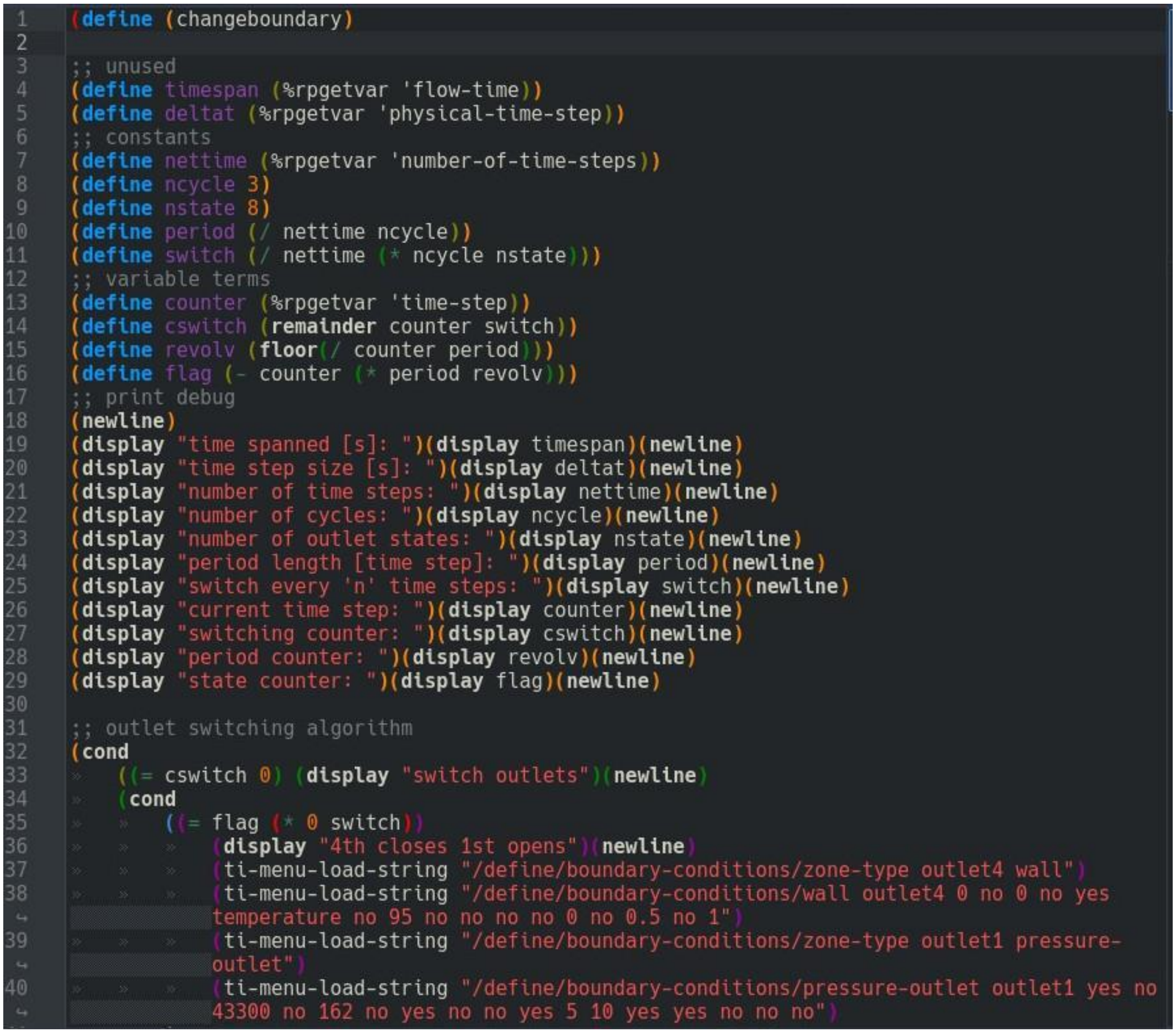


Figure A24: Trailblazer SS Mark 2 Side View

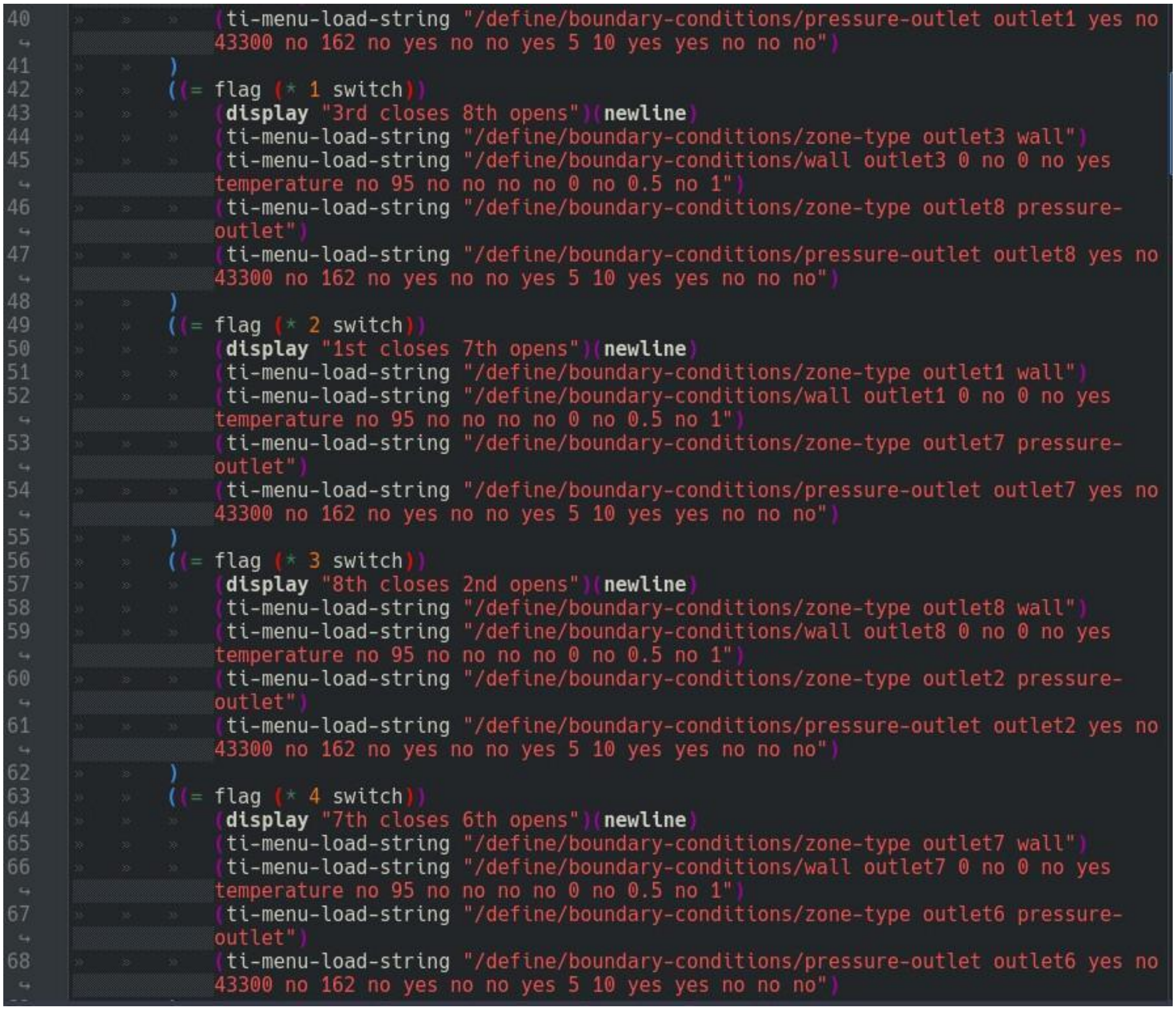
Appendix B

These are screenshots of the script that was used to change which runners were open during the simulation. This file is also included with the supporting material of this project.



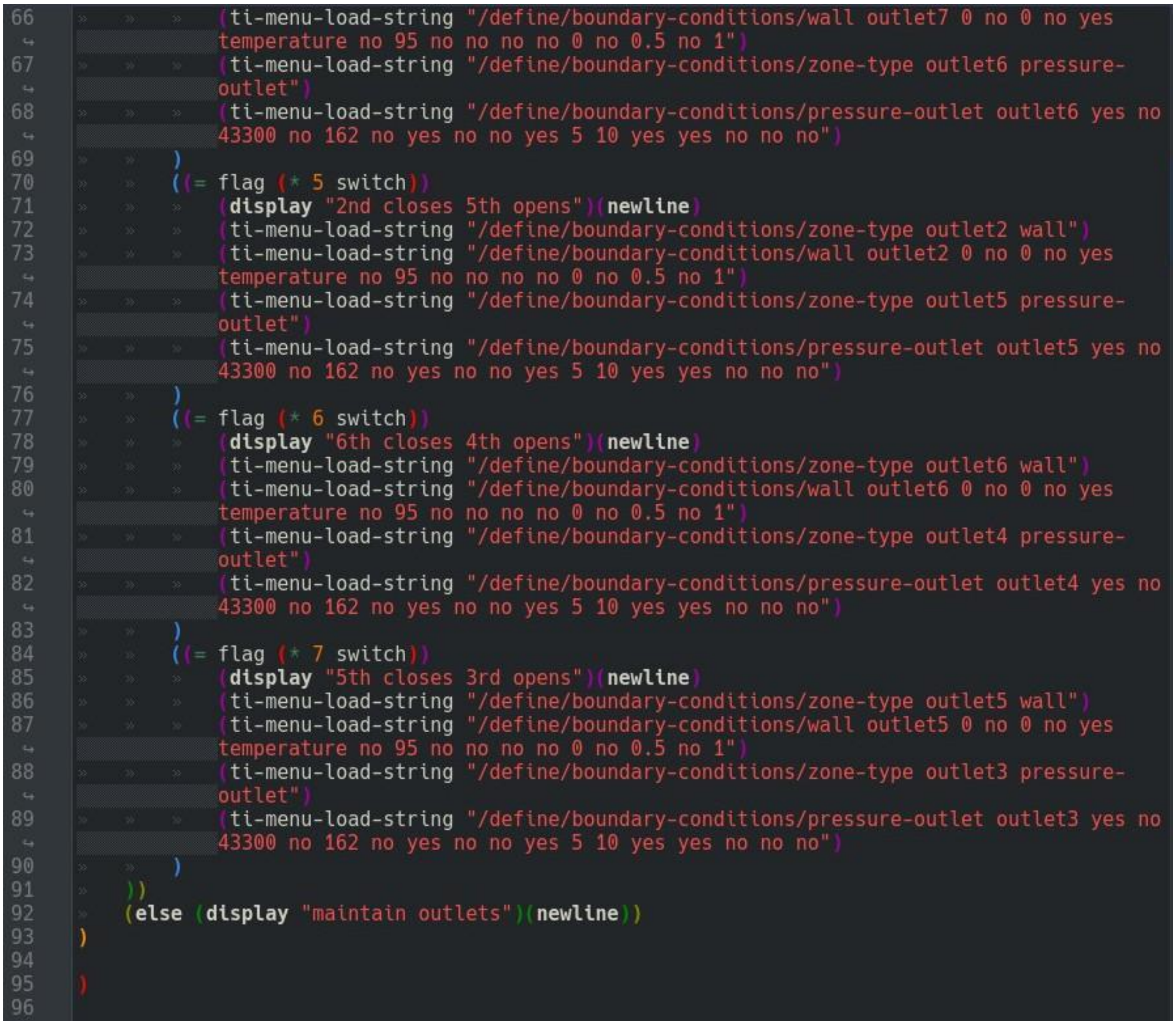
```scheme
(define (changeboundary)

;; unused
(define timespan (%rpgetvar 'flow-time))
(define deltat (%rpgetvar 'physical-time-step))
;; constants
(define nettime (%rpgetvar 'number-of-time-steps))
(define ncycle 3)
(define nstate 8)
(define period (/ nettime ncycle))
(define switch (/ nettime (* ncycle nstate)))
;; variable terms
(define counter (%rpgetvar 'time-step))
(define cswitch (remainder counter switch))
(define revolv (floor(/ counter period)))
(define flag (- counter (* period revolv)))
;; print debug
(newline)
(display "time spanned [s]: ")(display timespan)(newline)
(display "time step size [s]: ")(display deltat)(newline)
(display "number of time steps: ")(display nettime)(newline)
(display "number of cycles: ")(display ncycle)(newline)
(display "number of outlet states: ")(display nstate)(newline)
(display "period length [time step]: ")(display period)(newline)
(display "switch every 'n' time steps: ")(display switch)(newline)
(display "current time step: ")(display counter)(newline)
(display "switching counter: ")(display cswitch)(newline)
(display "period counter: ")(display revolv)(newline)
(display "state counter: ")(display flag)(newline)

;; outlet switching algorithm
(cond
    ((= cswitch 0) (display "switch outlets")(newline)
    (cond
        ((= flag (* 0 switch))
            (display "4th closes 1st opens")(newline)
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet4 wall")
            (ti-menu-load-string "/define/boundary-conditions/wall outlet4 0 no 0 no yes temperature no 95 no no no 0 no 0.5 no 1")
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet1 pressure-outlet")
            (ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet1 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
```

Figure B1: changeboundary.scm Lines 1-40



```
40 			(ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet1 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
41 		)
42 		((= flag (* 1 switch))
43 			(display "3rd closes 8th opens")(newline)
44 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet3 wall")
45 			(ti-menu-load-string "/define/boundary-conditions/wall outlet3 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
46 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet8 pressure-outlet")
47 			(ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet8 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
48 		)
49 		((= flag (* 2 switch))
50 			(display "1st closes 7th opens")(newline)
51 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet1 wall")
52 			(ti-menu-load-string "/define/boundary-conditions/wall outlet1 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
53 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet7 pressure-outlet")
54 			(ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet7 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
55 		)
56 		((= flag (* 3 switch))
57 			(display "8th closes 2nd opens")(newline)
58 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet8 wall")
59 			(ti-menu-load-string "/define/boundary-conditions/wall outlet8 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
60 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet2 pressure-outlet")
61 			(ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet2 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
62 		)
63 		((= flag (* 4 switch))
64 			(display "7th closes 6th opens")(newline)
65 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet7 wall")
66 			(ti-menu-load-string "/define/boundary-conditions/wall outlet7 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
67 			(ti-menu-load-string "/define/boundary-conditions/zone-type outlet6 pressure-outlet")
68 			(ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet6 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
```

Figure B2: changeboundary.scm Lines 40-68



```
            (ti-menu-load-string "/define/boundary-conditions/wall outlet7 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet6 pressure-outlet")
            (ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet6 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
        )
        ((= flag (* 5 switch))
            (display "2nd closes 5th opens")(newline)
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet2 wall")
            (ti-menu-load-string "/define/boundary-conditions/wall outlet2 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet5 pressure-outlet")
            (ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet5 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
        )
        ((= flag (* 6 switch))
            (display "6th closes 4th opens")(newline)
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet6 wall")
            (ti-menu-load-string "/define/boundary-conditions/wall outlet6 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet4 pressure-outlet")
            (ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet4 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
        )
        ((= flag (* 7 switch))
            (display "5th closes 3rd opens")(newline)
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet5 wall")
            (ti-menu-load-string "/define/boundary-conditions/wall outlet5 0 no 0 no yes temperature no 95 no no no no 0 no 0.5 no 1")
            (ti-menu-load-string "/define/boundary-conditions/zone-type outlet3 pressure-outlet")
            (ti-menu-load-string "/define/boundary-conditions/pressure-outlet outlet3 yes no 43300 no 162 no yes no no yes 5 10 yes yes no no no")
        )
    ))
    (else (display "maintain outlets")(newline))
)

)

```

Figure B3: changeboundary.scm Lines 66-96

Appendix C

These are the settings that the team modified from the default values to run and record data in the ANSYS Fluent simulations for both the LS6 and Trailblazer SS manifolds.

Menu Path	Value
SpaceClaim/Non-Joined Part/Check Box	Deselect box, right-click and deactivate for physics
Meshing/Mesh/Defaults/Element Size	1.0e-2 m
Meshing/Mesh/Inflation/Use Automatic Inflation	Program Controlled
Fluent/Setup/General/Units/Mass Flow	lbm/min
Fluent/Setup/General/Units/Temperature	F
Fluent/Setup/General/Mesh/Units/Volume-Flow-Rate	ft^3/s
Fluent/Setup/General/Mesh/Check	Minimum volume greater than zero
Fluent/Setup/General/Mesh/Report Quality	Maximum aspect ratio less than 3.5e1, minimum orthogonal quality greater than 1e-1
Fluent/Setup/General/Solver/Time	Transient
Fluent/Setup/Models/Energy	On
Fluent/Setup/Models/Viscous	K-epsilon, realizable
Fluent/Setup/Materials/Fluid/Air/Density	ideal-gas
Fluent/Setup/Materials/Fluid/Air/Specific Heat	Piecewise, use 250-400K values in [78]
Fluent/Setup/Materials/Fluid/Air/Thermal Conductivity	Piecewise, use 250-400K values in [78]
Fluent/Setup/Materials/Fluid/Air/Viscosity	Piecewise, use 250-400K values in [78]
Fluent/Setup/Materials/Solid/Right-Click/New	Granta MDS Database, plastic-pa66-30-33%-glass-fiber, Copy
Fluent/Setup/Boundary Conditions/Inlet/Type	mass-flow-inlet

Fluent/Setup/Boundary Conditions/Inlet/Momentum	mass flow=4.13, supersonic gauge pressure=43300, direction=normal to boundary
Fluent/Setup/Boundary Conditions/Inlet/Thermal	total temperature=75
Fluent/Setup/Boundary Conditions/Outlet/Momentum	gauge pressure=43300
Fluent/Setup/Boundary Conditions/Outlet/Thermal	backflow total temperature=162
Fluent/Setup/Boundary Conditions/Wall/Thermal/Thermal Conditions/Temperature	temperature=95
Fluent/Setup/Boundary Conditions	outlet1 & outlet 3 pressure-outlet only
Fluent/Setup/Boundary Conditions/Operating Conditions/Operating Pressure	0
Fluent/Solution/Methods/Spatial Discretization/Turbulent Kinetic Energy	Second Order Upwind
Fluent/Solution/Methods/Spatial Discretization/Turbulent Dissipation Rate	Second Order Upwind
Fluent/Solution/Report Definitions/Right Click/New/Surface Report/Volume Flow Rate	One for each inlet and outlet, change name and pick corresponding surface
Fluent/Solution/Report Definitions/Right Click/New/Surface Report/Mass Flow Rate	Select all inlets and outlets, rename to ‘net-mflow’
Fluent/Solution/Monitors/Convergence Conditions/Right Click/Create	Click add, then pick report definition as ‘net-mflow’ with stop criterion 0.001 and time step convergence
Fluent/Solution/Initialization/Compute from	inlet
Fluent/Solution/Calculation Activities/Execute Commands	/file/read-macros "R:\2021-22\MQP\ANSYS Fluent\<model name>\changeboundary.scm" (changeboundary)
Fluent/Solution/Calculation Activities/Execute Commands/When	Every 1 Time Step
Fluent/Solution/Run Calculation/Number of Time Steps	240

Fluent/Solution/Run Calculation/Time Step Size	0.00075
Fluent/Solution/Run Calculation/Max Iterations per Time Step	50
Fluent/Results/Surfaces/New	Plane in ZX called midplane (pick distance per manifold)
Fluent/Results/Surfaces/New	Plane in XY called runner5plane (pick distance per manifold)
Fluent/Results/Graphics/Contours/New	<plane>-pressure in total pressure with contour lines
Fluent/Results/Graphics/Contours/New	<plane>-velocity in velocity magnitude with contour lines
Fluent/Results/Graphics/Contours/New	<plane>-temperature in total temperature with contour lines
Fluent/Results/Graphics/Contours/New	<plane>-density in density magnitude with contour lines
Fluent/Solution/Calculation Activities/Solution Animations/New	<contour>-animation every 1 time step

Appendix D

These are the raw data values for the LS6 and Trailblazer SS manifold simulations. Tables D1-D10 list data for the LS6 manifold. Tables D11-D20 list data for the Trailblazer SS manifold.

time-step	inlet-vflow [ft^3/min]	flow-time [s]	time-step	inlet-vflow [ft^3/min]	flow-time [s]
0	1.30E+02	0	26	1.28E+02	0.0195
1	1.31E+02	0.00075	27	1.28E+02	0.02025
2	1.30E+02	0.0015	28	1.29E+02	0.021
3	1.28E+02	0.00225	29	1.29E+02	0.02175
4	1.28E+02	0.003	30	1.29E+02	0.0225
5	1.27E+02	0.00375	31	1.30E+02	0.02325
6	1.27E+02	0.0045	32	1.30E+02	0.024
7	1.28E+02	0.00525	33	1.29E+02	0.02475
8	1.28E+02	0.006	34	1.29E+02	0.0255
9	1.29E+02	0.00675	35	1.29E+02	0.02625
10	1.30E+02	0.0075	36	1.29E+02	0.027
11	1.30E+02	0.00825	37	1.29E+02	0.02775
12	1.30E+02	0.009	38	1.29E+02	0.0285
13	1.29E+02	0.00975	39	1.30E+02	0.02925
14	1.29E+02	0.0105	40	1.30E+02	0.03
15	1.29E+02	0.01125	41	1.30E+02	0.03075
16	1.29E+02	0.012	42	1.30E+02	0.0315
17	1.29E+02	0.01275	43	1.29E+02	0.03225
18	1.30E+02	0.0135	44	1.29E+02	0.033
19	1.30E+02	0.01425	45	1.29E+02	0.03375
20	1.30E+02	0.015	46	1.29E+02	0.0345
21	1.29E+02	0.01575	47	1.29E+02	0.03525
22	1.29E+02	0.0165	48	1.29E+02	0.036
23	1.28E+02	0.01725	49	1.29E+02	0.03675
24	1.28E+02	0.018	50	1.30E+02	0.0375
25	1.28E+02	0.01875	51	1.29E+02	0.03825

time-step	inlet-vflow [ft^3/min]	flow-time [s]	time-step	inlet-vflow [ft^3/min]	flow-time [s]
52	1.28E+02	0.039	84	1.29E+02	0.063
53	1.28E+02	0.03975	85	1.29E+02	0.06375
54	1.28E+02	0.0405	86	1.29E+02	0.0645
55	1.29E+02	0.04125	87	1.29E+02	0.06525
56	1.29E+02	0.042	88	1.29E+02	0.066
57	1.29E+02	0.04275	89	1.30E+02	0.06675
58	1.29E+02	0.0435	90	1.30E+02	0.0675
59	1.29E+02	0.04425	91	1.30E+02	0.06825
60	1.30E+02	0.045	92	1.29E+02	0.069
61	1.30E+02	0.04575	93	1.29E+02	0.06975
62	1.29E+02	0.0465	94	1.29E+02	0.0705
63	1.29E+02	0.04725	95	1.29E+02	0.07125
64	1.29E+02	0.048	96	1.29E+02	0.072
65	1.29E+02	0.04875	97	1.29E+02	0.07275
66	1.29E+02	0.0495	98	1.29E+02	0.0735
67	1.29E+02	0.05025	99	1.30E+02	0.07425
68	1.29E+02	0.051	100	1.30E+02	0.075
69	1.30E+02	0.05175	101	1.30E+02	0.07575
70	1.30E+02	0.0525	102	1.29E+02	0.0765
71	1.30E+02	0.05325	103	1.28E+02	0.07725
72	1.30E+02	0.054	104	1.28E+02	0.078
73	1.29E+02	0.05475	105	1.28E+02	0.07875
74	1.29E+02	0.0555	106	1.28E+02	0.0795
75	1.29E+02	0.05625	107	1.29E+02	0.08025
76	1.29E+02	0.057	108	1.29E+02	0.081
77	1.29E+02	0.05775	109	1.29E+02	0.08175
78	1.29E+02	0.0585	110	1.29E+02	0.0825
79	1.30E+02	0.05925	111	1.30E+02	0.08325
80	1.30E+02	0.06	112	1.30E+02	0.084
81	1.30E+02	0.06075	113	1.29E+02	0.08475
82	1.29E+02	0.0615	114	1.29E+02	0.0855
83	1.29E+02	0.06225	115	1.29E+02	0.08625

time-step	inlet-vflow [ft^3/min]	flow-time [s]	time-step	inlet-vflow [ft^3/min]	flow-time [s]
116	1.29E+02	0.087	148	1.29E+02	0.111
117	1.29E+02	0.08775	149	1.30E+02	0.11175
118	1.29E+02	0.0885	150	1.30E+02	0.1125
119	1.30E+02	0.08925	151	1.30E+02	0.11325
120	1.30E+02	0.09	152	1.30E+02	0.114
121	1.30E+02	0.09075	153	1.29E+02	0.11475
122	1.30E+02	0.0915	154	1.29E+02	0.1155
123	1.29E+02	0.09225	155	1.29E+02	0.11625
124	1.29E+02	0.093	156	1.29E+02	0.117
125	1.29E+02	0.09375	157	1.29E+02	0.11775
126	1.29E+02	0.0945	158	1.29E+02	0.1185
127	1.29E+02	0.09525	159	1.30E+02	0.11925
128	1.29E+02	0.096	160	1.30E+02	0.12
129	1.30E+02	0.09675	161	1.30E+02	0.12075
130	1.30E+02	0.0975	162	1.29E+02	0.1215
131	1.29E+02	0.09825	163	1.29E+02	0.12225
132	1.28E+02	0.099	164	1.29E+02	0.123
133	1.28E+02	0.09975	165	1.29E+02	0.12375
134	1.28E+02	0.1005	166	1.29E+02	0.1245
135	1.29E+02	0.10125	167	1.29E+02	0.12525
136	1.29E+02	0.102	168	1.29E+02	0.126
137	1.29E+02	0.10275	169	1.30E+02	0.12675
138	1.29E+02	0.1035	170	1.30E+02	0.1275
139	1.30E+02	0.10425	171	1.30E+02	0.12825
140	1.30E+02	0.105	172	1.29E+02	0.129
141	1.30E+02	0.10575	173	1.29E+02	0.12975
142	1.29E+02	0.1065	174	1.29E+02	0.1305
143	1.29E+02	0.10725	175	1.29E+02	0.13125
144	1.29E+02	0.108	176	1.29E+02	0.132
145	1.29E+02	0.10875	177	1.29E+02	0.13275
146	1.29E+02	0.1095	178	1.29E+02	0.1335
147	1.29E+02	0.11025	179	1.30E+02	0.13425

time-step	inlet-vflow [ft^3/min]	flow-time [s]	time-step	inlet-vflow [ft^3/min]	flow-time [s]
180	1.30E+02	0.135	211	1.29E+02	0.15825
181	1.30E+02	0.13575	212	1.28E+02	0.159
182	1.29E+02	0.1365	213	1.28E+02	0.15975
183	1.28E+02	0.13725	214	1.28E+02	0.1605
184	1.28E+02	0.138	215	1.29E+02	0.16125
185	1.28E+02	0.13875	216	1.29E+02	0.162
186	1.29E+02	0.1395	217	1.29E+02	0.16275
187	1.29E+02	0.14025	218	1.29E+02	0.1635
188	1.29E+02	0.141	219	1.30E+02	0.16425
189	1.29E+02	0.14175	220	1.30E+02	0.165
190	1.29E+02	0.1425	221	1.30E+02	0.16575
191	1.30E+02	0.14325	222	1.29E+02	0.1665
192	1.30E+02	0.144	223	1.29E+02	0.16725
193	1.29E+02	0.14475	224	1.29E+02	0.168
194	1.29E+02	0.1455	225	1.29E+02	0.16875
195	1.29E+02	0.14625	226	1.29E+02	0.1695
196	1.29E+02	0.147	227	1.29E+02	0.17025
197	1.29E+02	0.14775	228	1.29E+02	0.171
198	1.29E+02	0.1485	229	1.30E+02	0.17175
199	1.30E+02	0.14925	230	1.30E+02	0.1725
200	1.30E+02	0.15	231	1.30E+02	0.17325
201	1.30E+02	0.15075	232	1.30E+02	0.174
202	1.30E+02	0.1515	233	1.29E+02	0.17475
203	1.29E+02	0.15225	234	1.29E+02	0.1755
204	1.29E+02	0.153	235	1.29E+02	0.17625
205	1.29E+02	0.15375	236	1.29E+02	0.177
206	1.29E+02	0.1545	237	1.29E+02	0.17775
207	1.29E+02	0.15525	238	1.29E+02	0.1785
208	1.29E+02	0.156	239	1.30E+02	0.17925
209	1.30E+02	0.15675	240	1.30E+02	0.18
210	1.30E+02	0.1575			

Table D1: Throttle Volumetric Flow Data for LS6 Manifold

time-step	outlet1-vflow [ft^3/min]	flow-time [s]
0	-3.62E-13	0
1	9.60E+00	0.00075
2	3.52E+00	0.0015
3	-1.35E+01	0.00225
4	-3.62E+01	0.003
5	-5.94E+01	0.00375
6	-7.91E+01	0.0045
7	-9.34E+01	0.00525
8	-1.02E+02	0.006
9	-1.05E+02	0.00675
10	-1.03E+02	0.0075
11	-1.00E+02	0.00825
12	-1.01E+02	0.009
13	-1.03E+02	0.00975
14	-1.07E+02	0.0105
15	-1.09E+02	0.01125
16	-1.10E+02	0.012
17	-1.10E+02	0.01275
18	-1.08E+02	0.0135
19	-1.07E+02	0.01425
20	-1.03E+02	0.015
21	0.00E+00	0.01575
22	0.00E+00	0.0165
23	0.00E+00	0.01725
24	0.00E+00	0.018
25	0.00E+00	0.01875
26	0.00E+00	0.0195
27	0.00E+00	0.02025
28	0.00E+00	0.021
29	0.00E+00	0.02175
30	0.00E+00	0.0225
31	0.00E+00	0.02325
32	0.00E+00	0.024
33	0.00E+00	0.02475
34	0.00E+00	0.0255
35	0.00E+00	0.02625
36	0.00E+00	0.027
37	0.00E+00	0.02775
38	0.00E+00	0.0285
39	0.00E+00	0.02925
40	0.00E+00	0.03
41	0.00E+00	0.03075
42	0.00E+00	0.0315
43	0.00E+00	0.03225
44	0.00E+00	0.033
45	0.00E+00	0.03375
46	0.00E+00	0.0345
47	0.00E+00	0.03525
48	0.00E+00	0.036
49	0.00E+00	0.03675
50	0.00E+00	0.0375
51	0.00E+00	0.03825
52	0.00E+00	0.039
53	0.00E+00	0.03975
54	0.00E+00	0.0405
55	0.00E+00	0.04125
56	0.00E+00	0.042
57	0.00E+00	0.04275
58	0.00E+00	0.0435
59	0.00E+00	0.04425
60	0.00E+00	0.045
61	0.00E+00	0.04575
62	0.00E+00	0.0465
63	0.00E+00	0.04725

time-step	outlet1-vflow [ft^3/min]	flow-time [s]	time-step	outlet1-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	-9.81E+01	0.072
65	0.00E+00	0.04875	97	-1.01E+02	0.07275
66	0.00E+00	0.0495	98	-1.01E+02	0.0735
67	0.00E+00	0.05025	99	-1.00E+02	0.07425
68	0.00E+00	0.051	100	-9.76E+01	0.075
69	0.00E+00	0.05175	101	0.00E+00	0.07575
70	0.00E+00	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	-5.19E+00	0.06075	113	0.00E+00	0.08475
82	-1.38E+01	0.0615	114	0.00E+00	0.0855
83	-2.55E+01	0.06225	115	0.00E+00	0.08625
84	-3.61E+01	0.063	116	0.00E+00	0.087
85	-4.41E+01	0.06375	117	0.00E+00	0.08775
86	-5.00E+01	0.0645	118	0.00E+00	0.0885
87	-5.47E+01	0.06525	119	0.00E+00	0.08925
88	-5.82E+01	0.066	120	0.00E+00	0.09
89	-6.04E+01	0.06675	121	0.00E+00	0.09075
90	-6.15E+01	0.0675	122	0.00E+00	0.0915
91	-6.36E+01	0.06825	123	0.00E+00	0.09225
92	-6.92E+01	0.069	124	0.00E+00	0.093
93	-7.74E+01	0.06975	125	0.00E+00	0.09375
94	-8.61E+01	0.0705	126	0.00E+00	0.0945
95	-9.33E+01	0.07125	127	0.00E+00	0.09525

time-step	outlet1-vflow [ft^3/min]	flow-time [s]	time-step	outlet1-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	0.00E+00	0.12
129	0.00E+00	0.09675	161	-5.06E+00	0.12075
130	0.00E+00	0.0975	162	-1.36E+01	0.1215
131	0.00E+00	0.09825	163	-2.53E+01	0.12225
132	0.00E+00	0.099	164	-3.58E+01	0.123
133	0.00E+00	0.09975	165	-4.38E+01	0.12375
134	0.00E+00	0.1005	166	-4.97E+01	0.1245
135	0.00E+00	0.10125	167	-5.44E+01	0.12525
136	0.00E+00	0.102	168	-5.80E+01	0.126
137	0.00E+00	0.10275	169	-6.01E+01	0.12675
138	0.00E+00	0.1035	170	-6.10E+01	0.1275
139	0.00E+00	0.10425	171	-6.32E+01	0.12825
140	0.00E+00	0.105	172	-6.88E+01	0.129
141	0.00E+00	0.10575	173	-7.71E+01	0.12975
142	0.00E+00	0.1065	174	-8.59E+01	0.1305
143	0.00E+00	0.10725	175	-9.31E+01	0.13125
144	0.00E+00	0.108	176	-9.79E+01	0.132
145	0.00E+00	0.10875	177	-1.00E+02	0.13275
146	0.00E+00	0.1095	178	-1.01E+02	0.1335
147	0.00E+00	0.11025	179	-1.00E+02	0.13425
148	0.00E+00	0.111	180	-9.72E+01	0.135
149	0.00E+00	0.11175	181	0.00E+00	0.13575
150	0.00E+00	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	0.00E+00	0.14325

time-step	outlet1-vflow [ft^3/min]	flow-time [s]	time-step	outlet1-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	0.00E+00	0.16275
193	0.00E+00	0.14475	218	0.00E+00	0.1635
194	0.00E+00	0.1455	219	0.00E+00	0.16425
195	0.00E+00	0.14625	220	0.00E+00	0.165
196	0.00E+00	0.147	221	0.00E+00	0.16575
197	0.00E+00	0.14775	222	0.00E+00	0.1665
198	0.00E+00	0.1485	223	0.00E+00	0.16725
199	0.00E+00	0.14925	224	0.00E+00	0.168
200	0.00E+00	0.15	225	0.00E+00	0.16875
201	0.00E+00	0.15075	226	0.00E+00	0.1695
202	0.00E+00	0.1515	227	0.00E+00	0.17025
203	0.00E+00	0.15225	228	0.00E+00	0.171
204	0.00E+00	0.153	229	0.00E+00	0.17175
205	0.00E+00	0.15375	230	0.00E+00	0.1725
206	0.00E+00	0.1545	231	0.00E+00	0.17325
207	0.00E+00	0.15525	232	0.00E+00	0.174
208	0.00E+00	0.156	233	0.00E+00	0.17475
209	0.00E+00	0.15675	234	0.00E+00	0.1755
210	0.00E+00	0.1575	235	0.00E+00	0.17625
211	0.00E+00	0.15825	236	0.00E+00	0.177
212	0.00E+00	0.159	237	0.00E+00	0.17775
213	0.00E+00	0.15975	238	0.00E+00	0.1785
214	0.00E+00	0.1605	239	0.00E+00	0.17925
215	0.00E+00	0.16125	240	0.00E+00	0.18
216	0.00E+00	0.162			

Table D2: Runner #1 Volumetric Flow Data for LS6 Manifold

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	-8.81E+00	0.024
1	0.00E+00	0.00075	33	-1.54E+01	0.02475
2	0.00E+00	0.0015	34	-2.54E+01	0.0255
3	0.00E+00	0.00225	35	-3.60E+01	0.02625
4	0.00E+00	0.003	36	-4.52E+01	0.027
5	0.00E+00	0.00375	37	-5.17E+01	0.02775
6	0.00E+00	0.0045	38	-5.55E+01	0.0285
7	0.00E+00	0.00525	39	-5.71E+01	0.02925
8	0.00E+00	0.006	40	-5.71E+01	0.03
9	0.00E+00	0.00675	41	-5.65E+01	0.03075
10	0.00E+00	0.0075	42	-5.78E+01	0.0315
11	0.00E+00	0.00825	43	-6.25E+01	0.03225
12	0.00E+00	0.009	44	-7.08E+01	0.033
13	0.00E+00	0.00975	45	-8.06E+01	0.03375
14	0.00E+00	0.0105	46	-8.91E+01	0.0345
15	0.00E+00	0.01125	47	-9.47E+01	0.03525
16	0.00E+00	0.012	48	-9.70E+01	0.036
17	0.00E+00	0.01275	49	-9.66E+01	0.03675
18	0.00E+00	0.0135	50	-9.44E+01	0.0375
19	0.00E+00	0.01425	51	0.00E+00	0.03825
20	0.00E+00	0.015	52	0.00E+00	0.039
21	0.00E+00	0.01575	53	0.00E+00	0.03975
22	0.00E+00	0.0165	54	0.00E+00	0.0405
23	0.00E+00	0.01725	55	0.00E+00	0.04125
24	0.00E+00	0.018	56	0.00E+00	0.042
25	0.00E+00	0.01875	57	0.00E+00	0.04275
26	0.00E+00	0.0195	58	0.00E+00	0.0435
27	0.00E+00	0.02025	59	0.00E+00	0.04425
28	0.00E+00	0.021	60	0.00E+00	0.045
29	0.00E+00	0.02175	61	0.00E+00	0.04575
30	0.00E+00	0.0225	62	0.00E+00	0.0465
31	-6.82E+00	0.02325	63	0.00E+00	0.04725

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	0.00E+00	0.072
65	0.00E+00	0.04875	97	0.00E+00	0.07275
66	0.00E+00	0.0495	98	0.00E+00	0.0735
67	0.00E+00	0.05025	99	0.00E+00	0.07425
68	0.00E+00	0.051	100	0.00E+00	0.075
69	0.00E+00	0.05175	101	0.00E+00	0.07575
70	0.00E+00	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	-6.72E+00	0.08325
80	0.00E+00	0.06	112	-9.24E+00	0.084
81	0.00E+00	0.06075	113	-1.64E+01	0.08475
82	0.00E+00	0.0615	114	-2.69E+01	0.0855
83	0.00E+00	0.06225	115	-3.81E+01	0.08625
84	0.00E+00	0.063	116	-4.77E+01	0.087
85	0.00E+00	0.06375	117	-5.45E+01	0.08775
86	0.00E+00	0.0645	118	-5.84E+01	0.0885
87	0.00E+00	0.06525	119	-6.00E+01	0.08925
88	0.00E+00	0.066	120	-5.98E+01	0.09
89	0.00E+00	0.06675	121	-5.91E+01	0.09075
90	0.00E+00	0.0675	122	-5.99E+01	0.0915
91	0.00E+00	0.06825	123	-6.42E+01	0.09225
92	0.00E+00	0.069	124	-7.21E+01	0.093
93	0.00E+00	0.06975	125	-8.15E+01	0.09375
94	0.00E+00	0.0705	126	-8.97E+01	0.0945
95	0.00E+00	0.07125	127	-9.50E+01	0.09525

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
128	-9.71E+01	0.096	160	0.00E+00	0.12
129	-9.66E+01	0.09675	161	0.00E+00	0.12075
130	-9.43E+01	0.0975	162	0.00E+00	0.1215
131	0.00E+00	0.09825	163	0.00E+00	0.12225
132	0.00E+00	0.099	164	0.00E+00	0.123
133	0.00E+00	0.09975	165	0.00E+00	0.12375
134	0.00E+00	0.1005	166	0.00E+00	0.1245
135	0.00E+00	0.10125	167	0.00E+00	0.12525
136	0.00E+00	0.102	168	0.00E+00	0.126
137	0.00E+00	0.10275	169	0.00E+00	0.12675
138	0.00E+00	0.1035	170	0.00E+00	0.1275
139	0.00E+00	0.10425	171	0.00E+00	0.12825
140	0.00E+00	0.105	172	0.00E+00	0.129
141	0.00E+00	0.10575	173	0.00E+00	0.12975
142	0.00E+00	0.1065	174	0.00E+00	0.1305
143	0.00E+00	0.10725	175	0.00E+00	0.13125
144	0.00E+00	0.108	176	0.00E+00	0.132
145	0.00E+00	0.10875	177	0.00E+00	0.13275
146	0.00E+00	0.1095	178	0.00E+00	0.1335
147	0.00E+00	0.11025	179	0.00E+00	0.13425
148	0.00E+00	0.111	180	0.00E+00	0.135
149	0.00E+00	0.11175	181	0.00E+00	0.13575
150	0.00E+00	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	-6.59E+00	0.14325

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
192	-9.12E+00	0.144	217	0.00E+00	0.16275
193	-1.62E+01	0.14475	218	0.00E+00	0.1635
194	-2.67E+01	0.1455	219	0.00E+00	0.16425
195	-3.79E+01	0.14625	220	0.00E+00	0.165
196	-4.75E+01	0.147	221	0.00E+00	0.16575
197	-5.43E+01	0.14775	222	0.00E+00	0.1665
198	-5.82E+01	0.1485	223	0.00E+00	0.16725
199	-5.97E+01	0.14925	224	0.00E+00	0.168
200	-5.96E+01	0.15	225	0.00E+00	0.16875
201	-5.88E+01	0.15075	226	0.00E+00	0.1695
202	-5.97E+01	0.1515	227	0.00E+00	0.17025
203	-6.40E+01	0.15225	228	0.00E+00	0.171
204	-7.19E+01	0.153	229	0.00E+00	0.17175
205	-8.13E+01	0.15375	230	0.00E+00	0.1725
206	-8.95E+01	0.1545	231	0.00E+00	0.17325
207	-9.48E+01	0.15525	232	0.00E+00	0.174
208	-9.70E+01	0.156	233	0.00E+00	0.17475
209	-9.64E+01	0.15675	234	0.00E+00	0.1755
210	-9.42E+01	0.1575	235	0.00E+00	0.17625
211	0.00E+00	0.15825	236	0.00E+00	0.177
212	0.00E+00	0.159	237	0.00E+00	0.17775
213	0.00E+00	0.15975	238	0.00E+00	0.1785
214	0.00E+00	0.1605	239	0.00E+00	0.17925
215	0.00E+00	0.16125	240	0.00E+00	0.18
216	0.00E+00	0.162			

Table D3: Runner #2 Volumetric Flow Data for LS6 Manifold

time-step	outlet3-vflow [ft^3/min]	flow-time [s]	time-step	outlet3-vflow [ft^3/min]	flow-time [s]
0	4.40E-12	0	32	0.00E+00	0.024
1	3.80E+00	0.00075	33	0.00E+00	0.02475
2	-9.93E+00	0.0015	34	0.00E+00	0.0255
3	-3.09E+01	0.00225	35	0.00E+00	0.02625
4	-5.39E+01	0.003	36	0.00E+00	0.027
5	-7.56E+01	0.00375	37	0.00E+00	0.02775
6	-9.34E+01	0.0045	38	0.00E+00	0.0285
7	-1.06E+02	0.00525	39	0.00E+00	0.02925
8	-1.13E+02	0.006	40	0.00E+00	0.03
9	-1.15E+02	0.00675	41	0.00E+00	0.03075
10	-1.13E+02	0.0075	42	0.00E+00	0.0315
11	0.00E+00	0.00825	43	0.00E+00	0.03225
12	0.00E+00	0.009	44	0.00E+00	0.033
13	0.00E+00	0.00975	45	0.00E+00	0.03375
14	0.00E+00	0.0105	46	0.00E+00	0.0345
15	0.00E+00	0.01125	47	0.00E+00	0.03525
16	0.00E+00	0.012	48	0.00E+00	0.036
17	0.00E+00	0.01275	49	0.00E+00	0.03675
18	0.00E+00	0.0135	50	0.00E+00	0.0375
19	0.00E+00	0.01425	51	0.00E+00	0.03825
20	0.00E+00	0.015	52	0.00E+00	0.039
21	0.00E+00	0.01575	53	0.00E+00	0.03975
22	0.00E+00	0.0165	54	0.00E+00	0.0405
23	0.00E+00	0.01725	55	0.00E+00	0.04125
24	0.00E+00	0.018	56	0.00E+00	0.042
25	0.00E+00	0.01875	57	0.00E+00	0.04275
26	0.00E+00	0.0195	58	0.00E+00	0.0435
27	0.00E+00	0.02025	59	0.00E+00	0.04425
28	0.00E+00	0.021	60	0.00E+00	0.045
29	0.00E+00	0.02175	61	0.00E+00	0.04575
30	0.00E+00	0.0225	62	0.00E+00	0.0465
31	0.00E+00	0.02325	63	0.00E+00	0.04725

time-step	outlet3-vflow [ft^3/min]	flow-time [s]	time-step	outlet3-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	0.00E+00	0.072
65	0.00E+00	0.04875	97	0.00E+00	0.07275
66	0.00E+00	0.0495	98	0.00E+00	0.0735
67	0.00E+00	0.05025	99	0.00E+00	0.07425
68	0.00E+00	0.051	100	0.00E+00	0.075
69	0.00E+00	0.05175	101	0.00E+00	0.07575
70	0.00E+00	0.0525	102	0.00E+00	0.0765
71	-4.51E+00	0.05325	103	0.00E+00	0.07725
72	-1.12E+01	0.054	104	0.00E+00	0.078
73	-2.22E+01	0.05475	105	0.00E+00	0.07875
74	-3.47E+01	0.0555	106	0.00E+00	0.0795
75	-4.63E+01	0.05625	107	0.00E+00	0.08025
76	-5.60E+01	0.057	108	0.00E+00	0.081
77	-6.34E+01	0.05775	109	0.00E+00	0.08175
78	-6.83E+01	0.0585	110	0.00E+00	0.0825
79	-7.09E+01	0.05925	111	0.00E+00	0.08325
80	-7.17E+01	0.06	112	0.00E+00	0.084
81	-7.31E+01	0.06075	113	0.00E+00	0.08475
82	-7.75E+01	0.0615	114	0.00E+00	0.0855
83	-8.40E+01	0.06225	115	0.00E+00	0.08625
84	-9.08E+01	0.063	116	0.00E+00	0.087
85	-9.61E+01	0.06375	117	0.00E+00	0.08775
86	-9.97E+01	0.0645	118	0.00E+00	0.0885
87	-1.02E+02	0.06525	119	0.00E+00	0.08925
88	-1.02E+02	0.066	120	0.00E+00	0.09
89	-1.02E+02	0.06675	121	0.00E+00	0.09075
90	-9.98E+01	0.0675	122	0.00E+00	0.0915
91	0.00E+00	0.06825	123	0.00E+00	0.09225
92	0.00E+00	0.069	124	0.00E+00	0.093
93	0.00E+00	0.06975	125	0.00E+00	0.09375
94	0.00E+00	0.0705	126	0.00E+00	0.0945
95	0.00E+00	0.07125	127	0.00E+00	0.09525

time-step	outlet3-vflow [ft^3/min]	flow-time [s]	time-step	outlet3-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	-7.13E+01	0.12
129	0.00E+00	0.09675	161	-7.27E+01	0.12075
130	0.00E+00	0.0975	162	-7.70E+01	0.1215
131	0.00E+00	0.09825	163	-8.35E+01	0.12225
132	0.00E+00	0.099	164	-9.03E+01	0.123
133	0.00E+00	0.09975	165	-9.57E+01	0.12375
134	0.00E+00	0.1005	166	-9.93E+01	0.1245
135	0.00E+00	0.10125	167	-1.01E+02	0.12525
136	0.00E+00	0.102	168	-1.02E+02	0.126
137	0.00E+00	0.10275	169	-1.01E+02	0.12675
138	0.00E+00	0.1035	170	-1.00E+02	0.1275
139	0.00E+00	0.10425	171	0.00E+00	0.12825
140	0.00E+00	0.105	172	0.00E+00	0.129
141	0.00E+00	0.10575	173	0.00E+00	0.12975
142	0.00E+00	0.1065	174	0.00E+00	0.1305
143	0.00E+00	0.10725	175	0.00E+00	0.13125
144	0.00E+00	0.108	176	0.00E+00	0.132
145	0.00E+00	0.10875	177	0.00E+00	0.13275
146	0.00E+00	0.1095	178	0.00E+00	0.1335
147	0.00E+00	0.11025	179	0.00E+00	0.13425
148	0.00E+00	0.111	180	0.00E+00	0.135
149	0.00E+00	0.11175	181	0.00E+00	0.13575
150	0.00E+00	0.1125	182	0.00E+00	0.1365
151	-4.51E+00	0.11325	183	0.00E+00	0.13725
152	-1.11E+01	0.114	184	0.00E+00	0.138
153	-2.21E+01	0.11475	185	0.00E+00	0.13875
154	-3.45E+01	0.1155	186	0.00E+00	0.1395
155	-4.62E+01	0.11625	187	0.00E+00	0.14025
156	-5.59E+01	0.117	188	0.00E+00	0.141
157	-6.32E+01	0.11775	189	0.00E+00	0.14175
158	-6.81E+01	0.1185	190	0.00E+00	0.1425
159	-7.06E+01	0.11925	191	0.00E+00	0.14325

time-step	outlet3-vflow [ft^3/min]	flow-time [s]	time-step	outlet3-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	0.00E+00	0.16275
193	0.00E+00	0.14475	218	0.00E+00	0.1635
194	0.00E+00	0.1455	219	0.00E+00	0.16425
195	0.00E+00	0.14625	220	0.00E+00	0.165
196	0.00E+00	0.147	221	0.00E+00	0.16575
197	0.00E+00	0.14775	222	0.00E+00	0.1665
198	0.00E+00	0.1485	223	0.00E+00	0.16725
199	0.00E+00	0.14925	224	0.00E+00	0.168
200	0.00E+00	0.15	225	0.00E+00	0.16875
201	0.00E+00	0.15075	226	0.00E+00	0.1695
202	0.00E+00	0.1515	227	0.00E+00	0.17025
203	0.00E+00	0.15225	228	0.00E+00	0.171
204	0.00E+00	0.153	229	0.00E+00	0.17175
205	0.00E+00	0.15375	230	0.00E+00	0.1725
206	0.00E+00	0.1545	231	-4.50E+00	0.17325
207	0.00E+00	0.15525	232	-1.11E+01	0.174
208	0.00E+00	0.156	233	-2.21E+01	0.17475
209	0.00E+00	0.15675	234	-3.45E+01	0.1755
210	0.00E+00	0.1575	235	-4.62E+01	0.17625
211	0.00E+00	0.15825	236	-5.59E+01	0.177
212	0.00E+00	0.159	237	-6.32E+01	0.17775
213	0.00E+00	0.15975	238	-6.81E+01	0.1785
214	0.00E+00	0.1605	239	-7.06E+01	0.17925
215	0.00E+00	0.16125	240	-7.13E+01	0.18
216	0.00E+00	0.162			

Table D4: Runner #3 Volumetric Flow Data for LS6 Manifold

time-step	outlet4-vflow [ft^3/min]	flow-time [s]	time-step	outlet4-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	0.00E+00	0.024
1	0.00E+00	0.00075	33	0.00E+00	0.02475
2	0.00E+00	0.0015	34	0.00E+00	0.0255
3	0.00E+00	0.00225	35	0.00E+00	0.02625
4	0.00E+00	0.003	36	0.00E+00	0.027
5	0.00E+00	0.00375	37	0.00E+00	0.02775
6	0.00E+00	0.0045	38	0.00E+00	0.0285
7	0.00E+00	0.00525	39	0.00E+00	0.02925
8	0.00E+00	0.006	40	0.00E+00	0.03
9	0.00E+00	0.00675	41	0.00E+00	0.03075
10	0.00E+00	0.0075	42	0.00E+00	0.0315
11	0.00E+00	0.00825	43	0.00E+00	0.03225
12	0.00E+00	0.009	44	0.00E+00	0.033
13	0.00E+00	0.00975	45	0.00E+00	0.03375
14	0.00E+00	0.0105	46	0.00E+00	0.0345
15	0.00E+00	0.01125	47	0.00E+00	0.03525
16	0.00E+00	0.012	48	0.00E+00	0.036
17	0.00E+00	0.01275	49	0.00E+00	0.03675
18	0.00E+00	0.0135	50	0.00E+00	0.0375
19	0.00E+00	0.01425	51	0.00E+00	0.03825
20	0.00E+00	0.015	52	0.00E+00	0.039
21	0.00E+00	0.01575	53	0.00E+00	0.03975
22	0.00E+00	0.0165	54	0.00E+00	0.0405
23	0.00E+00	0.01725	55	0.00E+00	0.04125
24	0.00E+00	0.018	56	0.00E+00	0.042
25	0.00E+00	0.01875	57	0.00E+00	0.04275
26	0.00E+00	0.0195	58	0.00E+00	0.0435
27	0.00E+00	0.02025	59	0.00E+00	0.04425
28	0.00E+00	0.021	60	0.00E+00	0.045
29	0.00E+00	0.02175	61	-6.18E+00	0.04575
30	0.00E+00	0.0225	62	-1.28E+01	0.0465
31	0.00E+00	0.02325	63	-2.36E+01	0.04725

time-step	outlet4-vflow [ft^3/min]	flow-time [s]	time-step	outlet4-vflow [ft^3/min]	flow-time [s]
64	-3.54E+01	0.048	96	0.00E+00	0.072
65	-4.61E+01	0.04875	97	0.00E+00	0.07275
66	-5.47E+01	0.0495	98	0.00E+00	0.0735
67	-6.09E+01	0.05025	99	0.00E+00	0.07425
68	-6.47E+01	0.051	100	0.00E+00	0.075
69	-6.64E+01	0.05175	101	0.00E+00	0.07575
70	-6.63E+01	0.0525	102	0.00E+00	0.0765
71	-6.61E+01	0.05325	103	0.00E+00	0.07725
72	-6.83E+01	0.054	104	0.00E+00	0.078
73	-7.37E+01	0.05475	105	0.00E+00	0.07875
74	-8.15E+01	0.0555	106	0.00E+00	0.0795
75	-8.94E+01	0.05625	107	0.00E+00	0.08025
76	-9.56E+01	0.057	108	0.00E+00	0.081
77	-9.94E+01	0.05775	109	0.00E+00	0.08175
78	-1.01E+02	0.0585	110	0.00E+00	0.0825
79	-1.00E+02	0.05925	111	0.00E+00	0.08325
80	-9.78E+01	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	0.00E+00	0.06825	123	0.00E+00	0.09225
92	0.00E+00	0.069	124	0.00E+00	0.093
93	0.00E+00	0.06975	125	0.00E+00	0.09375
94	0.00E+00	0.0705	126	0.00E+00	0.0945
95	0.00E+00	0.07125	127	0.00E+00	0.09525

time-step	outlet4-vflow [ft^3/min]	flow-time [s]	time-step	outlet4-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	-9.76E+01	0.12
129	0.00E+00	0.09675	161	0.00E+00	0.12075
130	0.00E+00	0.0975	162	0.00E+00	0.1215
131	0.00E+00	0.09825	163	0.00E+00	0.12225
132	0.00E+00	0.099	164	0.00E+00	0.123
133	0.00E+00	0.09975	165	0.00E+00	0.12375
134	0.00E+00	0.1005	166	0.00E+00	0.1245
135	0.00E+00	0.10125	167	0.00E+00	0.12525
136	0.00E+00	0.102	168	0.00E+00	0.126
137	0.00E+00	0.10275	169	0.00E+00	0.12675
138	0.00E+00	0.1035	170	0.00E+00	0.1275
139	0.00E+00	0.10425	171	0.00E+00	0.12825
140	0.00E+00	0.105	172	0.00E+00	0.129
141	-6.08E+00	0.10575	173	0.00E+00	0.12975
142	-1.28E+01	0.1065	174	0.00E+00	0.1305
143	-2.36E+01	0.10725	175	0.00E+00	0.13125
144	-3.56E+01	0.108	176	0.00E+00	0.132
145	-4.64E+01	0.10875	177	0.00E+00	0.13275
146	-5.50E+01	0.1095	178	0.00E+00	0.1335
147	-6.13E+01	0.11025	179	0.00E+00	0.13425
148	-6.51E+01	0.111	180	0.00E+00	0.135
149	-6.67E+01	0.11175	181	0.00E+00	0.13575
150	-6.66E+01	0.1125	182	0.00E+00	0.1365
151	-6.64E+01	0.11325	183	0.00E+00	0.13725
152	-6.84E+01	0.114	184	0.00E+00	0.138
153	-7.37E+01	0.11475	185	0.00E+00	0.13875
154	-8.14E+01	0.1155	186	0.00E+00	0.1395
155	-8.92E+01	0.11625	187	0.00E+00	0.14025
156	-9.54E+01	0.117	188	0.00E+00	0.141
157	-9.91E+01	0.11775	189	0.00E+00	0.14175
158	-1.00E+02	0.1185	190	0.00E+00	0.1425
159	-9.97E+01	0.11925	191	0.00E+00	0.14325

time-step	outlet4-vflow [ft^3/min]	flow-time [s]	time-step	outlet4-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	0.00E+00	0.16275
193	0.00E+00	0.14475	218	0.00E+00	0.1635
194	0.00E+00	0.1455	219	0.00E+00	0.16425
195	0.00E+00	0.14625	220	0.00E+00	0.165
196	0.00E+00	0.147	221	-6.09E+00	0.16575
197	0.00E+00	0.14775	222	-1.28E+01	0.1665
198	0.00E+00	0.1485	223	-2.36E+01	0.16725
199	0.00E+00	0.14925	224	-3.55E+01	0.168
200	0.00E+00	0.15	225	-4.63E+01	0.16875
201	0.00E+00	0.15075	226	-5.49E+01	0.1695
202	0.00E+00	0.1515	227	-6.11E+01	0.17025
203	0.00E+00	0.15225	228	-6.49E+01	0.171
204	0.00E+00	0.153	229	-6.65E+01	0.17175
205	0.00E+00	0.15375	230	-6.64E+01	0.1725
206	0.00E+00	0.1545	231	-6.62E+01	0.17325
207	0.00E+00	0.15525	232	-6.83E+01	0.174
208	0.00E+00	0.156	233	-7.36E+01	0.17475
209	0.00E+00	0.15675	234	-8.12E+01	0.1755
210	0.00E+00	0.1575	235	-8.91E+01	0.17625
211	0.00E+00	0.15825	236	-9.52E+01	0.177
212	0.00E+00	0.159	237	-9.90E+01	0.17775
213	0.00E+00	0.15975	238	-1.00E+02	0.1785
214	0.00E+00	0.1605	239	-9.96E+01	0.17925
215	0.00E+00	0.16125	240	-9.74E+01	0.18
216	0.00E+00	0.162			

Table D5: Runner #4 Volumetric Flow Data for LS6 Manifold

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	0.00E+00	0.024
1	0.00E+00	0.00075	33	0.00E+00	0.02475
2	0.00E+00	0.0015	34	0.00E+00	0.0255
3	0.00E+00	0.00225	35	0.00E+00	0.02625
4	0.00E+00	0.003	36	0.00E+00	0.027
5	0.00E+00	0.00375	37	0.00E+00	0.02775
6	0.00E+00	0.0045	38	0.00E+00	0.0285
7	0.00E+00	0.00525	39	0.00E+00	0.02925
8	0.00E+00	0.006	40	0.00E+00	0.03
9	0.00E+00	0.00675	41	0.00E+00	0.03075
10	0.00E+00	0.0075	42	0.00E+00	0.0315
11	0.00E+00	0.00825	43	0.00E+00	0.03225
12	0.00E+00	0.009	44	0.00E+00	0.033
13	0.00E+00	0.00975	45	0.00E+00	0.03375
14	0.00E+00	0.0105	46	0.00E+00	0.0345
15	0.00E+00	0.01125	47	0.00E+00	0.03525
16	0.00E+00	0.012	48	0.00E+00	0.036
17	0.00E+00	0.01275	49	0.00E+00	0.03675
18	0.00E+00	0.0135	50	0.00E+00	0.0375
19	0.00E+00	0.01425	51	-5.07E+00	0.03825
20	0.00E+00	0.015	52	-7.81E+00	0.039
21	0.00E+00	0.01575	53	-1.49E+01	0.03975
22	0.00E+00	0.0165	54	-2.54E+01	0.0405
23	0.00E+00	0.01725	55	-3.68E+01	0.04125
24	0.00E+00	0.018	56	-4.72E+01	0.042
25	0.00E+00	0.01875	57	-5.51E+01	0.04275
26	0.00E+00	0.0195	58	-6.02E+01	0.0435
27	0.00E+00	0.02025	59	-6.29E+01	0.04425
28	0.00E+00	0.021	60	-6.38E+01	0.045
29	0.00E+00	0.02175	61	-6.58E+01	0.04575
30	0.00E+00	0.0225	62	-7.14E+01	0.0465
31	0.00E+00	0.02325	63	-7.98E+01	0.04725

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
64	-8.86E+01	0.048	96	0.00E+00	0.072
65	-9.56E+01	0.04875	97	0.00E+00	0.07275
66	-1.00E+02	0.0495	98	0.00E+00	0.0735
67	-1.03E+02	0.05025	99	0.00E+00	0.07425
68	-1.03E+02	0.051	100	0.00E+00	0.075
69	-1.02E+02	0.05175	101	0.00E+00	0.07575
70	-9.99E+01	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	0.00E+00	0.06825	123	0.00E+00	0.09225
92	0.00E+00	0.069	124	0.00E+00	0.093
93	0.00E+00	0.06975	125	0.00E+00	0.09375
94	0.00E+00	0.0705	126	0.00E+00	0.0945
95	0.00E+00	0.07125	127	0.00E+00	0.09525

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	0.00E+00	0.12
129	0.00E+00	0.09675	161	0.00E+00	0.12075
130	0.00E+00	0.0975	162	0.00E+00	0.1215
131	-5.01E+00	0.09825	163	0.00E+00	0.12225
132	-7.75E+00	0.099	164	0.00E+00	0.123
133	-1.50E+01	0.09975	165	0.00E+00	0.12375
134	-2.55E+01	0.1005	166	0.00E+00	0.1245
135	-3.70E+01	0.10125	167	0.00E+00	0.12525
136	-4.73E+01	0.102	168	0.00E+00	0.126
137	-5.52E+01	0.10275	169	0.00E+00	0.12675
138	-6.02E+01	0.1035	170	0.00E+00	0.1275
139	-6.26E+01	0.10425	171	0.00E+00	0.12825
140	-6.33E+01	0.105	172	0.00E+00	0.129
141	-6.52E+01	0.10575	173	0.00E+00	0.12975
142	-7.07E+01	0.1065	174	0.00E+00	0.1305
143	-7.90E+01	0.10725	175	0.00E+00	0.13125
144	-8.77E+01	0.108	176	0.00E+00	0.132
145	-9.48E+01	0.10875	177	0.00E+00	0.13275
146	-9.95E+01	0.1095	178	0.00E+00	0.1335
147	-1.02E+02	0.11025	179	0.00E+00	0.13425
148	-1.03E+02	0.111	180	0.00E+00	0.135
149	-1.02E+02	0.11175	181	0.00E+00	0.13575
150	-9.92E+01	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	0.00E+00	0.14325

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	-5.54E+01	0.16275
193	0.00E+00	0.14475	218	-6.04E+01	0.1635
194	0.00E+00	0.1455	219	-6.28E+01	0.16425
195	0.00E+00	0.14625	220	-6.35E+01	0.165
196	0.00E+00	0.147	221	-6.53E+01	0.16575
197	0.00E+00	0.14775	222	-7.08E+01	0.1665
198	0.00E+00	0.1485	223	-7.91E+01	0.16725
199	0.00E+00	0.14925	224	-8.78E+01	0.168
200	0.00E+00	0.15	225	-9.48E+01	0.16875
201	0.00E+00	0.15075	226	-9.94E+01	0.1695
202	0.00E+00	0.1515	227	-1.02E+02	0.17025
203	0.00E+00	0.15225	228	-1.02E+02	0.171
204	0.00E+00	0.153	229	-1.02E+02	0.17175
205	0.00E+00	0.15375	230	-9.90E+01	0.1725
206	0.00E+00	0.1545	231	0.00E+00	0.17325
207	0.00E+00	0.15525	232	0.00E+00	0.174
208	0.00E+00	0.156	233	0.00E+00	0.17475
209	0.00E+00	0.15675	234	0.00E+00	0.1755
210	0.00E+00	0.1575	235	0.00E+00	0.17625
211	-5.01E+00	0.15825	236	0.00E+00	0.177
212	-7.77E+00	0.159	237	0.00E+00	0.17775
213	-1.50E+01	0.15975	238	0.00E+00	0.1785
214	-2.55E+01	0.1605	239	0.00E+00	0.17925
215	-3.71E+01	0.16125	240	0.00E+00	0.18
216	-4.75E+01	0.162			

Table D6: Runner #5 Volumetric Flow Data for LS6 Manifold

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	0.00E+00	0.024
1	0.00E+00	0.00075	33	0.00E+00	0.02475
2	0.00E+00	0.0015	34	0.00E+00	0.0255
3	0.00E+00	0.00225	35	0.00E+00	0.02625
4	0.00E+00	0.003	36	0.00E+00	0.027
5	0.00E+00	0.00375	37	0.00E+00	0.02775
6	0.00E+00	0.0045	38	0.00E+00	0.0285
7	0.00E+00	0.00525	39	0.00E+00	0.02925
8	0.00E+00	0.006	40	0.00E+00	0.03
9	0.00E+00	0.00675	41	-5.26E+00	0.03075
10	0.00E+00	0.0075	42	-1.22E+01	0.0315
11	0.00E+00	0.00825	43	-2.46E+01	0.03225
12	0.00E+00	0.009	44	-3.95E+01	0.033
13	0.00E+00	0.00975	45	-5.38E+01	0.03375
14	0.00E+00	0.0105	46	-6.55E+01	0.0345
15	0.00E+00	0.01125	47	-7.40E+01	0.03525
16	0.00E+00	0.012	48	-7.93E+01	0.036
17	0.00E+00	0.01275	49	-8.18E+01	0.03675
18	0.00E+00	0.0135	50	-8.21E+01	0.0375
19	0.00E+00	0.01425	51	-8.19E+01	0.03825
20	0.00E+00	0.015	52	-8.38E+01	0.039
21	0.00E+00	0.01575	53	-8.85E+01	0.03975
22	0.00E+00	0.0165	54	-9.50E+01	0.0405
23	0.00E+00	0.01725	55	-1.01E+02	0.04125
24	0.00E+00	0.018	56	-1.05E+02	0.042
25	0.00E+00	0.01875	57	-1.07E+02	0.04275
26	0.00E+00	0.0195	58	-1.07E+02	0.0435
27	0.00E+00	0.02025	59	-1.05E+02	0.04425
28	0.00E+00	0.021	60	-1.02E+02	0.045
29	0.00E+00	0.02175	61	0.00E+00	0.04575
30	0.00E+00	0.0225	62	0.00E+00	0.0465
31	0.00E+00	0.02325	63	0.00E+00	0.04725

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	0.00E+00	0.072
65	0.00E+00	0.04875	97	0.00E+00	0.07275
66	0.00E+00	0.0495	98	0.00E+00	0.0735
67	0.00E+00	0.05025	99	0.00E+00	0.07425
68	0.00E+00	0.051	100	0.00E+00	0.075
69	0.00E+00	0.05175	101	0.00E+00	0.07575
70	0.00E+00	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	-5.17E+00	0.09075
90	0.00E+00	0.0675	122	-1.18E+01	0.0915
91	0.00E+00	0.06825	123	-2.39E+01	0.09225
92	0.00E+00	0.069	124	-3.87E+01	0.093
93	0.00E+00	0.06975	125	-5.29E+01	0.09375
94	0.00E+00	0.0705	126	-6.46E+01	0.0945
95	0.00E+00	0.07125	127	-7.30E+01	0.09525

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
128	-7.82E+01	0.096	160	0.00E+00	0.12
129	-8.06E+01	0.09675	161	0.00E+00	0.12075
130	-8.09E+01	0.0975	162	0.00E+00	0.1215
131	-8.08E+01	0.09825	163	0.00E+00	0.12225
132	-8.29E+01	0.099	164	0.00E+00	0.123
133	-8.79E+01	0.09975	165	0.00E+00	0.12375
134	-9.46E+01	0.1005	166	0.00E+00	0.1245
135	-1.01E+02	0.10125	167	0.00E+00	0.12525
136	-1.05E+02	0.102	168	0.00E+00	0.126
137	-1.07E+02	0.10275	169	0.00E+00	0.12675
138	-1.06E+02	0.1035	170	0.00E+00	0.1275
139	-1.05E+02	0.10425	171	0.00E+00	0.12825
140	-1.02E+02	0.105	172	0.00E+00	0.129
141	0.00E+00	0.10575	173	0.00E+00	0.12975
142	0.00E+00	0.1065	174	0.00E+00	0.1305
143	0.00E+00	0.10725	175	0.00E+00	0.13125
144	0.00E+00	0.108	176	0.00E+00	0.132
145	0.00E+00	0.10875	177	0.00E+00	0.13275
146	0.00E+00	0.1095	178	0.00E+00	0.1335
147	0.00E+00	0.11025	179	0.00E+00	0.13425
148	0.00E+00	0.111	180	0.00E+00	0.135
149	0.00E+00	0.11175	181	0.00E+00	0.13575
150	0.00E+00	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	0.00E+00	0.14325

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	-1.06E+02	0.16275
193	0.00E+00	0.14475	218	-1.06E+02	0.1635
194	0.00E+00	0.1455	219	-1.05E+02	0.16425
195	0.00E+00	0.14625	220	-1.02E+02	0.165
196	0.00E+00	0.147	221	0.00E+00	0.16575
197	0.00E+00	0.14775	222	0.00E+00	0.1665
198	0.00E+00	0.1485	223	0.00E+00	0.16725
199	0.00E+00	0.14925	224	0.00E+00	0.168
200	0.00E+00	0.15	225	0.00E+00	0.16875
201	-5.10E+00	0.15075	226	0.00E+00	0.1695
202	-1.17E+01	0.1515	227	0.00E+00	0.17025
203	-2.39E+01	0.15225	228	0.00E+00	0.171
204	-3.86E+01	0.153	229	0.00E+00	0.17175
205	-5.28E+01	0.15375	230	0.00E+00	0.1725
206	-6.44E+01	0.1545	231	0.00E+00	0.17325
207	-7.28E+01	0.15525	232	0.00E+00	0.174
208	-7.80E+01	0.156	233	0.00E+00	0.17475
209	-8.03E+01	0.15675	234	0.00E+00	0.1755
210	-8.07E+01	0.1575	235	0.00E+00	0.17625
211	-8.05E+01	0.15825	236	0.00E+00	0.177
212	-8.26E+01	0.159	237	0.00E+00	0.17775
213	-8.76E+01	0.15975	238	0.00E+00	0.1785
214	-9.42E+01	0.1605	239	0.00E+00	0.17925
215	-1.00E+02	0.16125	240	0.00E+00	0.18
216	-1.04E+02	0.162			

Table D7: Runner #6 Volumetric Flow Data for LS6 Manifold

time-step	outlet7-vflow [ft^3/min]	flow-time [s]	time-step	outlet7-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	-8.70E+01	0.024
1	0.00E+00	0.00075	33	-9.69E+01	0.02475
2	0.00E+00	0.0015	34	-1.04E+02	0.0255
3	0.00E+00	0.00225	35	-1.08E+02	0.02625
4	0.00E+00	0.003	36	-1.10E+02	0.027
5	0.00E+00	0.00375	37	-1.10E+02	0.02775
6	0.00E+00	0.0045	38	-1.10E+02	0.0285
7	0.00E+00	0.00525	39	-1.09E+02	0.02925
8	0.00E+00	0.006	40	-1.06E+02	0.03
9	0.00E+00	0.00675	41	0.00E+00	0.03075
10	0.00E+00	0.0075	42	0.00E+00	0.0315
11	0.00E+00	0.00825	43	0.00E+00	0.03225
12	0.00E+00	0.009	44	0.00E+00	0.033
13	0.00E+00	0.00975	45	0.00E+00	0.03375
14	0.00E+00	0.0105	46	0.00E+00	0.0345
15	0.00E+00	0.01125	47	0.00E+00	0.03525
16	0.00E+00	0.012	48	0.00E+00	0.036
17	0.00E+00	0.01275	49	0.00E+00	0.03675
18	0.00E+00	0.0135	50	0.00E+00	0.0375
19	0.00E+00	0.01425	51	0.00E+00	0.03825
20	0.00E+00	0.015	52	0.00E+00	0.039
21	-3.27E+00	0.01575	53	0.00E+00	0.03975
22	-7.40E+00	0.0165	54	0.00E+00	0.0405
23	-1.62E+01	0.01725	55	0.00E+00	0.04125
24	-2.83E+01	0.018	56	0.00E+00	0.042
25	-4.13E+01	0.01875	57	0.00E+00	0.04275
26	-5.31E+01	0.0195	58	0.00E+00	0.0435
27	-6.23E+01	0.02025	59	0.00E+00	0.04425
28	-6.88E+01	0.021	60	0.00E+00	0.045
29	-7.29E+01	0.02175	61	0.00E+00	0.04575
30	-7.47E+01	0.0225	62	0.00E+00	0.0465
31	-7.86E+01	0.02325	63	0.00E+00	0.04725

time-step	outlet7-vflow [ft^3/min]	flow-time [s]	time-step	outlet7-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	0.00E+00	0.072
65	0.00E+00	0.04875	97	0.00E+00	0.07275
66	0.00E+00	0.0495	98	0.00E+00	0.0735
67	0.00E+00	0.05025	99	0.00E+00	0.07425
68	0.00E+00	0.051	100	0.00E+00	0.075
69	0.00E+00	0.05175	101	-2.55E+00	0.07575
70	0.00E+00	0.0525	102	-5.53E+00	0.0765
71	0.00E+00	0.05325	103	-1.30E+01	0.07725
72	0.00E+00	0.054	104	-2.37E+01	0.078
73	0.00E+00	0.05475	105	-3.54E+01	0.07875
74	0.00E+00	0.0555	106	-4.61E+01	0.0795
75	0.00E+00	0.05625	107	-5.46E+01	0.08025
76	0.00E+00	0.057	108	-6.06E+01	0.081
77	0.00E+00	0.05775	109	-6.44E+01	0.08175
78	0.00E+00	0.0585	110	-6.64E+01	0.0825
79	0.00E+00	0.05925	111	-7.10E+01	0.08325
80	0.00E+00	0.06	112	-8.04E+01	0.084
81	0.00E+00	0.06075	113	-9.14E+01	0.08475
82	0.00E+00	0.0615	114	-1.00E+02	0.0855
83	0.00E+00	0.06225	115	-1.05E+02	0.08625
84	0.00E+00	0.063	116	-1.08E+02	0.087
85	0.00E+00	0.06375	117	-1.09E+02	0.08775
86	0.00E+00	0.0645	118	-1.09E+02	0.0885
87	0.00E+00	0.06525	119	-1.08E+02	0.08925
88	0.00E+00	0.066	120	-1.06E+02	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	0.00E+00	0.06825	123	0.00E+00	0.09225
92	0.00E+00	0.069	124	0.00E+00	0.093
93	0.00E+00	0.06975	125	0.00E+00	0.09375
94	0.00E+00	0.0705	126	0.00E+00	0.0945
95	0.00E+00	0.07125	127	0.00E+00	0.09525

time-step	outlet7-vflow [ft^3/min]	flow-time [s]	time-step	outlet7-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	0.00E+00	0.12
129	0.00E+00	0.09675	161	0.00E+00	0.12075
130	0.00E+00	0.0975	162	0.00E+00	0.1215
131	0.00E+00	0.09825	163	0.00E+00	0.12225
132	0.00E+00	0.099	164	0.00E+00	0.123
133	0.00E+00	0.09975	165	0.00E+00	0.12375
134	0.00E+00	0.1005	166	0.00E+00	0.1245
135	0.00E+00	0.10125	167	0.00E+00	0.12525
136	0.00E+00	0.102	168	0.00E+00	0.126
137	0.00E+00	0.10275	169	0.00E+00	0.12675
138	0.00E+00	0.1035	170	0.00E+00	0.1275
139	0.00E+00	0.10425	171	0.00E+00	0.12825
140	0.00E+00	0.105	172	0.00E+00	0.129
141	0.00E+00	0.10575	173	0.00E+00	0.12975
142	0.00E+00	0.1065	174	0.00E+00	0.1305
143	0.00E+00	0.10725	175	0.00E+00	0.13125
144	0.00E+00	0.108	176	0.00E+00	0.132
145	0.00E+00	0.10875	177	0.00E+00	0.13275
146	0.00E+00	0.1095	178	0.00E+00	0.1335
147	0.00E+00	0.11025	179	0.00E+00	0.13425
148	0.00E+00	0.111	180	0.00E+00	0.135
149	0.00E+00	0.11175	181	-2.55E+00	0.13575
150	0.00E+00	0.1125	182	-5.55E+00	0.1365
151	0.00E+00	0.11325	183	-1.30E+01	0.13725
152	0.00E+00	0.114	184	-2.38E+01	0.138
153	0.00E+00	0.11475	185	-3.55E+01	0.13875
154	0.00E+00	0.1155	186	-4.62E+01	0.1395
155	0.00E+00	0.11625	187	-5.46E+01	0.14025
156	0.00E+00	0.117	188	-6.06E+01	0.141
157	0.00E+00	0.11775	189	-6.44E+01	0.14175
158	0.00E+00	0.1185	190	-6.64E+01	0.1425
159	0.00E+00	0.11925	191	-7.09E+01	0.14325

time-step	outlet7-vflow [ft^3/min]	flow-time [s]
192	-8.02E+01	0.144
193	-9.12E+01	0.14475
194	-9.98E+01	0.1455
195	-1.05E+02	0.14625
196	-1.07E+02	0.147
197	-1.09E+02	0.14775
198	-1.09E+02	0.1485
199	-1.08E+02	0.14925
200	-1.06E+02	0.15
201	0.00E+00	0.15075
202	0.00E+00	0.1515
203	0.00E+00	0.15225
204	0.00E+00	0.153
205	0.00E+00	0.15375
206	0.00E+00	0.1545
207	0.00E+00	0.15525
208	0.00E+00	0.156
209	0.00E+00	0.15675
210	0.00E+00	0.1575
211	0.00E+00	0.15825
212	0.00E+00	0.159
213	0.00E+00	0.15975
214	0.00E+00	0.1605
215	0.00E+00	0.16125
216	0.00E+00	0.162
217	0.00E+00	0.16275
218	0.00E+00	0.1635
219	0.00E+00	0.16425
220	0.00E+00	0.165
221	0.00E+00	0.16575
222	0.00E+00	0.1665
223	0.00E+00	0.16725
224	0.00E+00	0.168
225	0.00E+00	0.16875
226	0.00E+00	0.1695
227	0.00E+00	0.17025
228	0.00E+00	0.171
229	0.00E+00	0.17175
230	0.00E+00	0.1725
231	0.00E+00	0.17325
232	0.00E+00	0.174
233	0.00E+00	0.17475
234	0.00E+00	0.1755
235	0.00E+00	0.17625
236	0.00E+00	0.177
237	0.00E+00	0.17775
238	0.00E+00	0.1785
239	0.00E+00	0.17925
240	0.00E+00	0.18

Table D8: Runner #7 Volumetric Flow Data for LS6 Manifold

time-step	outlet8-vflow [ft^3/min]	flow-time [s]	time-step	outlet8-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	0.00E+00	0.024
1	0.00E+00	0.00075	33	0.00E+00	0.02475
2	0.00E+00	0.0015	34	0.00E+00	0.0255
3	0.00E+00	0.00225	35	0.00E+00	0.02625
4	0.00E+00	0.003	36	0.00E+00	0.027
5	0.00E+00	0.00375	37	0.00E+00	0.02775
6	0.00E+00	0.0045	38	0.00E+00	0.0285
7	0.00E+00	0.00525	39	0.00E+00	0.02925
8	0.00E+00	0.006	40	0.00E+00	0.03
9	0.00E+00	0.00675	41	0.00E+00	0.03075
10	0.00E+00	0.0075	42	0.00E+00	0.0315
11	-4.00E+00	0.00825	43	0.00E+00	0.03225
12	-7.24E+00	0.009	44	0.00E+00	0.033
13	-1.51E+01	0.00975	45	0.00E+00	0.03375
14	-2.44E+01	0.0105	46	0.00E+00	0.0345
15	-3.29E+01	0.01125	47	0.00E+00	0.03525
16	-3.98E+01	0.012	48	0.00E+00	0.036
17	-4.51E+01	0.01275	49	0.00E+00	0.03675
18	-4.88E+01	0.0135	50	0.00E+00	0.0375
19	-5.11E+01	0.01425	51	0.00E+00	0.03825
20	-5.24E+01	0.015	52	0.00E+00	0.039
21	-5.39E+01	0.01575	53	0.00E+00	0.03975
22	-5.81E+01	0.0165	54	0.00E+00	0.0405
23	-6.60E+01	0.01725	55	0.00E+00	0.04125
24	-7.65E+01	0.018	56	0.00E+00	0.042
25	-8.75E+01	0.01875	57	0.00E+00	0.04275
26	-9.64E+01	0.0195	58	0.00E+00	0.0435
27	-1.03E+02	0.02025	59	0.00E+00	0.04425
28	-1.06E+02	0.021	60	0.00E+00	0.045
29	-1.07E+02	0.02175	61	0.00E+00	0.04575
30	-1.05E+02	0.0225	62	0.00E+00	0.0465
31	0.00E+00	0.02325	63	0.00E+00	0.04725

time-step	outlet8-vflow [ft^3/min]	flow-time [s]	time-step	outlet8-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	-5.85E+01	0.072
65	0.00E+00	0.04875	97	-6.52E+01	0.07275
66	0.00E+00	0.0495	98	-6.92E+01	0.0735
67	0.00E+00	0.05025	99	-7.10E+01	0.07425
68	0.00E+00	0.051	100	-7.11E+01	0.075
69	0.00E+00	0.05175	101	-7.06E+01	0.07575
70	0.00E+00	0.0525	102	-7.23E+01	0.0765
71	0.00E+00	0.05325	103	-7.73E+01	0.07725
72	0.00E+00	0.054	104	-8.51E+01	0.078
73	0.00E+00	0.05475	105	-9.34E+01	0.07875
74	0.00E+00	0.0555	106	-1.00E+02	0.0795
75	0.00E+00	0.05625	107	-1.04E+02	0.08025
76	0.00E+00	0.057	108	-1.06E+02	0.081
77	0.00E+00	0.05775	109	-1.06E+02	0.08175
78	0.00E+00	0.0585	110	-1.05E+02	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	-5.72E+00	0.06825	123	0.00E+00	0.09225
92	-1.27E+01	0.069	124	0.00E+00	0.093
93	-2.42E+01	0.06975	125	0.00E+00	0.09375
94	-3.73E+01	0.0705	126	0.00E+00	0.0945
95	-4.91E+01	0.07125	127	0.00E+00	0.09525

time-step	outlet8-vflow [ft^3/min]	flow-time [s]	time-step	outlet8-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	0.00E+00	0.12
129	0.00E+00	0.09675	161	0.00E+00	0.12075
130	0.00E+00	0.0975	162	0.00E+00	0.1215
131	0.00E+00	0.09825	163	0.00E+00	0.12225
132	0.00E+00	0.099	164	0.00E+00	0.123
133	0.00E+00	0.09975	165	0.00E+00	0.12375
134	0.00E+00	0.1005	166	0.00E+00	0.1245
135	0.00E+00	0.10125	167	0.00E+00	0.12525
136	0.00E+00	0.102	168	0.00E+00	0.126
137	0.00E+00	0.10275	169	0.00E+00	0.12675
138	0.00E+00	0.1035	170	0.00E+00	0.1275
139	0.00E+00	0.10425	171	-5.62E+00	0.12825
140	0.00E+00	0.105	172	-1.26E+01	0.129
141	0.00E+00	0.10575	173	-2.42E+01	0.12975
142	0.00E+00	0.1065	174	-3.73E+01	0.1305
143	0.00E+00	0.10725	175	-4.91E+01	0.13125
144	0.00E+00	0.108	176	-5.85E+01	0.132
145	0.00E+00	0.10875	177	-6.52E+01	0.13275
146	0.00E+00	0.1095	178	-6.93E+01	0.1335
147	0.00E+00	0.11025	179	-7.10E+01	0.13425
148	0.00E+00	0.111	180	-7.10E+01	0.135
149	0.00E+00	0.11175	181	-7.05E+01	0.13575
150	0.00E+00	0.1125	182	-7.22E+01	0.1365
151	0.00E+00	0.11325	183	-7.72E+01	0.13725
152	0.00E+00	0.114	184	-8.49E+01	0.138
153	0.00E+00	0.11475	185	-9.31E+01	0.13875
154	0.00E+00	0.1155	186	-9.97E+01	0.1395
155	0.00E+00	0.11625	187	-1.04E+02	0.14025
156	0.00E+00	0.117	188	-1.06E+02	0.141
157	0.00E+00	0.11775	189	-1.06E+02	0.14175
158	0.00E+00	0.1185	190	-1.04E+02	0.1425
159	0.00E+00	0.11925	191	0.00E+00	0.14325

time-step	outlet8-vflow [ft^3/min]	flow-time [s]	time-step	outlet8-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	0.00E+00	0.16275
193	0.00E+00	0.14475	218	0.00E+00	0.1635
194	0.00E+00	0.1455	219	0.00E+00	0.16425
195	0.00E+00	0.14625	220	0.00E+00	0.165
196	0.00E+00	0.147	221	0.00E+00	0.16575
197	0.00E+00	0.14775	222	0.00E+00	0.1665
198	0.00E+00	0.1485	223	0.00E+00	0.16725
199	0.00E+00	0.14925	224	0.00E+00	0.168
200	0.00E+00	0.15	225	0.00E+00	0.16875
201	0.00E+00	0.15075	226	0.00E+00	0.1695
202	0.00E+00	0.1515	227	0.00E+00	0.17025
203	0.00E+00	0.15225	228	0.00E+00	0.171
204	0.00E+00	0.153	229	0.00E+00	0.17175
205	0.00E+00	0.15375	230	0.00E+00	0.1725
206	0.00E+00	0.1545	231	0.00E+00	0.17325
207	0.00E+00	0.15525	232	0.00E+00	0.174
208	0.00E+00	0.156	233	0.00E+00	0.17475
209	0.00E+00	0.15675	234	0.00E+00	0.1755
210	0.00E+00	0.1575	235	0.00E+00	0.17625
211	0.00E+00	0.15825	236	0.00E+00	0.177
212	0.00E+00	0.159	237	0.00E+00	0.17775
213	0.00E+00	0.15975	238	0.00E+00	0.1785
214	0.00E+00	0.1605	239	0.00E+00	0.17925
215	0.00E+00	0.16125	240	0.00E+00	0.18
216	0.00E+00	0.162			

Table D9: Runner #8 Volumetric Flow Data for LS6 Manifold

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
0	8.13E+00	0	32	2.11E+00	0.024
1	9.01E+00	0.00075	33	1.06E+00	0.02475
2	7.69E+00	0.0015	34	-4.23E-02	0.0255
3	5.24E+00	0.00225	35	-9.56E-01	0.02625
4	2.34E+00	0.003	36	-1.62E+00	0.027
5	-4.79E-01	0.00375	37	-2.05E+00	0.02775
6	-2.82E+00	0.0045	38	-2.25E+00	0.0285
7	-4.48E+00	0.00525	39	-2.26E+00	0.02925
8	-5.41E+00	0.006	40	-2.08E+00	0.03
9	-5.67E+00	0.00675	41	4.25E+00	0.03075
10	-5.39E+00	0.0075	42	3.73E+00	0.0315
11	1.59E+00	0.00825	43	2.63E+00	0.03225
12	1.35E+00	0.009	44	1.16E+00	0.033
13	6.65E-01	0.00975	45	-3.64E-01	0.03375
14	-1.37E-01	0.0105	46	-1.62E+00	0.0345
15	-8.06E-01	0.01125	47	-2.49E+00	0.03525
16	-1.28E+00	0.012	48	-2.94E+00	0.036
17	-1.58E+00	0.01275	49	-3.06E+00	0.03675
18	-1.73E+00	0.0135	50	-2.92E+00	0.0375
19	-1.75E+00	0.01425	51	2.63E+00	0.03825
20	-1.62E+00	0.015	52	2.29E+00	0.039
21	4.51E+00	0.01575	53	1.54E+00	0.03975
22	3.94E+00	0.0165	54	5.06E-01	0.0405
23	2.87E+00	0.01725	55	-5.57E-01	0.04125
24	1.44E+00	0.018	56	-1.44E+00	0.042
25	-4.81E-02	0.01875	57	-2.04E+00	0.04275
26	-1.33E+00	0.0195	58	-2.35E+00	0.0435
27	-2.28E+00	0.02025	59	-2.42E+00	0.04425
28	-2.87E+00	0.021	60	-2.28E+00	0.045
29	-3.15E+00	0.02175	61	3.61E+00	0.04575
30	-3.16E+00	0.0225	62	2.82E+00	0.0465
31	2.76E+00	0.02325	63	1.60E+00	0.04725

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
64	3.00E-01	0.048	96	-1.73E+00	0.072
65	-8.11E-01	0.04875	97	-2.29E+00	0.07275
66	-1.63E+00	0.0495	98	-2.56E+00	0.0735
67	-2.16E+00	0.05025	99	-2.60E+00	0.07425
68	-2.42E+00	0.051	100	-2.42E+00	0.075
69	-2.45E+00	0.05175	101	3.52E+00	0.07575
70	-2.27E+00	0.0525	102	3.18E+00	0.0765
71	3.70E+00	0.05325	103	2.38E+00	0.07725
72	3.14E+00	0.054	104	1.22E+00	0.078
73	2.08E+00	0.05475	105	-2.89E-02	0.07875
74	7.95E-01	0.0555	106	-1.10E+00	0.0795
75	-4.37E-01	0.05625	107	-1.89E+00	0.08025
76	-1.43E+00	0.057	108	-2.38E+00	0.081
77	-2.11E+00	0.05775	109	-2.60E+00	0.08175
78	-2.48E+00	0.0585	110	-2.63E+00	0.0825
79	-2.59E+00	0.05925	111	3.24E+00	0.08325
80	-2.48E+00	0.06	112	2.49E+00	0.084
81	3.20E+00	0.06075	113	1.34E+00	0.08475
82	2.36E+00	0.0615	114	1.18E-01	0.0855
83	1.20E+00	0.06225	115	-9.04E-01	0.08625
84	1.22E-01	0.063	116	-1.65E+00	0.087
85	-6.94E-01	0.06375	117	-2.14E+00	0.08775
86	-1.27E+00	0.0645	118	-2.38E+00	0.0885
87	-1.68E+00	0.06525	119	-2.41E+00	0.08925
88	-1.93E+00	0.066	120	-2.24E+00	0.09
89	-2.02E+00	0.06675	121	4.10E+00	0.09075
90	-1.97E+00	0.0675	122	3.62E+00	0.0915
91	3.76E+00	0.06825	123	2.57E+00	0.09225
92	2.96E+00	0.069	124	1.13E+00	0.093
93	1.70E+00	0.06975	125	-3.64E-01	0.09375
94	3.27E-01	0.0705	126	-1.60E+00	0.0945
95	-8.54E-01	0.07125	127	-2.44E+00	0.09525

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
128	-2.88E+00	0.096	160	-2.44E+00	0.12
129	-2.97E+00	0.09675	161	3.23E+00	0.12075
130	-2.84E+00	0.0975	162	2.40E+00	0.1215
131	2.70E+00	0.09825	163	1.24E+00	0.12225
132	2.34E+00	0.099	164	1.67E-01	0.123
133	1.58E+00	0.09975	165	-6.49E-01	0.12375
134	5.29E-01	0.1005	166	-1.23E+00	0.1245
135	-5.47E-01	0.10125	167	-1.64E+00	0.12525
136	-1.43E+00	0.102	168	-1.90E+00	0.126
137	-2.03E+00	0.10275	169	-1.99E+00	0.12675
138	-2.33E+00	0.1035	170	-1.96E+00	0.1275
139	-2.39E+00	0.10425	171	3.80E+00	0.12825
140	-2.24E+00	0.105	172	2.99E+00	0.129
141	3.65E+00	0.10575	173	1.72E+00	0.12975
142	2.87E+00	0.1065	174	3.42E-01	0.1305
143	1.65E+00	0.10725	175	-8.44E-01	0.13125
144	3.41E-01	0.108	176	-1.72E+00	0.132
145	-7.76E-01	0.10875	177	-2.28E+00	0.13275
146	-1.60E+00	0.1095	178	-2.55E+00	0.1335
147	-2.13E+00	0.11025	179	-2.58E+00	0.13425
148	-2.39E+00	0.111	180	-2.40E+00	0.135
149	-2.42E+00	0.11175	181	3.52E+00	0.13575
150	-2.24E+00	0.1125	182	3.19E+00	0.1365
151	3.69E+00	0.11325	183	2.39E+00	0.13725
152	3.13E+00	0.114	184	1.23E+00	0.138
153	2.09E+00	0.11475	185	-1.46E-02	0.13875
154	8.10E-01	0.1155	186	-1.08E+00	0.1395
155	-4.18E-01	0.11625	187	-1.87E+00	0.14025
156	-1.40E+00	0.117	188	-2.34E+00	0.141
157	-2.08E+00	0.11775	189	-2.56E+00	0.14175
158	-2.45E+00	0.1185	190	-2.58E+00	0.1425
159	-2.54E+00	0.11925	191	3.25E+00	0.14325

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
192	2.51E+00	0.144	217	-2.02E+00	0.16275
193	1.36E+00	0.14475	218	-2.32E+00	0.1635
194	1.47E-01	0.1455	219	-2.37E+00	0.16425
195	-8.71E-01	0.14625	220	-2.23E+00	0.165
196	-1.62E+00	0.147	221	3.64E+00	0.16575
197	-2.11E+00	0.14775	222	2.86E+00	0.1665
198	-2.35E+00	0.1485	223	1.65E+00	0.16725
199	-2.38E+00	0.14925	224	3.43E-01	0.168
200	-2.21E+00	0.15	225	-7.67E-01	0.16875
201	4.12E+00	0.15075	226	-1.59E+00	0.1695
202	3.64E+00	0.1515	227	-2.11E+00	0.17025
203	2.59E+00	0.15225	228	-2.36E+00	0.171
204	1.14E+00	0.153	229	-2.39E+00	0.17175
205	-3.45E-01	0.15375	230	-2.22E+00	0.1725
206	-1.58E+00	0.1545	231	3.70E+00	0.17325
207	-2.42E+00	0.15525	232	3.14E+00	0.174
208	-2.85E+00	0.156	233	2.10E+00	0.17475
209	-2.95E+00	0.15675	234	8.19E-01	0.1755
210	-2.81E+00	0.1575	235	-4.07E-01	0.17625
211	2.71E+00	0.15825	236	-1.39E+00	0.177
212	2.36E+00	0.159	237	-2.07E+00	0.17775
213	1.60E+00	0.15975	238	-2.44E+00	0.1785
214	5.44E-01	0.1605	239	-2.53E+00	0.17925
215	-5.34E-01	0.16125	240	-2.42E+00	0.18
216	-1.42E+00	0.162			

Table D10: Net Mass Flow Data for LS6 Manifold

time-step	inlet-vflow [ft^3/min]	flow-time [s]	time-step	inlet-vflow [ft^3/min]	flow-time [s]
0	1.30E+02	0	32	1.29E+02	0.024
1	1.30E+02	0.00075	33	1.28E+02	0.02475
2	1.29E+02	0.0015	34	1.28E+02	0.0255
3	1.28E+02	0.00225	35	1.28E+02	0.02625
4	1.27E+02	0.003	36	1.28E+02	0.027
5	1.27E+02	0.00375	37	1.29E+02	0.02775
6	1.27E+02	0.0045	38	1.29E+02	0.0285
7	1.27E+02	0.00525	39	1.29E+02	0.02925
8	1.28E+02	0.006	40	1.29E+02	0.03
9	1.28E+02	0.00675	41	1.29E+02	0.03075
10	1.28E+02	0.0075	42	1.29E+02	0.0315
11	1.28E+02	0.00825	43	1.29E+02	0.03225
12	1.28E+02	0.009	44	1.28E+02	0.033
13	1.28E+02	0.00975	45	1.28E+02	0.03375
14	1.28E+02	0.0105	46	1.28E+02	0.0345
15	1.28E+02	0.01125	47	1.29E+02	0.03525
16	1.29E+02	0.012	48	1.29E+02	0.036
17	1.29E+02	0.01275	49	1.29E+02	0.03675
18	1.29E+02	0.0135	50	1.29E+02	0.0375
19	1.29E+02	0.01425	51	1.29E+02	0.03825
20	1.30E+02	0.015	52	1.29E+02	0.039
21	1.29E+02	0.01575	53	1.28E+02	0.03975
22	1.29E+02	0.0165	54	1.28E+02	0.0405
23	1.29E+02	0.01725	55	1.28E+02	0.04125
24	1.28E+02	0.018	56	1.29E+02	0.042
25	1.28E+02	0.01875	57	1.29E+02	0.04275
26	1.28E+02	0.0195	58	1.29E+02	0.0435
27	1.29E+02	0.02025	59	1.29E+02	0.04425
28	1.29E+02	0.021	60	1.29E+02	0.045
29	1.29E+02	0.02175	61	1.29E+02	0.04575
30	1.29E+02	0.0225	62	1.29E+02	0.0465
31	1.29E+02	0.02325	63	1.29E+02	0.04725

time-step	inlet-vflow [ft^3/min]	flow-time [s]
64	1.28E+02	0.048
65	1.29E+02	0.04875
66	1.29E+02	0.0495
67	1.29E+02	0.05025
68	1.29E+02	0.051
69	1.29E+02	0.05175
70	1.29E+02	0.0525
71	1.29E+02	0.05325
72	1.29E+02	0.054
73	1.29E+02	0.05475
74	1.28E+02	0.0555
75	1.28E+02	0.05625
76	1.29E+02	0.057
77	1.29E+02	0.05775
78	1.29E+02	0.0585
79	1.29E+02	0.05925
80	1.29E+02	0.06
81	1.29E+02	0.06075
82	1.29E+02	0.0615
83	1.29E+02	0.06225
84	1.29E+02	0.063
85	1.29E+02	0.06375
86	1.29E+02	0.0645
87	1.29E+02	0.06525
88	1.29E+02	0.066
89	1.29E+02	0.06675
90	1.29E+02	0.0675
91	1.29E+02	0.06825
92	1.29E+02	0.069
93	1.29E+02	0.06975
94	1.28E+02	0.0705
95	1.28E+02	0.07125
96	1.29E+02	0.072
97	1.29E+02	0.07275
98	1.29E+02	0.0735
99	1.29E+02	0.07425
100	1.29E+02	0.075
101	1.29E+02	0.07575
102	1.29E+02	0.0765
103	1.28E+02	0.07725
104	1.28E+02	0.078
105	1.28E+02	0.07875
106	1.28E+02	0.0795
107	1.29E+02	0.08025
108	1.29E+02	0.081
109	1.29E+02	0.08175
110	1.29E+02	0.0825
111	1.29E+02	0.08325
112	1.29E+02	0.084
113	1.29E+02	0.08475
114	1.28E+02	0.0855
115	1.28E+02	0.08625
116	1.28E+02	0.087
117	1.29E+02	0.08775
118	1.29E+02	0.0885
119	1.29E+02	0.08925
120	1.29E+02	0.09
121	1.29E+02	0.09075
122	1.29E+02	0.0915
123	1.29E+02	0.09225
124	1.28E+02	0.093
125	1.28E+02	0.09375
126	1.28E+02	0.0945
127	1.29E+02	0.09525

time-step	inlet-vflow [ft^3/min]	flow-time [s]	time-step	inlet-vflow [ft^3/min]	flow-time [s]
128	1.29E+02	0.096	160	1.29E+02	0.12
129	1.29E+02	0.09675	161	1.29E+02	0.12075
130	1.29E+02	0.0975	162	1.29E+02	0.1215
131	1.29E+02	0.09825	163	1.29E+02	0.12225
132	1.29E+02	0.099	164	1.29E+02	0.123
133	1.28E+02	0.09975	165	1.29E+02	0.12375
134	1.28E+02	0.1005	166	1.29E+02	0.1245
135	1.28E+02	0.10125	167	1.29E+02	0.12525
136	1.29E+02	0.102	168	1.29E+02	0.126
137	1.29E+02	0.10275	169	1.29E+02	0.12675
138	1.29E+02	0.1035	170	1.29E+02	0.1275
139	1.29E+02	0.10425	171	1.29E+02	0.12825
140	1.29E+02	0.105	172	1.29E+02	0.129
141	1.29E+02	0.10575	173	1.29E+02	0.12975
142	1.29E+02	0.1065	174	1.28E+02	0.1305
143	1.29E+02	0.10725	175	1.29E+02	0.13125
144	1.28E+02	0.108	176	1.29E+02	0.132
145	1.29E+02	0.10875	177	1.29E+02	0.13275
146	1.29E+02	0.1095	178	1.29E+02	0.1335
147	1.29E+02	0.11025	179	1.29E+02	0.13425
148	1.29E+02	0.111	180	1.29E+02	0.135
149	1.29E+02	0.11175	181	1.29E+02	0.13575
150	1.29E+02	0.1125	182	1.29E+02	0.1365
151	1.29E+02	0.11325	183	1.28E+02	0.13725
152	1.29E+02	0.114	184	1.28E+02	0.138
153	1.29E+02	0.11475	185	1.28E+02	0.13875
154	1.28E+02	0.1155	186	1.28E+02	0.1395
155	1.28E+02	0.11625	187	1.29E+02	0.14025
156	1.29E+02	0.117	188	1.29E+02	0.141
157	1.29E+02	0.11775	189	1.29E+02	0.14175
158	1.29E+02	0.1185	190	1.29E+02	0.1425
159	1.29E+02	0.11925	191	1.29E+02	0.14325

time-step	inlet-vflow [ft^3/min]	flow-time [s]	time-step	inlet-vflow [ft^3/min]	flow-time [s]
192	1.29E+02	0.144	217	1.29E+02	0.16275
193	1.29E+02	0.14475	218	1.29E+02	0.1635
194	1.28E+02	0.1455	219	1.29E+02	0.16425
195	1.28E+02	0.14625	220	1.29E+02	0.165
196	1.28E+02	0.147	221	1.29E+02	0.16575
197	1.29E+02	0.14775	222	1.29E+02	0.1665
198	1.29E+02	0.1485	223	1.29E+02	0.16725
199	1.29E+02	0.14925	224	1.28E+02	0.168
200	1.29E+02	0.15	225	1.29E+02	0.16875
201	1.29E+02	0.15075	226	1.29E+02	0.1695
202	1.29E+02	0.1515	227	1.29E+02	0.17025
203	1.29E+02	0.15225	228	1.29E+02	0.171
204	1.28E+02	0.153	229	1.29E+02	0.17175
205	1.28E+02	0.15375	230	1.29E+02	0.1725
206	1.28E+02	0.1545	231	1.29E+02	0.17325
207	1.29E+02	0.15525	232	1.29E+02	0.174
208	1.29E+02	0.156	233	1.29E+02	0.17475
209	1.29E+02	0.15675	234	1.29E+02	0.1755
210	1.29E+02	0.1575	235	1.28E+02	0.17625
211	1.29E+02	0.15825	236	1.29E+02	0.177
212	1.29E+02	0.159	237	1.29E+02	0.17775
213	1.28E+02	0.15975	238	1.29E+02	0.1785
214	1.28E+02	0.1605	239	1.29E+02	0.17925
215	1.28E+02	0.16125	240	1.29E+02	0.18
216	1.29E+02	0.162			

Table D11: Throttle Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet1-vflow [ft^3/min]	flow-time	time-step	outlet1-vflow [ft^3/min]	flow-time
0	-4.30E-14	0	32	0.00E+00	0.024
1	1.06E+01	0.00075	33	0.00E+00	0.02475
2	6.53E+00	0.0015	34	0.00E+00	0.0255
3	-7.31E+00	0.00225	35	0.00E+00	0.02625
4	-2.50E+01	0.003	36	0.00E+00	0.027
5	-4.31E+01	0.00375	37	0.00E+00	0.02775
6	-5.93E+01	0.0045	38	0.00E+00	0.0285
7	-7.28E+01	0.00525	39	0.00E+00	0.02925
8	-8.31E+01	0.006	40	0.00E+00	0.03
9	-9.03E+01	0.00675	41	0.00E+00	0.03075
10	-9.46E+01	0.0075	42	0.00E+00	0.0315
11	-9.83E+01	0.00825	43	0.00E+00	0.03225
12	-1.03E+02	0.009	44	0.00E+00	0.033
13	-1.07E+02	0.00975	45	0.00E+00	0.03375
14	-1.09E+02	0.0105	46	0.00E+00	0.0345
15	-1.11E+02	0.01125	47	0.00E+00	0.03525
16	-1.11E+02	0.012	48	0.00E+00	0.036
17	-1.09E+02	0.01275	49	0.00E+00	0.03675
18	-1.08E+02	0.0135	50	0.00E+00	0.0375
19	-1.05E+02	0.01425	51	0.00E+00	0.03825
20	-1.00E+02	0.015	52	0.00E+00	0.039
21	0.00E+00	0.01575	53	0.00E+00	0.03975
22	0.00E+00	0.0165	54	0.00E+00	0.0405
23	0.00E+00	0.01725	55	0.00E+00	0.04125
24	0.00E+00	0.018	56	0.00E+00	0.042
25	0.00E+00	0.01875	57	0.00E+00	0.04275
26	0.00E+00	0.0195	58	0.00E+00	0.0435
27	0.00E+00	0.02025	59	0.00E+00	0.04425
28	0.00E+00	0.021	60	0.00E+00	0.045
29	0.00E+00	0.02175	61	0.00E+00	0.04575
30	0.00E+00	0.0225	62	0.00E+00	0.0465
31	0.00E+00	0.02325	63	0.00E+00	0.04725

time-step	outlet1-vflow [ft^3/min]	flow-time	time-step	outlet1-vflow [ft^3/min]	flow-time
64	0.00E+00	0.048	96	-9.42E+01	0.072
65	0.00E+00	0.04875	97	-9.61E+01	0.07275
66	0.00E+00	0.0495	98	-9.67E+01	0.0735
67	0.00E+00	0.05025	99	-9.64E+01	0.07425
68	0.00E+00	0.051	100	-9.54E+01	0.075
69	0.00E+00	0.05175	101	0.00E+00	0.07575
70	0.00E+00	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	-8.47E+00	0.06075	113	0.00E+00	0.08475
82	-1.59E+01	0.0615	114	0.00E+00	0.0855
83	-2.58E+01	0.06225	115	0.00E+00	0.08625
84	-3.57E+01	0.063	116	0.00E+00	0.087
85	-4.44E+01	0.06375	117	0.00E+00	0.08775
86	-5.20E+01	0.0645	118	0.00E+00	0.0885
87	-5.83E+01	0.06525	119	0.00E+00	0.08925
88	-6.32E+01	0.066	120	0.00E+00	0.09
89	-6.65E+01	0.06675	121	0.00E+00	0.09075
90	-6.83E+01	0.0675	122	0.00E+00	0.0915
91	-7.11E+01	0.06825	123	0.00E+00	0.09225
92	-7.55E+01	0.069	124	0.00E+00	0.093
93	-8.11E+01	0.06975	125	0.00E+00	0.09375
94	-8.65E+01	0.0705	126	0.00E+00	0.0945
95	-9.10E+01	0.07125	127	0.00E+00	0.09525

time-step	outlet1-vflow [ft^3/min]	flow-time	time-step	outlet1-vflow [ft^3/min]	flow-time
128	0.00E+00	0.096	160	0.00E+00	0.12
129	0.00E+00	0.09675	161	-8.52E+00	0.12075
130	0.00E+00	0.0975	162	-1.60E+01	0.1215
131	0.00E+00	0.09825	163	-2.60E+01	0.12225
132	0.00E+00	0.099	164	-3.59E+01	0.123
133	0.00E+00	0.09975	165	-4.48E+01	0.12375
134	0.00E+00	0.1005	166	-5.24E+01	0.1245
135	0.00E+00	0.10125	167	-5.88E+01	0.12525
136	0.00E+00	0.102	168	-6.37E+01	0.126
137	0.00E+00	0.10275	169	-6.70E+01	0.12675
138	0.00E+00	0.1035	170	-6.88E+01	0.1275
139	0.00E+00	0.10425	171	-7.16E+01	0.12825
140	0.00E+00	0.105	172	-7.59E+01	0.129
141	0.00E+00	0.10575	173	-8.15E+01	0.12975
142	0.00E+00	0.1065	174	-8.69E+01	0.1305
143	0.00E+00	0.10725	175	-9.13E+01	0.13125
144	0.00E+00	0.108	176	-9.44E+01	0.132
145	0.00E+00	0.10875	177	-9.62E+01	0.13275
146	0.00E+00	0.1095	178	-9.69E+01	0.1335
147	0.00E+00	0.11025	179	-9.65E+01	0.13425
148	0.00E+00	0.111	180	-9.55E+01	0.135
149	0.00E+00	0.11175	181	0.00E+00	0.13575
150	0.00E+00	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	0.00E+00	0.14325

time-step	outlet1-vflow [ft^3/min]	flow-time	time-step	outlet1-vflow [ft^3/min]	flow-time
192	0.00E+00	0.144	217	0.00E+00	0.16275
193	0.00E+00	0.14475	218	0.00E+00	0.1635
194	0.00E+00	0.1455	219	0.00E+00	0.16425
195	0.00E+00	0.14625	220	0.00E+00	0.165
196	0.00E+00	0.147	221	0.00E+00	0.16575
197	0.00E+00	0.14775	222	0.00E+00	0.1665
198	0.00E+00	0.1485	223	0.00E+00	0.16725
199	0.00E+00	0.14925	224	0.00E+00	0.168
200	0.00E+00	0.15	225	0.00E+00	0.16875
201	0.00E+00	0.15075	226	0.00E+00	0.1695
202	0.00E+00	0.1515	227	0.00E+00	0.17025
203	0.00E+00	0.15225	228	0.00E+00	0.171
204	0.00E+00	0.153	229	0.00E+00	0.17175
205	0.00E+00	0.15375	230	0.00E+00	0.1725
206	0.00E+00	0.1545	231	0.00E+00	0.17325
207	0.00E+00	0.15525	232	0.00E+00	0.174
208	0.00E+00	0.156	233	0.00E+00	0.17475
209	0.00E+00	0.15675	234	0.00E+00	0.1755
210	0.00E+00	0.1575	235	0.00E+00	0.17625
211	0.00E+00	0.15825	236	0.00E+00	0.177
212	0.00E+00	0.159	237	0.00E+00	0.17775
213	0.00E+00	0.15975	238	0.00E+00	0.1785
214	0.00E+00	0.1605	239	0.00E+00	0.17925
215	0.00E+00	0.16125	240	0.00E+00	0.18
216	0.00E+00	0.162			

Table D12: Runner #1 Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	-1.54E+01	0.024
1	0.00E+00	0.00075	33	-2.47E+01	0.02475
2	0.00E+00	0.0015	34	-3.54E+01	0.0255
3	0.00E+00	0.00225	35	-4.56E+01	0.02625
4	0.00E+00	0.003	36	-5.40E+01	0.027
5	0.00E+00	0.00375	37	-6.05E+01	0.02775
6	0.00E+00	0.0045	38	-6.52E+01	0.0285
7	0.00E+00	0.00525	39	-6.81E+01	0.02925
8	0.00E+00	0.006	40	-6.95E+01	0.03
9	0.00E+00	0.00675	41	-7.07E+01	0.03075
10	0.00E+00	0.0075	42	-7.28E+01	0.0315
11	0.00E+00	0.00825	43	-7.70E+01	0.03225
12	0.00E+00	0.009	44	-8.27E+01	0.033
13	0.00E+00	0.00975	45	-8.83E+01	0.03375
14	0.00E+00	0.0105	46	-9.25E+01	0.0345
15	0.00E+00	0.01125	47	-9.49E+01	0.03525
16	0.00E+00	0.012	48	-9.58E+01	0.036
17	0.00E+00	0.01275	49	-9.56E+01	0.03675
18	0.00E+00	0.0135	50	-9.47E+01	0.0375
19	0.00E+00	0.01425	51	0.00E+00	0.03825
20	0.00E+00	0.015	52	0.00E+00	0.039
21	0.00E+00	0.01575	53	0.00E+00	0.03975
22	0.00E+00	0.0165	54	0.00E+00	0.0405
23	0.00E+00	0.01725	55	0.00E+00	0.04125
24	0.00E+00	0.018	56	0.00E+00	0.042
25	0.00E+00	0.01875	57	0.00E+00	0.04275
26	0.00E+00	0.0195	58	0.00E+00	0.0435
27	0.00E+00	0.02025	59	0.00E+00	0.04425
28	0.00E+00	0.021	60	0.00E+00	0.045
29	0.00E+00	0.02175	61	0.00E+00	0.04575
30	0.00E+00	0.0225	62	0.00E+00	0.0465
31	-9.51E+00	0.02325	63	0.00E+00	0.04725

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	0.00E+00	0.072
65	0.00E+00	0.04875	97	0.00E+00	0.07275
66	0.00E+00	0.0495	98	0.00E+00	0.0735
67	0.00E+00	0.05025	99	0.00E+00	0.07425
68	0.00E+00	0.051	100	0.00E+00	0.075
69	0.00E+00	0.05175	101	0.00E+00	0.07575
70	0.00E+00	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	-8.23E+00	0.08325
80	0.00E+00	0.06	112	-1.36E+01	0.084
81	0.00E+00	0.06075	113	-2.25E+01	0.08475
82	0.00E+00	0.0615	114	-3.29E+01	0.0855
83	0.00E+00	0.06225	115	-4.29E+01	0.08625
84	0.00E+00	0.063	116	-5.13E+01	0.087
85	0.00E+00	0.06375	117	-5.79E+01	0.08775
86	0.00E+00	0.0645	118	-6.28E+01	0.0885
87	0.00E+00	0.06525	119	-6.60E+01	0.08925
88	0.00E+00	0.066	120	-6.78E+01	0.09
89	0.00E+00	0.06675	121	-6.93E+01	0.09075
90	0.00E+00	0.0675	122	-7.17E+01	0.0915
91	0.00E+00	0.06825	123	-7.62E+01	0.09225
92	0.00E+00	0.069	124	-8.22E+01	0.093
93	0.00E+00	0.06975	125	-8.81E+01	0.09375
94	0.00E+00	0.0705	126	-9.24E+01	0.0945
95	0.00E+00	0.07125	127	-9.50E+01	0.09525

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
128	-9.60E+01	0.096	160	0.00E+00	0.12
129	-9.58E+01	0.09675	161	0.00E+00	0.12075
130	-9.49E+01	0.0975	162	0.00E+00	0.1215
131	0.00E+00	0.09825	163	0.00E+00	0.12225
132	0.00E+00	0.099	164	0.00E+00	0.123
133	0.00E+00	0.09975	165	0.00E+00	0.12375
134	0.00E+00	0.1005	166	0.00E+00	0.1245
135	0.00E+00	0.10125	167	0.00E+00	0.12525
136	0.00E+00	0.102	168	0.00E+00	0.126
137	0.00E+00	0.10275	169	0.00E+00	0.12675
138	0.00E+00	0.1035	170	0.00E+00	0.1275
139	0.00E+00	0.10425	171	0.00E+00	0.12825
140	0.00E+00	0.105	172	0.00E+00	0.129
141	0.00E+00	0.10575	173	0.00E+00	0.12975
142	0.00E+00	0.1065	174	0.00E+00	0.1305
143	0.00E+00	0.10725	175	0.00E+00	0.13125
144	0.00E+00	0.108	176	0.00E+00	0.132
145	0.00E+00	0.10875	177	0.00E+00	0.13275
146	0.00E+00	0.1095	178	0.00E+00	0.1335
147	0.00E+00	0.11025	179	0.00E+00	0.13425
148	0.00E+00	0.111	180	0.00E+00	0.135
149	0.00E+00	0.11175	181	0.00E+00	0.13575
150	0.00E+00	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	-8.31E+00	0.14325

time-step	outlet2-vflow [ft^3/min]	flow-time [s]	time-step	outlet2-vflow [ft^3/min]	flow-time [s]
192	-1.37E+01	0.144	217	0.00E+00	0.16275
193	-2.27E+01	0.14475	218	0.00E+00	0.1635
194	-3.31E+01	0.1455	219	0.00E+00	0.16425
195	-4.31E+01	0.14625	220	0.00E+00	0.165
196	-5.16E+01	0.147	221	0.00E+00	0.16575
197	-5.82E+01	0.14775	222	0.00E+00	0.1665
198	-6.31E+01	0.1485	223	0.00E+00	0.16725
199	-6.63E+01	0.14925	224	0.00E+00	0.168
200	-6.80E+01	0.15	225	0.00E+00	0.16875
201	-6.95E+01	0.15075	226	0.00E+00	0.1695
202	-7.19E+01	0.1515	227	0.00E+00	0.17025
203	-7.63E+01	0.15225	228	0.00E+00	0.171
204	-8.23E+01	0.153	229	0.00E+00	0.17175
205	-8.81E+01	0.15375	230	0.00E+00	0.1725
206	-9.25E+01	0.1545	231	0.00E+00	0.17325
207	-9.50E+01	0.15525	232	0.00E+00	0.174
208	-9.60E+01	0.156	233	0.00E+00	0.17475
209	-9.57E+01	0.15675	234	0.00E+00	0.1755
210	-9.48E+01	0.1575	235	0.00E+00	0.17625
211	0.00E+00	0.15825	236	0.00E+00	0.177
212	0.00E+00	0.159	237	0.00E+00	0.17775
213	0.00E+00	0.15975	238	0.00E+00	0.1785
214	0.00E+00	0.1605	239	0.00E+00	0.17925
215	0.00E+00	0.16125	240	0.00E+00	0.18
216	0.00E+00	0.162			

Table D13: Runner #2 Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet3-vflow [ft^3/min]	flow-time [s]
0	5.78E-10	0
1	2.440696115	0.00075
2	-8.449541598	0.0015
3	-23.45897223	0.00225
4	-39.82182418	0.003
5	-56.32599573	0.00375
6	-71.54029374	0.0045
7	-84.16333684	0.00525
8	-93.6780912	0.006
9	-99.98690845	0.00675
10	-103.2881988	0.0075
11	0	0.00825
12	0	0.009
13	0	0.00975
14	0	0.0105
15	0	0.01125
16	0	0.012
17	0	0.01275
18	0	0.0135
19	0	0.01425
20	0	0.015
21	0	0.01575
22	0	0.0165
23	0	0.01725
24	0	0.018
25	0	0.01875
26	0	0.0195
27	0	0.02025
28	0	0.021
29	0	0.02175
30	0	0.0225
31	0	0.02325
32	0	0.024
33	0	0.02475
34	0	0.0255
35	0	0.02625
36	0	0.027
37	0	0.02775
38	0	0.0285
39	0	0.02925
40	0	0.03
41	0	0.03075
42	0	0.0315
43	0	0.03225
44	0	0.033
45	0	0.03375
46	0	0.0345
47	0	0.03525
48	0	0.036
49	0	0.03675
50	0	0.0375
51	0	0.03825
52	0	0.039
53	0	0.03975
54	0	0.0405
55	0	0.04125
56	0	0.042
57	0	0.04275
58	0	0.0435
59	0	0.04425
60	0	0.045
61	0	0.04575
62	0	0.0465
63	0	0.04725

time-step	outlet3-vflow [ft^3/min]	flow-time [s]	time-step	outlet3-vflow [ft^3/min]	flow-time [s]
64	0	0.048	96	0	0.072
65	0	0.04875	97	0	0.07275
66	0	0.0495	98	0	0.0735
67	0	0.05025	99	0	0.07425
68	0	0.051	100	0	0.075
69	0	0.05175	101	0	0.07575
70	0	0.0525	102	0	0.0765
71	-8.712958005	0.05325	103	0	0.07725
72	-16.30237767	0.054	104	0	0.078
73	-26.68299795	0.05475	105	0	0.07875
74	-37.42331023	0.0555	106	0	0.0795
75	-47.24833496	0.05625	107	0	0.08025
76	-55.62447734	0.057	108	0	0.081
77	-62.31905954	0.05775	109	0	0.08175
78	-67.23646083	0.0585	110	0	0.0825
79	-70.39376905	0.05925	111	0	0.08325
80	-71.883324	0.06	112	0	0.084
81	-73.95710211	0.06075	113	0	0.08475
82	-77.3610084	0.0615	114	0	0.0855
83	-82.17380337	0.06225	115	0	0.08625
84	-87.15669087	0.063	116	0	0.087
85	-91.34633398	0.06375	117	0	0.08775
86	-94.32584588	0.0645	118	0	0.0885
87	-96.12423967	0.06525	119	0	0.08925
88	-96.82341091	0.066	120	0	0.09
89	-96.54609961	0.06675	121	0	0.09075
90	-95.61286742	0.0675	122	0	0.0915
91	0	0.06825	123	0	0.09225
92	0	0.069	124	0	0.093
93	0	0.06975	125	0	0.09375
94	0	0.0705	126	0	0.0945
95	0	0.07125	127	0	0.09525

time-step	outlet3-vflow [ft^3/min]	flow-time [s]	time-step	outlet3-vflow [ft^3/min]	flow-time [s]
128	0	0.096	160	-71.39677045	0.12
129	0	0.09675	161	-73.46377993	0.12075
130	0	0.0975	162	-76.83633082	0.1215
131	0	0.09825	163	-81.61229379	0.12225
132	0	0.099	164	-86.55692406	0.123
133	0	0.09975	165	-90.71116865	0.12375
134	0	0.1005	166	-93.65721706	0.1245
135	0	0.10125	167	-95.42801739	0.12525
136	0	0.102	168	-96.09896219	0.126
137	0	0.10275	169	-95.80826858	0.12675
138	0	0.1035	170	-94.8878213	0.1275
139	0	0.10425	171	0	0.12825
140	0	0.105	172	0	0.129
141	0	0.10575	173	0	0.12975
142	0	0.1065	174	0	0.1305
143	0	0.10725	175	0	0.13125
144	0	0.108	176	0	0.132
145	0	0.10875	177	0	0.13275
146	0	0.1095	178	0	0.1335
147	0	0.11025	179	0	0.13425
148	0	0.111	180	0	0.135
149	0	0.11175	181	0	0.13575
150	0	0.1125	182	0	0.1365
151	-8.596464056	0.11325	183	0	0.13725
152	-16.16168377	0.114	184	0	0.138
153	-26.49929511	0.11475	185	0	0.13875
154	-37.19149897	0.1155	186	0	0.1395
155	-46.96114801	0.11625	187	0	0.14025
156	-55.28734225	0.117	188	0	0.141
157	-61.94788735	0.11775	189	0	0.14175
158	-66.84920473	0.1185	190	0	0.1425
159	-70.00222687	0.11925	191	0	0.14325

time-step	outlet3-vflow [ft^3/min]	flow-time [s]	time-step	outlet3-vflow [ft^3/min]	flow-time [s]
192	0	0.144	217	0	0.16275
193	0	0.14475	218	0	0.1635
194	0	0.1455	219	0	0.16425
195	0	0.14625	220	0	0.165
196	0	0.147	221	0	0.16575
197	0	0.14775	222	0	0.1665
198	0	0.1485	223	0	0.16725
199	0	0.14925	224	0	0.168
200	0	0.15	225	0	0.16875
201	0	0.15075	226	0	0.1695
202	0	0.1515	227	0	0.17025
203	0	0.15225	228	0	0.171
204	0	0.153	229	0	0.17175
205	0	0.15375	230	0	0.1725
206	0	0.1545	231	-8.533686214	0.17325
207	0	0.15525	232	-16.06018788	0.174
208	0	0.156	233	-26.36760912	0.17475
209	0	0.15675	234	-37.02759141	0.1755
210	0	0.1575	235	-46.77288304	0.17625
211	0	0.15825	236	-55.08615142	0.177
212	0	0.159	237	-61.73399017	0.17775
213	0	0.15975	238	-66.62616183	0.1785
214	0	0.1605	239	-69.77326278	0.17925
215	0	0.16125	240	-71.15377188	0.18
216	0	0.162			

Table D14: Runner #3 Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet4-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0
1	0.00E+00	0.00075
2	0.00E+00	0.0015
3	0.00E+00	0.00225
4	0.00E+00	0.003
5	0.00E+00	0.00375
6	0.00E+00	0.0045
7	0.00E+00	0.00525
8	0.00E+00	0.006
9	0.00E+00	0.00675
10	0.00E+00	0.0075
11	0.00E+00	0.00825
12	0.00E+00	0.009
13	0.00E+00	0.00975
14	0.00E+00	0.0105
15	0.00E+00	0.01125
16	0.00E+00	0.012
17	0.00E+00	0.01275
18	0.00E+00	0.0135
19	0.00E+00	0.01425
20	0.00E+00	0.015
21	0.00E+00	0.01575
22	0.00E+00	0.0165
23	0.00E+00	0.01725
24	0.00E+00	0.018
25	0.00E+00	0.01875
26	0.00E+00	0.0195
27	0.00E+00	0.02025
28	0.00E+00	0.021
29	0.00E+00	0.02175
30	0.00E+00	0.0225
31	0.00E+00	0.02325
32	0.00E+00	0.024
33	0.00E+00	0.02475
34	0.00E+00	0.0255
35	0.00E+00	0.02625
36	0.00E+00	0.027
37	0.00E+00	0.02775
38	0.00E+00	0.0285
39	0.00E+00	0.02925
40	0.00E+00	0.03
41	0.00E+00	0.03075
42	0.00E+00	0.0315
43	0.00E+00	0.03225
44	0.00E+00	0.033
45	0.00E+00	0.03375
46	0.00E+00	0.0345
47	0.00E+00	0.03525
48	0.00E+00	0.036
49	0.00E+00	0.03675
50	0.00E+00	0.0375
51	0.00E+00	0.03825
52	0.00E+00	0.039
53	0.00E+00	0.03975
54	0.00E+00	0.0405
55	0.00E+00	0.04125
56	0.00E+00	0.042
57	0.00E+00	0.04275
58	0.00E+00	0.0435
59	0.00E+00	0.04425
60	0.00E+00	0.045
61	-8.62E+00	0.04575
62	-1.57E+01	0.0465
63	-2.55E+01	0.04725

time-step	outlet4-vflow [ft^3/min]	flow-time [s]	time-step	outlet4-vflow [ft^3/min]	flow-time [s]
64	-3.58E+01	0.048	96	0.00E+00	0.072
65	-4.51E+01	0.04875	97	0.00E+00	0.07275
66	-5.30E+01	0.0495	98	0.00E+00	0.0735
67	-5.93E+01	0.05025	99	0.00E+00	0.07425
68	-6.40E+01	0.051	100	0.00E+00	0.075
69	-6.70E+01	0.05175	101	0.00E+00	0.07575
70	-6.84E+01	0.0525	102	0.00E+00	0.0765
71	-7.00E+01	0.05325	103	0.00E+00	0.07725
72	-7.28E+01	0.054	104	0.00E+00	0.078
73	-7.76E+01	0.05475	105	0.00E+00	0.07875
74	-8.33E+01	0.0555	106	0.00E+00	0.0795
75	-8.85E+01	0.05625	107	0.00E+00	0.08025
76	-9.23E+01	0.057	108	0.00E+00	0.081
77	-9.44E+01	0.05775	109	0.00E+00	0.08175
78	-9.52E+01	0.0585	110	0.00E+00	0.0825
79	-9.50E+01	0.05925	111	0.00E+00	0.08325
80	-9.40E+01	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	0.00E+00	0.06825	123	0.00E+00	0.09225
92	0.00E+00	0.069	124	0.00E+00	0.093
93	0.00E+00	0.06975	125	0.00E+00	0.09375
94	0.00E+00	0.0705	126	0.00E+00	0.0945
95	0.00E+00	0.07125	127	0.00E+00	0.09525

time-step	outlet4-vflow [ft^3/min]	flow-time [s]	time-step	outlet4-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	-9.41E+01	0.12
129	0.00E+00	0.09675	161	0.00E+00	0.12075
130	0.00E+00	0.0975	162	0.00E+00	0.1215
131	0.00E+00	0.09825	163	0.00E+00	0.12225
132	0.00E+00	0.099	164	0.00E+00	0.123
133	0.00E+00	0.09975	165	0.00E+00	0.12375
134	0.00E+00	0.1005	166	0.00E+00	0.1245
135	0.00E+00	0.10125	167	0.00E+00	0.12525
136	0.00E+00	0.102	168	0.00E+00	0.126
137	0.00E+00	0.10275	169	0.00E+00	0.12675
138	0.00E+00	0.1035	170	0.00E+00	0.1275
139	0.00E+00	0.10425	171	0.00E+00	0.12825
140	0.00E+00	0.105	172	0.00E+00	0.129
141	-8.59E+00	0.10575	173	0.00E+00	0.12975
142	-1.57E+01	0.1065	174	0.00E+00	0.1305
143	-2.56E+01	0.10725	175	0.00E+00	0.13125
144	-3.59E+01	0.108	176	0.00E+00	0.132
145	-4.52E+01	0.10875	177	0.00E+00	0.13275
146	-5.31E+01	0.1095	178	0.00E+00	0.1335
147	-5.94E+01	0.11025	179	0.00E+00	0.13425
148	-6.41E+01	0.111	180	0.00E+00	0.135
149	-6.71E+01	0.11175	181	0.00E+00	0.13575
150	-6.84E+01	0.1125	182	0.00E+00	0.1365
151	-7.00E+01	0.11325	183	0.00E+00	0.13725
152	-7.28E+01	0.114	184	0.00E+00	0.138
153	-7.76E+01	0.11475	185	0.00E+00	0.13875
154	-8.33E+01	0.1155	186	0.00E+00	0.1395
155	-8.85E+01	0.11625	187	0.00E+00	0.14025
156	-9.22E+01	0.117	188	0.00E+00	0.141
157	-9.44E+01	0.11775	189	0.00E+00	0.14175
158	-9.52E+01	0.1185	190	0.00E+00	0.1425
159	-9.49E+01	0.11925	191	0.00E+00	0.14325

time-step	outlet4-vflow [ft^3/min]	flow-time [s]	time-step	outlet4-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	0.00E+00	0.16275
193	0.00E+00	0.14475	218	0.00E+00	0.1635
194	0.00E+00	0.1455	219	0.00E+00	0.16425
195	0.00E+00	0.14625	220	0.00E+00	0.165
196	0.00E+00	0.147	221	-8.69E+00	0.16575
197	0.00E+00	0.14775	222	-1.59E+01	0.1665
198	0.00E+00	0.1485	223	-2.58E+01	0.16725
199	0.00E+00	0.14925	224	-3.62E+01	0.168
200	0.00E+00	0.15	225	-4.55E+01	0.16875
201	0.00E+00	0.15075	226	-5.35E+01	0.1695
202	0.00E+00	0.1515	227	-5.98E+01	0.17025
203	0.00E+00	0.15225	228	-6.44E+01	0.171
204	0.00E+00	0.153	229	-6.74E+01	0.17175
205	0.00E+00	0.15375	230	-6.86E+01	0.1725
206	0.00E+00	0.1545	231	-7.02E+01	0.17325
207	0.00E+00	0.15525	232	-7.30E+01	0.174
208	0.00E+00	0.156	233	-7.77E+01	0.17475
209	0.00E+00	0.15675	234	-8.34E+01	0.1755
210	0.00E+00	0.1575	235	-8.85E+01	0.17625
211	0.00E+00	0.15825	236	-9.23E+01	0.177
212	0.00E+00	0.159	237	-9.44E+01	0.17775
213	0.00E+00	0.15975	238	-9.52E+01	0.1785
214	0.00E+00	0.1605	239	-9.49E+01	0.17925
215	0.00E+00	0.16125	240	-9.41E+01	0.18
216	0.00E+00	0.162			

Table D15: Runner #4 Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	0.00E+00	0.024
1	0.00E+00	0.00075	33	0.00E+00	0.02475
2	0.00E+00	0.0015	34	0.00E+00	0.0255
3	0.00E+00	0.00225	35	0.00E+00	0.02625
4	0.00E+00	0.003	36	0.00E+00	0.027
5	0.00E+00	0.00375	37	0.00E+00	0.02775
6	0.00E+00	0.0045	38	0.00E+00	0.0285
7	0.00E+00	0.00525	39	0.00E+00	0.02925
8	0.00E+00	0.006	40	0.00E+00	0.03
9	0.00E+00	0.00675	41	0.00E+00	0.03075
10	0.00E+00	0.0075	42	0.00E+00	0.0315
11	0.00E+00	0.00825	43	0.00E+00	0.03225
12	0.00E+00	0.009	44	0.00E+00	0.033
13	0.00E+00	0.00975	45	0.00E+00	0.03375
14	0.00E+00	0.0105	46	0.00E+00	0.0345
15	0.00E+00	0.01125	47	0.00E+00	0.03525
16	0.00E+00	0.012	48	0.00E+00	0.036
17	0.00E+00	0.01275	49	0.00E+00	0.03675
18	0.00E+00	0.0135	50	0.00E+00	0.0375
19	0.00E+00	0.01425	51	-8.11E+00	0.03825
20	0.00E+00	0.015	52	-1.34E+01	0.039
21	0.00E+00	0.01575	53	-2.23E+01	0.03975
22	0.00E+00	0.0165	54	-3.29E+01	0.0405
23	0.00E+00	0.01725	55	-4.33E+01	0.04125
24	0.00E+00	0.018	56	-5.22E+01	0.042
25	0.00E+00	0.01875	57	-5.93E+01	0.04275
26	0.00E+00	0.0195	58	-6.44E+01	0.0435
27	0.00E+00	0.02025	59	-6.78E+01	0.04425
28	0.00E+00	0.021	60	-6.97E+01	0.045
29	0.00E+00	0.02175	61	-7.23E+01	0.04575
30	0.00E+00	0.0225	62	-7.64E+01	0.0465
31	0.00E+00	0.02325	63	-8.20E+01	0.04725

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
64	-8.76E+01	0.048	96	0.00E+00	0.072
65	-9.23E+01	0.04875	97	0.00E+00	0.07275
66	-9.55E+01	0.0495	98	0.00E+00	0.0735
67	-9.75E+01	0.05025	99	0.00E+00	0.07425
68	-9.83E+01	0.051	100	0.00E+00	0.075
69	-9.80E+01	0.05175	101	0.00E+00	0.07575
70	-9.71E+01	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	0.00E+00	0.06825	123	0.00E+00	0.09225
92	0.00E+00	0.069	124	0.00E+00	0.093
93	0.00E+00	0.06975	125	0.00E+00	0.09375
94	0.00E+00	0.0705	126	0.00E+00	0.0945
95	0.00E+00	0.07125	127	0.00E+00	0.09525

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	0.00E+00	0.12
129	0.00E+00	0.09675	161	0.00E+00	0.12075
130	0.00E+00	0.0975	162	0.00E+00	0.1215
131	-8.09E+00	0.09825	163	0.00E+00	0.12225
132	-1.34E+01	0.099	164	0.00E+00	0.123
133	-2.24E+01	0.09975	165	0.00E+00	0.12375
134	-3.30E+01	0.1005	166	0.00E+00	0.1245
135	-4.35E+01	0.10125	167	0.00E+00	0.12525
136	-5.24E+01	0.102	168	0.00E+00	0.126
137	-5.94E+01	0.10275	169	0.00E+00	0.12675
138	-6.45E+01	0.1035	170	0.00E+00	0.1275
139	-6.79E+01	0.10425	171	0.00E+00	0.12825
140	-6.97E+01	0.105	172	0.00E+00	0.129
141	-7.23E+01	0.10575	173	0.00E+00	0.12975
142	-7.64E+01	0.1065	174	0.00E+00	0.1305
143	-8.19E+01	0.10725	175	0.00E+00	0.13125
144	-8.75E+01	0.108	176	0.00E+00	0.132
145	-9.21E+01	0.10875	177	0.00E+00	0.13275
146	-9.53E+01	0.1095	178	0.00E+00	0.1335
147	-9.72E+01	0.11025	179	0.00E+00	0.13425
148	-9.79E+01	0.111	180	0.00E+00	0.135
149	-9.77E+01	0.11175	181	0.00E+00	0.13575
150	-9.68E+01	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	0.00E+00	0.14325

time-step	outlet5-vflow [ft^3/min]	flow-time [s]	time-step	outlet5-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	-5.92E+01	0.16275
193	0.00E+00	0.14475	218	-6.43E+01	0.1635
194	0.00E+00	0.1455	219	-6.77E+01	0.16425
195	0.00E+00	0.14625	220	-6.94E+01	0.165
196	0.00E+00	0.147	221	-7.21E+01	0.16575
197	0.00E+00	0.14775	222	-7.62E+01	0.1665
198	0.00E+00	0.1485	223	-8.17E+01	0.16725
199	0.00E+00	0.14925	224	-8.73E+01	0.168
200	0.00E+00	0.15	225	-9.19E+01	0.16875
201	0.00E+00	0.15075	226	-9.51E+01	0.1695
202	0.00E+00	0.1515	227	-9.70E+01	0.17025
203	0.00E+00	0.15225	228	-9.77E+01	0.171
204	0.00E+00	0.153	229	-9.74E+01	0.17175
205	0.00E+00	0.15375	230	-9.66E+01	0.1725
206	0.00E+00	0.1545	231	0.00E+00	0.17325
207	0.00E+00	0.15525	232	0.00E+00	0.174
208	0.00E+00	0.156	233	0.00E+00	0.17475
209	0.00E+00	0.15675	234	0.00E+00	0.1755
210	0.00E+00	0.1575	235	0.00E+00	0.17625
211	-8.02E+00	0.15825	236	0.00E+00	0.177
212	-1.33E+01	0.159	237	0.00E+00	0.17775
213	-2.22E+01	0.15975	238	0.00E+00	0.1785
214	-3.29E+01	0.1605	239	0.00E+00	0.17925
215	-4.33E+01	0.16125	240	0.00E+00	0.18
216	-5.22E+01	0.162			

Table D16: Runner #5 Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	0.00E+00	0.024
1	0.00E+00	0.00075	33	0.00E+00	0.02475
2	0.00E+00	0.0015	34	0.00E+00	0.0255
3	0.00E+00	0.00225	35	0.00E+00	0.02625
4	0.00E+00	0.003	36	0.00E+00	0.027
5	0.00E+00	0.00375	37	0.00E+00	0.02775
6	0.00E+00	0.0045	38	0.00E+00	0.0285
7	0.00E+00	0.00525	39	0.00E+00	0.02925
8	0.00E+00	0.006	40	0.00E+00	0.03
9	0.00E+00	0.00675	41	-8.30E+00	0.03075
10	0.00E+00	0.0075	42	-1.51E+01	0.0315
11	0.00E+00	0.00825	43	-2.54E+01	0.03225
12	0.00E+00	0.009	44	-3.66E+01	0.033
13	0.00E+00	0.00975	45	-4.71E+01	0.03375
14	0.00E+00	0.0105	46	-5.59E+01	0.0345
15	0.00E+00	0.01125	47	-6.29E+01	0.03525
16	0.00E+00	0.012	48	-6.80E+01	0.036
17	0.00E+00	0.01275	49	-7.12E+01	0.03675
18	0.00E+00	0.0135	50	-7.29E+01	0.0375
19	0.00E+00	0.01425	51	-7.48E+01	0.03825
20	0.00E+00	0.015	52	-7.80E+01	0.039
21	0.00E+00	0.01575	53	-8.29E+01	0.03975
22	0.00E+00	0.0165	54	-8.83E+01	0.0405
23	0.00E+00	0.01725	55	-9.28E+01	0.04125
24	0.00E+00	0.018	56	-9.59E+01	0.042
25	0.00E+00	0.01875	57	-9.75E+01	0.04275
26	0.00E+00	0.0195	58	-9.80E+01	0.0435
27	0.00E+00	0.02025	59	-9.74E+01	0.04425
28	0.00E+00	0.021	60	-9.62E+01	0.045
29	0.00E+00	0.02175	61	0.00E+00	0.04575
30	0.00E+00	0.0225	62	0.00E+00	0.0465
31	0.00E+00	0.02325	63	0.00E+00	0.04725

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	0.00E+00	0.072
65	0.00E+00	0.04875	97	0.00E+00	0.07275
66	0.00E+00	0.0495	98	0.00E+00	0.0735
67	0.00E+00	0.05025	99	0.00E+00	0.07425
68	0.00E+00	0.051	100	0.00E+00	0.075
69	0.00E+00	0.05175	101	0.00E+00	0.07575
70	0.00E+00	0.0525	102	0.00E+00	0.0765
71	0.00E+00	0.05325	103	0.00E+00	0.07725
72	0.00E+00	0.054	104	0.00E+00	0.078
73	0.00E+00	0.05475	105	0.00E+00	0.07875
74	0.00E+00	0.0555	106	0.00E+00	0.0795
75	0.00E+00	0.05625	107	0.00E+00	0.08025
76	0.00E+00	0.057	108	0.00E+00	0.081
77	0.00E+00	0.05775	109	0.00E+00	0.08175
78	0.00E+00	0.0585	110	0.00E+00	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	-8.46E+00	0.09075
90	0.00E+00	0.0675	122	-1.54E+01	0.0915
91	0.00E+00	0.06825	123	-2.58E+01	0.09225
92	0.00E+00	0.069	124	-3.73E+01	0.093
93	0.00E+00	0.06975	125	-4.78E+01	0.09375
94	0.00E+00	0.0705	126	-5.67E+01	0.0945
95	0.00E+00	0.07125	127	-6.36E+01	0.09525

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
128	-6.86E+01	0.096	160	0.00E+00	0.12
129	-7.18E+01	0.09675	161	0.00E+00	0.12075
130	-7.32E+01	0.0975	162	0.00E+00	0.1215
131	-7.50E+01	0.09825	163	0.00E+00	0.12225
132	-7.80E+01	0.099	164	0.00E+00	0.123
133	-8.28E+01	0.09975	165	0.00E+00	0.12375
134	-8.81E+01	0.1005	166	0.00E+00	0.1245
135	-9.25E+01	0.10125	167	0.00E+00	0.12525
136	-9.55E+01	0.102	168	0.00E+00	0.126
137	-9.71E+01	0.10275	169	0.00E+00	0.12675
138	-9.75E+01	0.1035	170	0.00E+00	0.1275
139	-9.70E+01	0.10425	171	0.00E+00	0.12825
140	-9.58E+01	0.105	172	0.00E+00	0.129
141	0.00E+00	0.10575	173	0.00E+00	0.12975
142	0.00E+00	0.1065	174	0.00E+00	0.1305
143	0.00E+00	0.10725	175	0.00E+00	0.13125
144	0.00E+00	0.108	176	0.00E+00	0.132
145	0.00E+00	0.10875	177	0.00E+00	0.13275
146	0.00E+00	0.1095	178	0.00E+00	0.1335
147	0.00E+00	0.11025	179	0.00E+00	0.13425
148	0.00E+00	0.111	180	0.00E+00	0.135
149	0.00E+00	0.11175	181	0.00E+00	0.13575
150	0.00E+00	0.1125	182	0.00E+00	0.1365
151	0.00E+00	0.11325	183	0.00E+00	0.13725
152	0.00E+00	0.114	184	0.00E+00	0.138
153	0.00E+00	0.11475	185	0.00E+00	0.13875
154	0.00E+00	0.1155	186	0.00E+00	0.1395
155	0.00E+00	0.11625	187	0.00E+00	0.14025
156	0.00E+00	0.117	188	0.00E+00	0.141
157	0.00E+00	0.11775	189	0.00E+00	0.14175
158	0.00E+00	0.1185	190	0.00E+00	0.1425
159	0.00E+00	0.11925	191	0.00E+00	0.14325

time-step	outlet6-vflow [ft^3/min]	flow-time [s]	time-step	outlet6-vflow [ft^3/min]	flow-time [s]
192	0.00E+00	0.144	217	-9.70E+01	0.16275
193	0.00E+00	0.14475	218	-9.74E+01	0.1635
194	0.00E+00	0.1455	219	-9.69E+01	0.16425
195	0.00E+00	0.14625	220	-9.57E+01	0.165
196	0.00E+00	0.147	221	0.00E+00	0.16575
197	0.00E+00	0.14775	222	0.00E+00	0.1665
198	0.00E+00	0.1485	223	0.00E+00	0.16725
199	0.00E+00	0.14925	224	0.00E+00	0.168
200	0.00E+00	0.15	225	0.00E+00	0.16875
201	-8.40E+00	0.15075	226	0.00E+00	0.1695
202	-1.53E+01	0.1515	227	0.00E+00	0.17025
203	-2.57E+01	0.15225	228	0.00E+00	0.171
204	-3.71E+01	0.153	229	0.00E+00	0.17175
205	-4.76E+01	0.15375	230	0.00E+00	0.1725
206	-5.65E+01	0.1545	231	0.00E+00	0.17325
207	-6.34E+01	0.15525	232	0.00E+00	0.174
208	-6.84E+01	0.156	233	0.00E+00	0.17475
209	-7.15E+01	0.15675	234	0.00E+00	0.1755
210	-7.29E+01	0.1575	235	0.00E+00	0.17625
211	-7.48E+01	0.15825	236	0.00E+00	0.177
212	-7.79E+01	0.159	237	0.00E+00	0.17775
213	-8.26E+01	0.15975	238	0.00E+00	0.1785
214	-8.79E+01	0.1605	239	0.00E+00	0.17925
215	-9.24E+01	0.16125	240	0.00E+00	0.18
216	-9.54E+01	0.162			

Table D17: Runner #6 Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet7-vflow [ft^3/min]	flow-time [s]	time-step	outlet7-vflow [ft^3/min]	flow-time [s]
0	0.00E+00	0	32	-7.87E+01	0.024
1	0.00E+00	0.00075	33	-8.59E+01	0.02475
2	0.00E+00	0.0015	34	-9.18E+01	0.0255
3	0.00E+00	0.00225	35	-9.59E+01	0.02625
4	0.00E+00	0.003	36	-9.88E+01	0.027
5	0.00E+00	0.00375	37	-1.01E+02	0.02775
6	0.00E+00	0.0045	38	-1.02E+02	0.0285
7	0.00E+00	0.00525	39	-1.01E+02	0.02925
8	0.00E+00	0.006	40	-1.00E+02	0.03
9	0.00E+00	0.00675	41	0.00E+00	0.03075
10	0.00E+00	0.0075	42	0.00E+00	0.0315
11	0.00E+00	0.00825	43	0.00E+00	0.03225
12	0.00E+00	0.009	44	0.00E+00	0.033
13	0.00E+00	0.00975	45	0.00E+00	0.03375
14	0.00E+00	0.0105	46	0.00E+00	0.0345
15	0.00E+00	0.01125	47	0.00E+00	0.03525
16	0.00E+00	0.012	48	0.00E+00	0.036
17	0.00E+00	0.01275	49	0.00E+00	0.03675
18	0.00E+00	0.0135	50	0.00E+00	0.0375
19	0.00E+00	0.01425	51	0.00E+00	0.03825
20	0.00E+00	0.015	52	0.00E+00	0.039
21	-4.73E+00	0.01575	53	0.00E+00	0.03975
22	-9.09E+00	0.0165	54	0.00E+00	0.0405
23	-1.68E+01	0.01725	55	0.00E+00	0.04125
24	-2.64E+01	0.018	56	0.00E+00	0.042
25	-3.62E+01	0.01875	57	0.00E+00	0.04275
26	-4.51E+01	0.0195	58	0.00E+00	0.0435
27	-5.27E+01	0.02025	59	0.00E+00	0.04425
28	-5.90E+01	0.021	60	0.00E+00	0.045
29	-6.39E+01	0.02175	61	0.00E+00	0.04575
30	-6.73E+01	0.0225	62	0.00E+00	0.0465
31	-7.20E+01	0.02325	63	0.00E+00	0.04725

time-step	outlet7-vflow [ft^3/min]	flow-time [s]	time-step	outlet7-vflow [ft^3/min]	flow-time [s]
64	0.00E+00	0.048	96	0.00E+00	0.072
65	0.00E+00	0.04875	97	0.00E+00	0.07275
66	0.00E+00	0.0495	98	0.00E+00	0.0735
67	0.00E+00	0.05025	99	0.00E+00	0.07425
68	0.00E+00	0.051	100	0.00E+00	0.075
69	0.00E+00	0.05175	101	-7.46E+00	0.07575
70	0.00E+00	0.0525	102	-1.26E+01	0.0765
71	0.00E+00	0.05325	103	-2.10E+01	0.07725
72	0.00E+00	0.054	104	-3.11E+01	0.078
73	0.00E+00	0.05475	105	-4.10E+01	0.07875
74	0.00E+00	0.0555	106	-4.96E+01	0.0795
75	0.00E+00	0.05625	107	-5.66E+01	0.08025
76	0.00E+00	0.057	108	-6.21E+01	0.081
77	0.00E+00	0.05775	109	-6.61E+01	0.08175
78	0.00E+00	0.0585	110	-6.86E+01	0.0825
79	0.00E+00	0.05925	111	-7.25E+01	0.08325
80	0.00E+00	0.06	112	-7.85E+01	0.084
81	0.00E+00	0.06075	113	-8.51E+01	0.08475
82	0.00E+00	0.0615	114	-9.06E+01	0.0855
83	0.00E+00	0.06225	115	-9.46E+01	0.08625
84	0.00E+00	0.063	116	-9.74E+01	0.087
85	0.00E+00	0.06375	117	-9.95E+01	0.08775
86	0.00E+00	0.0645	118	-1.00E+02	0.0885
87	0.00E+00	0.06525	119	-1.00E+02	0.08925
88	0.00E+00	0.066	120	-9.95E+01	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	0.00E+00	0.06825	123	0.00E+00	0.09225
92	0.00E+00	0.069	124	0.00E+00	0.093
93	0.00E+00	0.06975	125	0.00E+00	0.09375
94	0.00E+00	0.0705	126	0.00E+00	0.0945
95	0.00E+00	0.07125	127	0.00E+00	0.09525

time-step	outlet7-vflow [ft^3/min]	flow-time [s]	time-step	outlet7-vflow [ft^3/min]	flow-time [s]
128	0.00E+00	0.096	160	0.00E+00	0.12
129	0.00E+00	0.09675	161	0.00E+00	0.12075
130	0.00E+00	0.0975	162	0.00E+00	0.1215
131	0.00E+00	0.09825	163	0.00E+00	0.12225
132	0.00E+00	0.099	164	0.00E+00	0.123
133	0.00E+00	0.09975	165	0.00E+00	0.12375
134	0.00E+00	0.1005	166	0.00E+00	0.1245
135	0.00E+00	0.10125	167	0.00E+00	0.12525
136	0.00E+00	0.102	168	0.00E+00	0.126
137	0.00E+00	0.10275	169	0.00E+00	0.12675
138	0.00E+00	0.1035	170	0.00E+00	0.1275
139	0.00E+00	0.10425	171	0.00E+00	0.12825
140	0.00E+00	0.105	172	0.00E+00	0.129
141	0.00E+00	0.10575	173	0.00E+00	0.12975
142	0.00E+00	0.1065	174	0.00E+00	0.1305
143	0.00E+00	0.10725	175	0.00E+00	0.13125
144	0.00E+00	0.108	176	0.00E+00	0.132
145	0.00E+00	0.10875	177	0.00E+00	0.13275
146	0.00E+00	0.1095	178	0.00E+00	0.1335
147	0.00E+00	0.11025	179	0.00E+00	0.13425
148	0.00E+00	0.111	180	0.00E+00	0.135
149	0.00E+00	0.11175	181	-7.41E+00	0.13575
150	0.00E+00	0.1125	182	-1.25E+01	0.1365
151	0.00E+00	0.11325	183	-2.10E+01	0.13725
152	0.00E+00	0.114	184	-3.11E+01	0.138
153	0.00E+00	0.11475	185	-4.10E+01	0.13875
154	0.00E+00	0.1155	186	-4.97E+01	0.1395
155	0.00E+00	0.11625	187	-5.68E+01	0.14025
156	0.00E+00	0.117	188	-6.23E+01	0.141
157	0.00E+00	0.11775	189	-6.63E+01	0.14175
158	0.00E+00	0.1185	190	-6.88E+01	0.1425
159	0.00E+00	0.11925	191	-7.27E+01	0.14325

time-step	outlet7-vflow [ft^3/min]	flow-time [s]	time-step	outlet7-vflow [ft^3/min]	flow-time [s]
192	-7.86E+01	0.144	217	0.00E+00	0.16275
193	-8.52E+01	0.14475	218	0.00E+00	0.1635
194	-9.06E+01	0.1455	219	0.00E+00	0.16425
195	-9.45E+01	0.14625	220	0.00E+00	0.165
196	-9.73E+01	0.147	221	0.00E+00	0.16575
197	-9.93E+01	0.14775	222	0.00E+00	0.1665
198	-1.00E+02	0.1485	223	0.00E+00	0.16725
199	-1.00E+02	0.14925	224	0.00E+00	0.168
200	-9.92E+01	0.15	225	0.00E+00	0.16875
201	0.00E+00	0.15075	226	0.00E+00	0.1695
202	0.00E+00	0.1515	227	0.00E+00	0.17025
203	0.00E+00	0.15225	228	0.00E+00	0.171
204	0.00E+00	0.153	229	0.00E+00	0.17175
205	0.00E+00	0.15375	230	0.00E+00	0.1725
206	0.00E+00	0.1545	231	0.00E+00	0.17325
207	0.00E+00	0.15525	232	0.00E+00	0.174
208	0.00E+00	0.156	233	0.00E+00	0.17475
209	0.00E+00	0.15675	234	0.00E+00	0.1755
210	0.00E+00	0.1575	235	0.00E+00	0.17625
211	0.00E+00	0.15825	236	0.00E+00	0.177
212	0.00E+00	0.159	237	0.00E+00	0.17775
213	0.00E+00	0.15975	238	0.00E+00	0.1785
214	0.00E+00	0.1605	239	0.00E+00	0.17925
215	0.00E+00	0.16125	240	0.00E+00	0.18
216	0.00E+00	0.162			

Table D18: Runner #7 Volumetric Flow Data for Trailblazer SS Manifold

time-step	outlet8-vflow [ft^3/min]	flow-time
0	0.00E+00	0
1	0.00E+00	0.00075
2	0.00E+00	0.0015
3	0.00E+00	0.00225
4	0.00E+00	0.003
5	0.00E+00	0.00375
6	0.00E+00	0.0045
7	0.00E+00	0.00525
8	0.00E+00	0.006
9	0.00E+00	0.00675
10	0.00E+00	0.0075
11	-1.48E+01	0.00825
12	-2.30E+01	0.009
13	-3.42E+01	0.00975
14	-4.50E+01	0.0105
15	-5.38E+01	0.01125
16	-6.03E+01	0.012
17	-6.47E+01	0.01275
18	-6.73E+01	0.0135
19	-6.87E+01	0.01425
20	-6.88E+01	0.015
21	-6.90E+01	0.01575
22	-7.11E+01	0.0165
23	-7.53E+01	0.01725
24	-8.08E+01	0.018
25	-8.61E+01	0.01875
26	-9.06E+01	0.0195
27	-9.37E+01	0.02025
28	-9.57E+01	0.021
29	-9.66E+01	0.02175
30	-9.65E+01	0.0225
31	0.00E+00	0.02325
32	0.00E+00	0.024
33	0.00E+00	0.02475
34	0.00E+00	0.0255
35	0.00E+00	0.02625
36	0.00E+00	0.027
37	0.00E+00	0.02775
38	0.00E+00	0.0285
39	0.00E+00	0.02925
40	0.00E+00	0.03
41	0.00E+00	0.03075
42	0.00E+00	0.0315
43	0.00E+00	0.03225
44	0.00E+00	0.033
45	0.00E+00	0.03375
46	0.00E+00	0.0345
47	0.00E+00	0.03525
48	0.00E+00	0.036
49	0.00E+00	0.03675
50	0.00E+00	0.0375
51	0.00E+00	0.03825
52	0.00E+00	0.039
53	0.00E+00	0.03975
54	0.00E+00	0.0405
55	0.00E+00	0.04125
56	0.00E+00	0.042
57	0.00E+00	0.04275
58	0.00E+00	0.0435
59	0.00E+00	0.04425
60	0.00E+00	0.045
61	0.00E+00	0.04575
62	0.00E+00	0.0465
63	0.00E+00	0.04725

time-step	outlet8-vflow [ft^3/min]	flow-time	time-step	outlet8-vflow [ft^3/min]	flow-time
64	0.00E+00	0.048	96	-5.47E+01	0.072
65	0.00E+00	0.04875	97	-6.13E+01	0.07275
66	0.00E+00	0.0495	98	-6.62E+01	0.0735
67	0.00E+00	0.05025	99	-6.95E+01	0.07425
68	0.00E+00	0.051	100	-7.10E+01	0.075
69	0.00E+00	0.05175	101	-7.29E+01	0.07575
70	0.00E+00	0.0525	102	-7.58E+01	0.0765
71	0.00E+00	0.05325	103	-8.06E+01	0.07725
72	0.00E+00	0.054	104	-8.62E+01	0.078
73	0.00E+00	0.05475	105	-9.13E+01	0.07875
74	0.00E+00	0.0555	106	-9.50E+01	0.0795
75	0.00E+00	0.05625	107	-9.74E+01	0.08025
76	0.00E+00	0.057	108	-9.85E+01	0.081
77	0.00E+00	0.05775	109	-9.86E+01	0.08175
78	0.00E+00	0.0585	110	-9.78E+01	0.0825
79	0.00E+00	0.05925	111	0.00E+00	0.08325
80	0.00E+00	0.06	112	0.00E+00	0.084
81	0.00E+00	0.06075	113	0.00E+00	0.08475
82	0.00E+00	0.0615	114	0.00E+00	0.0855
83	0.00E+00	0.06225	115	0.00E+00	0.08625
84	0.00E+00	0.063	116	0.00E+00	0.087
85	0.00E+00	0.06375	117	0.00E+00	0.08775
86	0.00E+00	0.0645	118	0.00E+00	0.0885
87	0.00E+00	0.06525	119	0.00E+00	0.08925
88	0.00E+00	0.066	120	0.00E+00	0.09
89	0.00E+00	0.06675	121	0.00E+00	0.09075
90	0.00E+00	0.0675	122	0.00E+00	0.0915
91	-9.02E+00	0.06825	123	0.00E+00	0.09225
92	-1.62E+01	0.069	124	0.00E+00	0.093
93	-2.63E+01	0.06975	125	0.00E+00	0.09375
94	-3.68E+01	0.0705	126	0.00E+00	0.0945
95	-4.65E+01	0.07125	127	0.00E+00	0.09525

time-step	outlet8-vflow [ft^3/min]	flow-time
128	0.00E+00	0.096
129	0.00E+00	0.09675
130	0.00E+00	0.0975
131	0.00E+00	0.09825
132	0.00E+00	0.099
133	0.00E+00	0.09975
134	0.00E+00	0.1005
135	0.00E+00	0.10125
136	0.00E+00	0.102
137	0.00E+00	0.10275
138	0.00E+00	0.1035
139	0.00E+00	0.10425
140	0.00E+00	0.105
141	0.00E+00	0.10575
142	0.00E+00	0.1065
143	0.00E+00	0.10725
144	0.00E+00	0.108
145	0.00E+00	0.10875
146	0.00E+00	0.1095
147	0.00E+00	0.11025
148	0.00E+00	0.111
149	0.00E+00	0.11175
150	0.00E+00	0.1125
151	0.00E+00	0.11325
152	0.00E+00	0.114
153	0.00E+00	0.11475
154	0.00E+00	0.1155
155	0.00E+00	0.11625
156	0.00E+00	0.117
157	0.00E+00	0.11775
158	0.00E+00	0.1185
159	0.00E+00	0.11925
160	0.00E+00	0.12
161	0.00E+00	0.12075
162	0.00E+00	0.1215
163	0.00E+00	0.12225
164	0.00E+00	0.123
165	0.00E+00	0.12375
166	0.00E+00	0.1245
167	0.00E+00	0.12525
168	0.00E+00	0.126
169	0.00E+00	0.12675
170	0.00E+00	0.1275
171	-9.00E+00	0.12825
172	-1.61E+01	0.129
173	-2.61E+01	0.12975
174	-3.66E+01	0.1305
175	-4.62E+01	0.13125
176	-5.43E+01	0.132
177	-6.09E+01	0.13275
178	-6.57E+01	0.1335
179	-6.89E+01	0.13425
180	-7.04E+01	0.135
181	-7.23E+01	0.13575
182	-7.52E+01	0.1365
183	-8.00E+01	0.13725
184	-8.56E+01	0.138
185	-9.08E+01	0.13875
186	-9.46E+01	0.1395
187	-9.70E+01	0.14025
188	-9.82E+01	0.141
189	-9.83E+01	0.14175
190	-9.76E+01	0.1425
191	0.00E+00	0.14325

time-step	outlet8-vflow [ft^3/min]	flow-time	time-step	outlet8-vflow [ft^3/min]	flow-time
192	0.00E+00	0.144	217	0.00E+00	0.16275
193	0.00E+00	0.14475	218	0.00E+00	0.1635
194	0.00E+00	0.1455	219	0.00E+00	0.16425
195	0.00E+00	0.14625	220	0.00E+00	0.165
196	0.00E+00	0.147	221	0.00E+00	0.16575
197	0.00E+00	0.14775	222	0.00E+00	0.1665
198	0.00E+00	0.1485	223	0.00E+00	0.16725
199	0.00E+00	0.14925	224	0.00E+00	0.168
200	0.00E+00	0.15	225	0.00E+00	0.16875
201	0.00E+00	0.15075	226	0.00E+00	0.1695
202	0.00E+00	0.1515	227	0.00E+00	0.17025
203	0.00E+00	0.15225	228	0.00E+00	0.171
204	0.00E+00	0.153	229	0.00E+00	0.17175
205	0.00E+00	0.15375	230	0.00E+00	0.1725
206	0.00E+00	0.1545	231	0.00E+00	0.17325
207	0.00E+00	0.15525	232	0.00E+00	0.174
208	0.00E+00	0.156	233	0.00E+00	0.17475
209	0.00E+00	0.15675	234	0.00E+00	0.1755
210	0.00E+00	0.1575	235	0.00E+00	0.17625
211	0.00E+00	0.15825	236	0.00E+00	0.177
212	0.00E+00	0.159	237	0.00E+00	0.17775
213	0.00E+00	0.15975	238	0.00E+00	0.1785
214	0.00E+00	0.1605	239	0.00E+00	0.17925
215	0.00E+00	0.16125	240	0.00E+00	0.18
216	0.00E+00	0.162			

Table D19: Runner #8 Volumetric Flow Data for Trailblazer SS Manifold

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
0	4.13E+00	0	32	1.17E+00	0.024
1	4.43E+00	0.00075	33	6.48E-01	0.02475
2	4.02E+00	0.0015	34	1.24E-01	0.0255
3	3.18E+00	0.00225	35	-3.25E-01	0.02625
4	2.14E+00	0.003	36	-6.83E-01	0.027
5	1.04E+00	0.00375	37	-9.48E-01	0.02775
6	1.46E-02	0.0045	38	-1.12E+00	0.0285
7	-8.27E-01	0.00525	39	-1.20E+00	0.02925
8	-1.46E+00	0.006	40	-1.21E+00	0.03
9	-1.89E+00	0.00675	41	1.64E+00	0.03075
10	-2.12E+00	0.0075	42	1.37E+00	0.0315
11	5.58E-01	0.00825	43	9.11E-01	0.03225
12	1.62E-01	0.009	44	3.76E-01	0.033
13	-3.20E-01	0.00975	45	-1.30E-01	0.03375
14	-7.48E-01	0.0105	46	-5.39E-01	0.0345
15	-1.06E+00	0.01125	47	-8.34E-01	0.03525
16	-1.26E+00	0.012	48	-1.02E+00	0.036
17	-1.37E+00	0.01275	49	-1.12E+00	0.03675
18	-1.39E+00	0.0135	50	-1.14E+00	0.0375
19	-1.34E+00	0.01425	51	1.52E+00	0.03825
20	-1.21E+00	0.015	52	1.26E+00	0.039
21	1.80E+00	0.01575	53	8.23E-01	0.03975
22	1.60E+00	0.0165	54	3.22E-01	0.0405
23	1.22E+00	0.01725	55	-1.48E-01	0.04125
24	7.49E-01	0.018	56	-5.26E-01	0.042
25	2.72E-01	0.01875	57	-7.99E-01	0.04275
26	-1.47E-01	0.0195	58	-9.74E-01	0.0435
27	-4.86E-01	0.02025	59	-1.06E+00	0.04425
28	-7.45E-01	0.021	60	-1.09E+00	0.045
29	-9.27E-01	0.02175	61	1.59E+00	0.04575
30	-1.03E+00	0.0225	62	1.24E+00	0.0465
31	1.56E+00	0.02325	63	7.54E-01	0.04725

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
64	2.55E-01	0.048	96	-5.15E-01	0.072
65	-1.84E-01	0.04875	97	-7.82E-01	0.07275
66	-5.35E-01	0.0495	98	-9.58E-01	0.0735
67	-7.96E-01	0.05025	99	-1.05E+00	0.07425
68	-9.66E-01	0.051	100	-1.07E+00	0.075
69	-1.05E+00	0.05175	101	1.63E+00	0.07575
70	-1.07E+00	0.0525	102	1.37E+00	0.0765
71	1.66E+00	0.05325	103	9.58E-01	0.07725
72	1.33E+00	0.054	104	4.69E-01	0.078
73	8.58E-01	0.05475	105	1.08E-03	0.07875
74	3.43E-01	0.0555	106	-3.87E-01	0.0795
75	-1.27E-01	0.05625	107	-6.82E-01	0.08025
76	-5.07E-01	0.057	108	-8.90E-01	0.081
77	-7.85E-01	0.05775	109	-1.02E+00	0.08175
78	-9.64E-01	0.0585	110	-1.08E+00	0.0825
79	-1.05E+00	0.05925	111	1.61E+00	0.08325
80	-1.07E+00	0.06	112	1.26E+00	0.084
81	1.55E+00	0.06075	113	7.74E-01	0.08475
82	1.21E+00	0.0615	114	2.78E-01	0.0855
83	7.52E-01	0.06225	115	-1.59E-01	0.08625
84	2.88E-01	0.063	116	-5.13E-01	0.087
85	-1.17E-01	0.06375	117	-7.85E-01	0.08775
86	-4.48E-01	0.0645	118	-9.70E-01	0.0885
87	-7.02E-01	0.06525	119	-1.07E+00	0.08925
88	-8.77E-01	0.066	120	-1.10E+00	0.09
89	-9.74E-01	0.06675	121	1.70E+00	0.09075
90	-1.00E+00	0.0675	122	1.41E+00	0.0915
91	1.63E+00	0.06825	123	9.49E-01	0.09225
92	1.27E+00	0.069	124	4.05E-01	0.093
93	7.82E-01	0.06975	125	-1.09E-01	0.09375
94	2.82E-01	0.0705	126	-5.23E-01	0.0945
95	-1.59E-01	0.07125	127	-8.20E-01	0.09525

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
128	-1.01E+00	0.096	160	-1.03E+00	0.12
129	-1.10E+00	0.09675	161	1.58E+00	0.12075
130	-1.12E+00	0.0975	162	1.24E+00	0.1215
131	1.54E+00	0.09825	163	7.78E-01	0.12225
132	1.28E+00	0.099	164	3.14E-01	0.123
133	8.50E-01	0.09975	165	-9.20E-02	0.12375
134	3.54E-01	0.1005	166	-4.23E-01	0.1245
135	-1.12E-01	0.10125	167	-6.78E-01	0.12525
136	-4.87E-01	0.102	168	-8.54E-01	0.126
137	-7.58E-01	0.10275	169	-9.51E-01	0.12675
138	-9.31E-01	0.1035	170	-9.79E-01	0.1275
139	-1.02E+00	0.10425	171	1.63E+00	0.12825
140	-1.04E+00	0.105	172	1.27E+00	0.129
141	1.61E+00	0.10575	173	7.86E-01	0.12975
142	1.26E+00	0.1065	174	2.91E-01	0.1305
143	7.81E-01	0.10725	175	-1.45E-01	0.13125
144	2.86E-01	0.108	176	-4.98E-01	0.132
145	-1.49E-01	0.10875	177	-7.60E-01	0.13275
146	-4.98E-01	0.1095	178	-9.34E-01	0.1335
147	-7.56E-01	0.11025	179	-1.02E+00	0.13425
148	-9.25E-01	0.111	180	-1.04E+00	0.135
149	-1.01E+00	0.11175	181	1.65E+00	0.13575
150	-1.03E+00	0.1125	182	1.40E+00	0.1365
151	1.68E+00	0.11325	183	9.87E-01	0.13725
152	1.36E+00	0.114	184	4.97E-01	0.138
153	8.90E-01	0.11475	185	2.66E-02	0.13875
154	3.78E-01	0.1155	186	-3.64E-01	0.1395
155	-8.93E-02	0.11625	187	-6.63E-01	0.14025
156	-4.66E-01	0.117	188	-8.74E-01	0.141
157	-7.43E-01	0.11775	189	-1.01E+00	0.14175
158	-9.22E-01	0.1185	190	-1.06E+00	0.1425
159	-1.01E+00	0.11925	191	1.61E+00	0.14325

time-step	net-mflow [lbm/min]	flow-time [s]	time-step	net-mflow [lbm/min]	flow-time [s]
192	1.26E+00	0.144	217	-7.39E-01	0.16275
193	7.76E-01	0.14475	218	-9.12E-01	0.1635
194	2.82E-01	0.1455	219	-1.00E+00	0.16425
195	-1.51E-01	0.14625	220	-1.02E+00	0.165
196	-5.03E-01	0.147	221	1.62E+00	0.16575
197	-7.70E-01	0.14775	222	1.27E+00	0.1665
198	-9.51E-01	0.1485	223	7.86E-01	0.16725
199	-1.05E+00	0.14925	224	2.90E-01	0.168
200	-1.08E+00	0.15	225	-1.46E-01	0.16875
201	1.71E+00	0.15075	226	-4.95E-01	0.1695
202	1.42E+00	0.1515	227	-7.52E-01	0.17025
203	9.61E-01	0.15225	228	-9.21E-01	0.171
204	4.21E-01	0.153	229	-1.01E+00	0.17175
205	-9.01E-02	0.15375	230	-1.02E+00	0.1725
206	-5.01E-01	0.1545	231	1.68E+00	0.17325
207	-7.96E-01	0.15525	232	1.36E+00	0.174
208	-9.82E-01	0.156	233	8.97E-01	0.17475
209	-1.07E+00	0.15675	234	3.88E-01	0.1755
210	-1.09E+00	0.1575	235	-7.69E-02	0.17625
211	1.56E+00	0.15825	236	-4.53E-01	0.177
212	1.29E+00	0.159	237	-7.28E-01	0.17775
213	8.67E-01	0.15975	238	-9.07E-01	0.1785
214	3.71E-01	0.1605	239	-9.98E-01	0.17925
215	-9.39E-02	0.16125	240	-1.02E+00	0.18
216	-4.68E-01	0.162			

Table D20: Net Mass Flow Data for Trailblazer SS Manifold

Appendix E

These are the plots of the data from Appendix D. Figures E1-E10 correspond to the data in Tables D1-D10 and are for the LS6 Manifold. Figures E11-E20 correspond to the data in Tables D11-D20 and are for the Trailblazer SS Manifold.

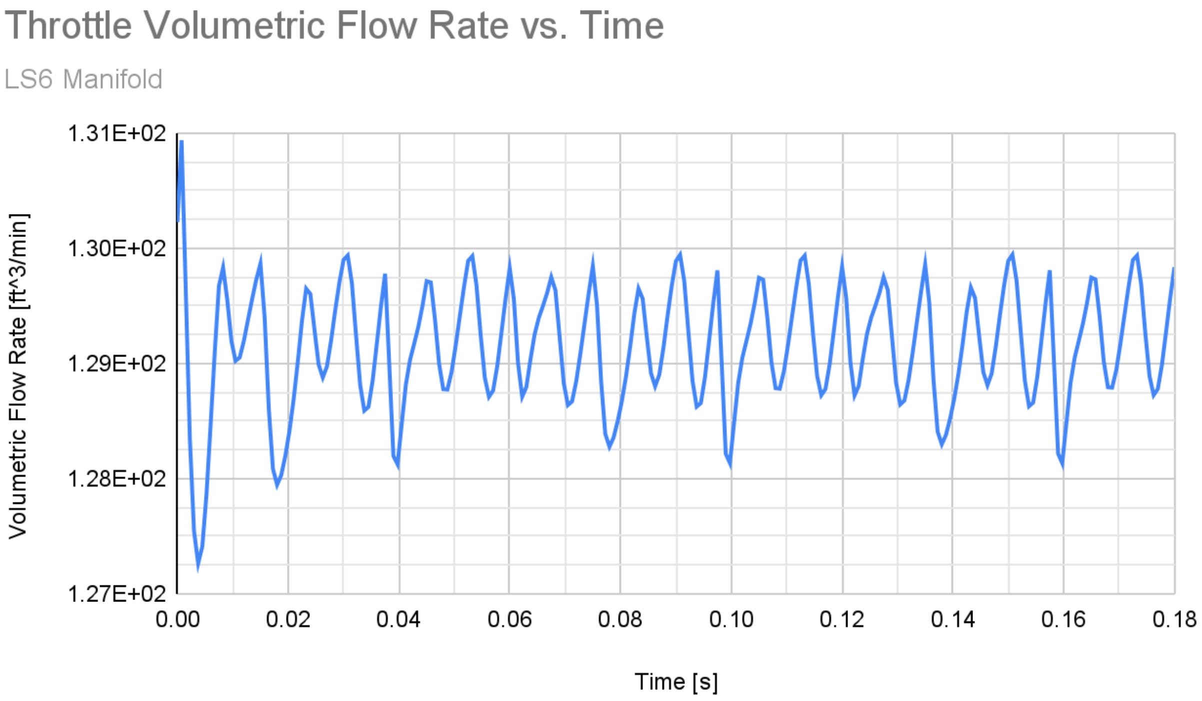


Figure E1: Volumetric Flow vs. Time of LS6 Manifold Inlet

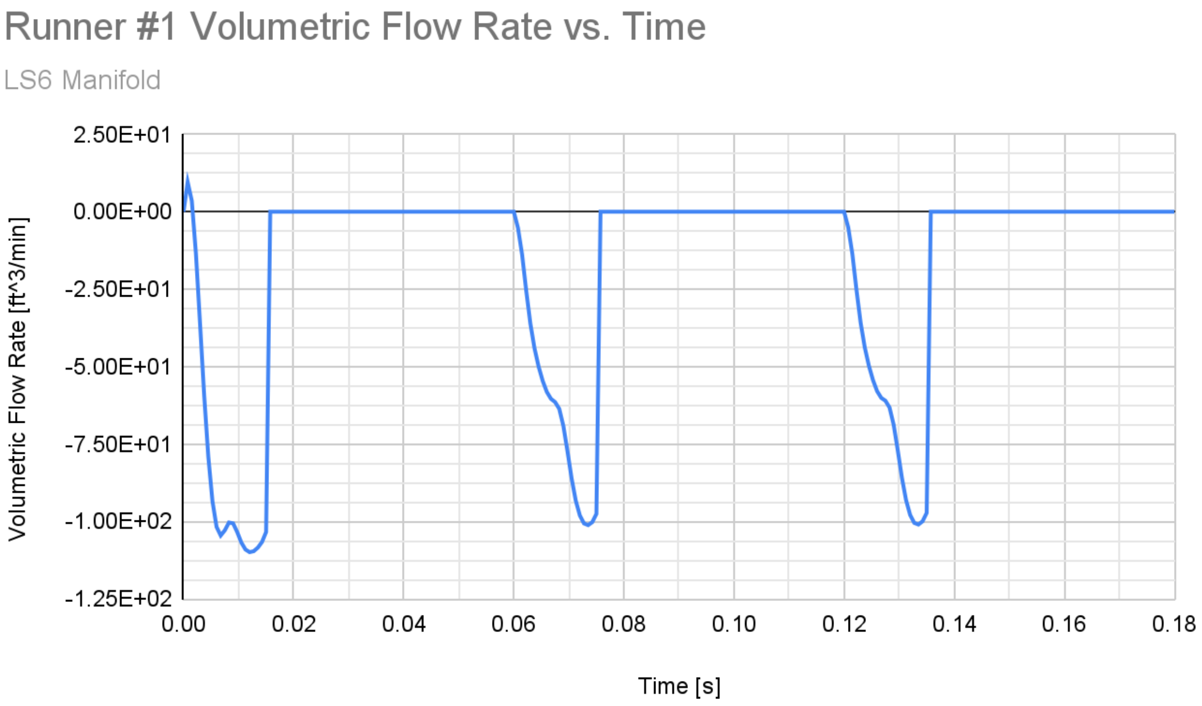


Figure E2: Volumetric Flow vs. Time of LS6 Manifold Outlet #1

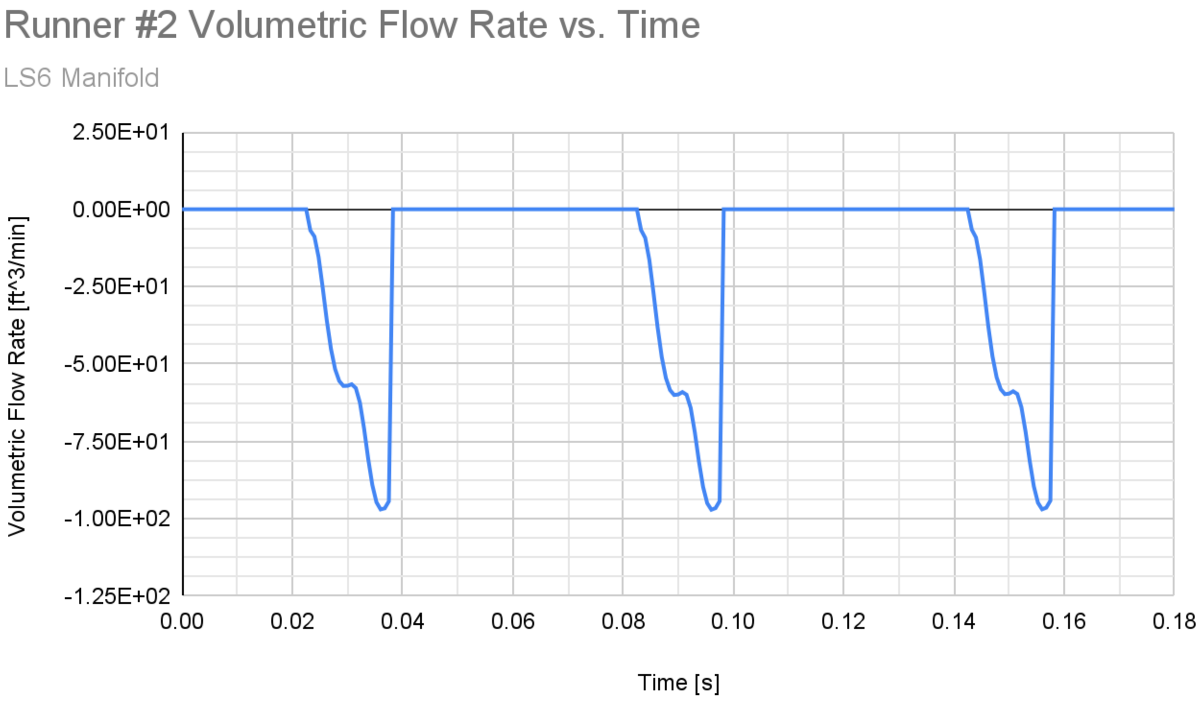


Figure E3: Volumetric Flow vs. Time of LS6 Manifold Outlet #2

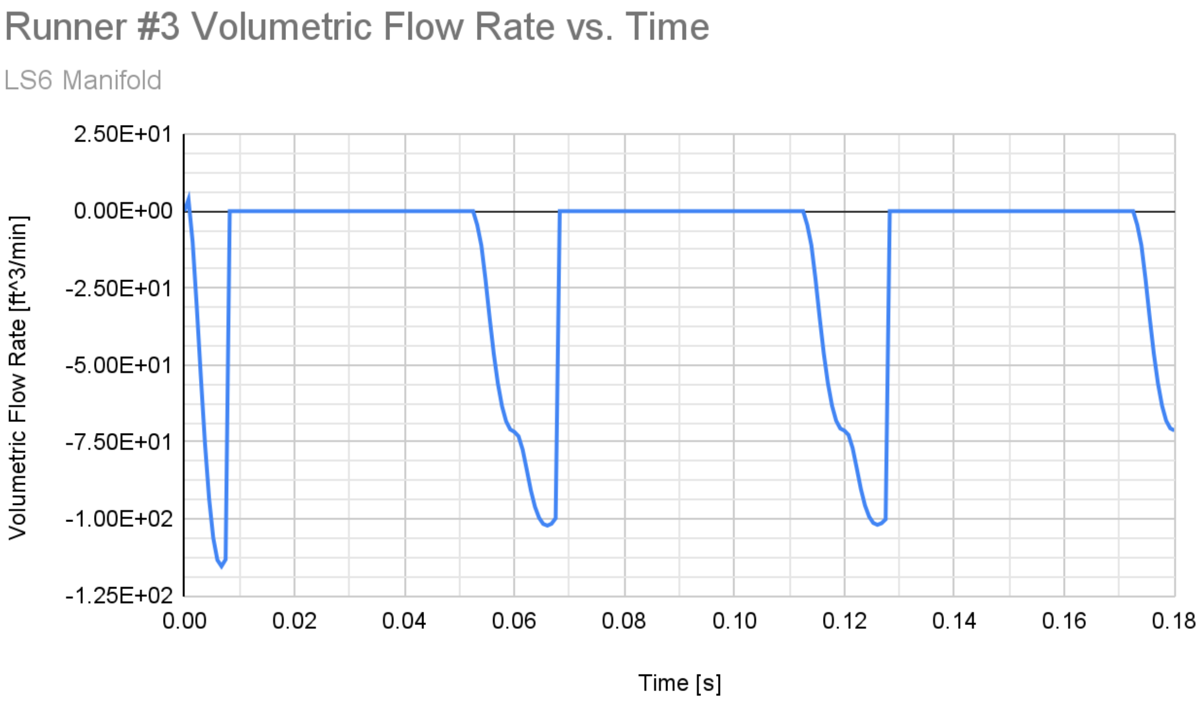


Figure E4: Volumetric Flow vs. Time of LS6 Manifold Outlet #3

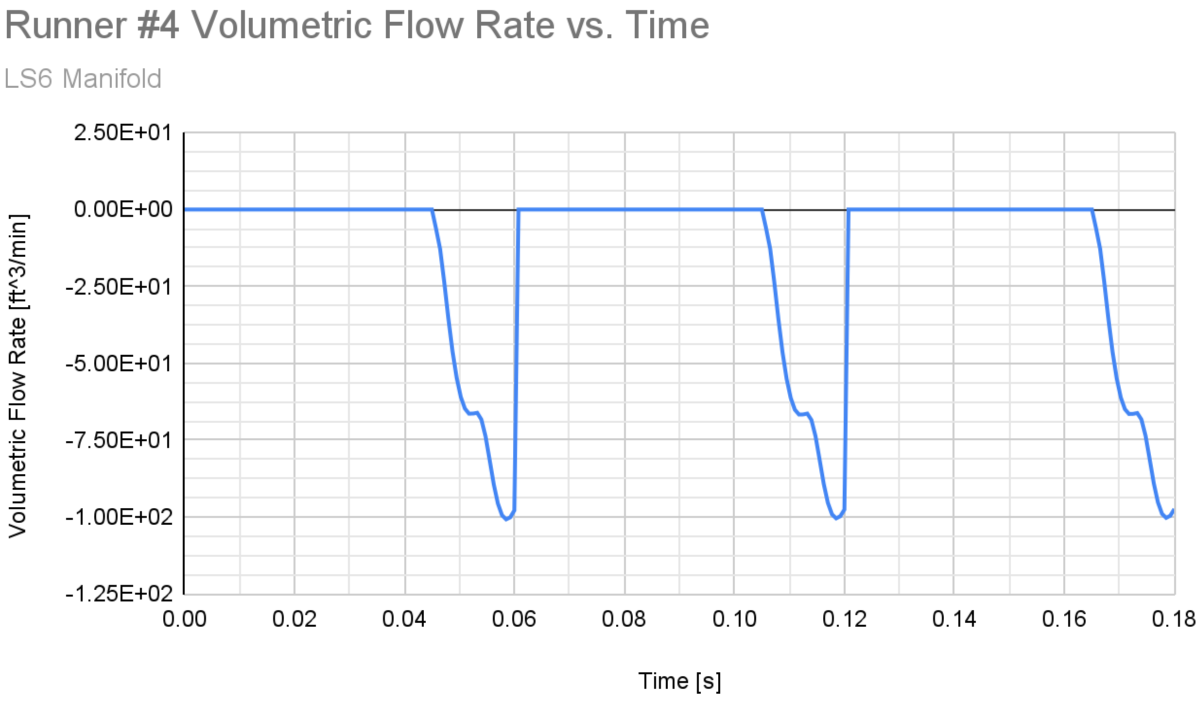


Figure E5: Volumetric Flow vs. Time of LS6 Manifold Outlet #4

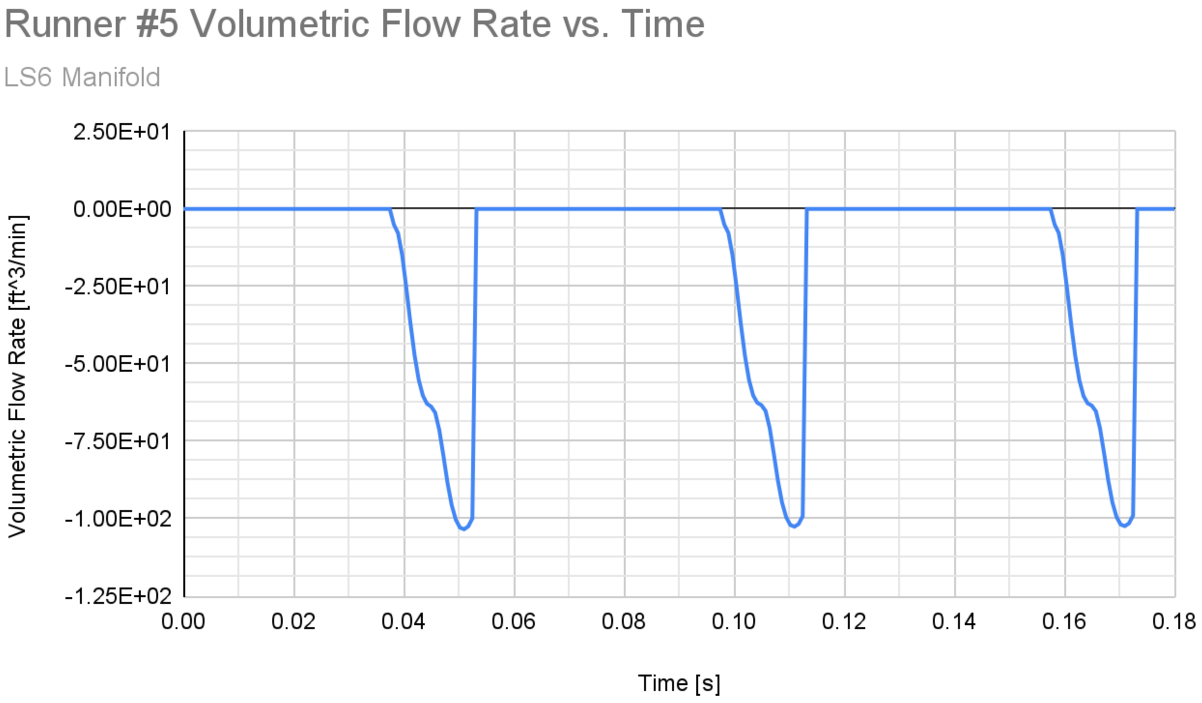


Figure E6: Volumetric Flow vs. Time of LS6 Manifold Outlet #5

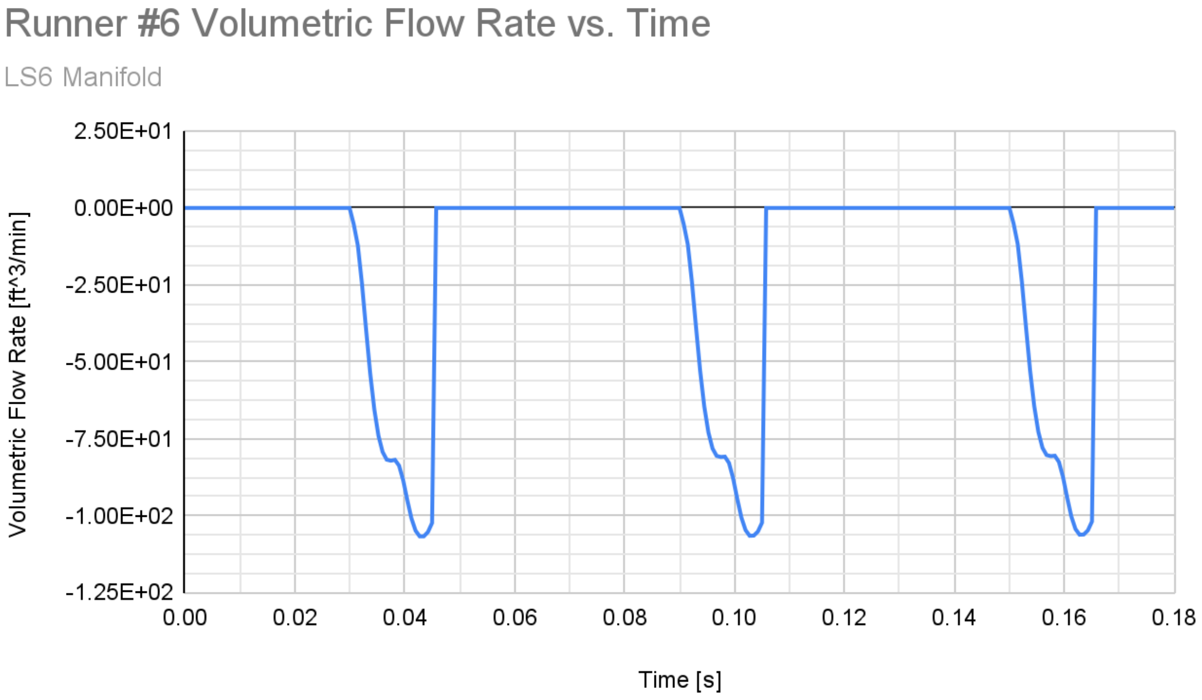


Figure E7: Volumetric Flow vs. Time of LS6 Manifold Outlet #6

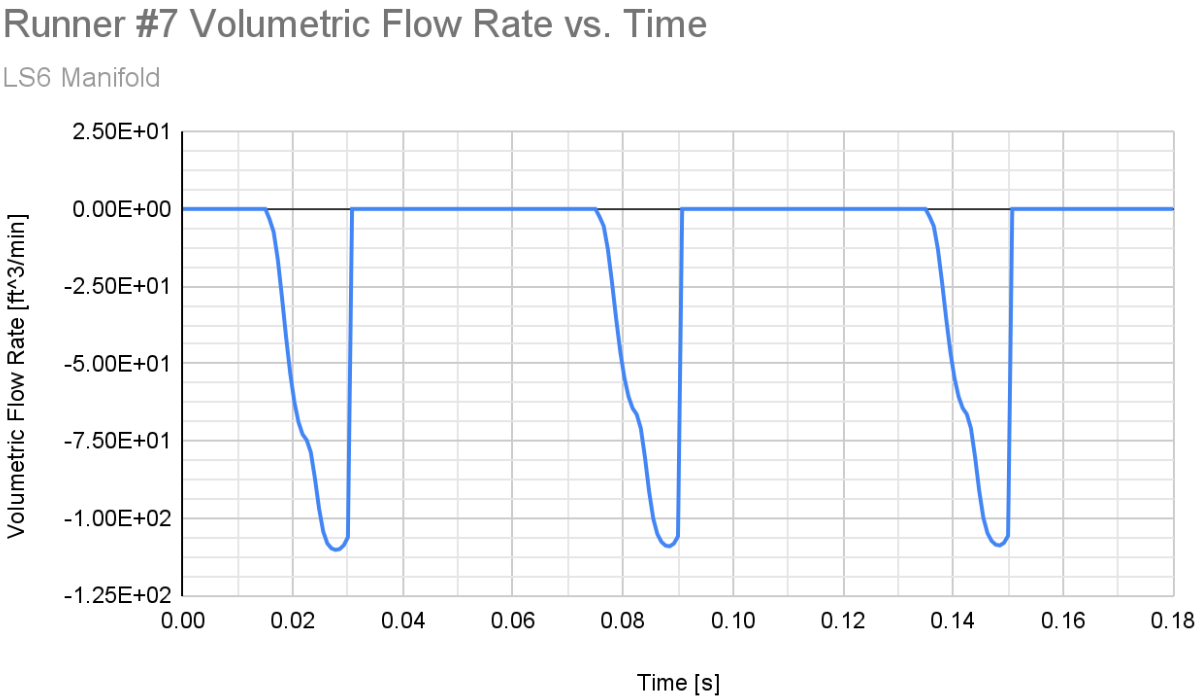


Figure E8: Volumetric Flow vs. Time of LS6 Manifold Outlet #7

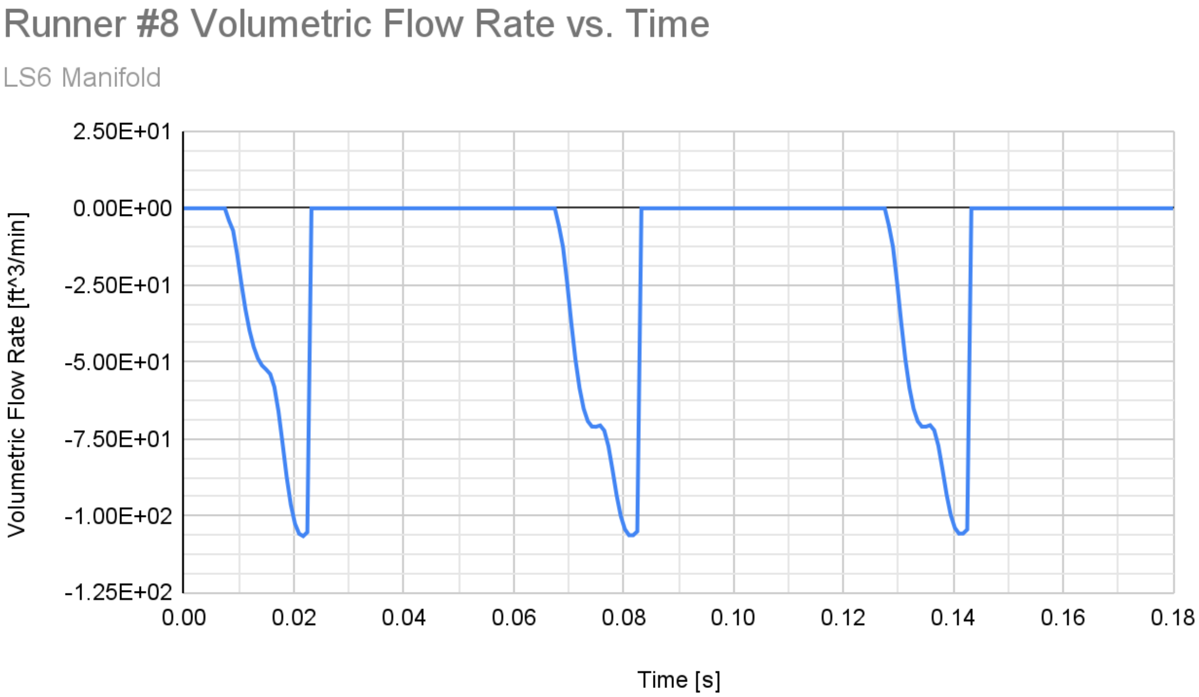


Figure E9: Volumetric Flow vs. Time of LS6 Manifold Outlet #8

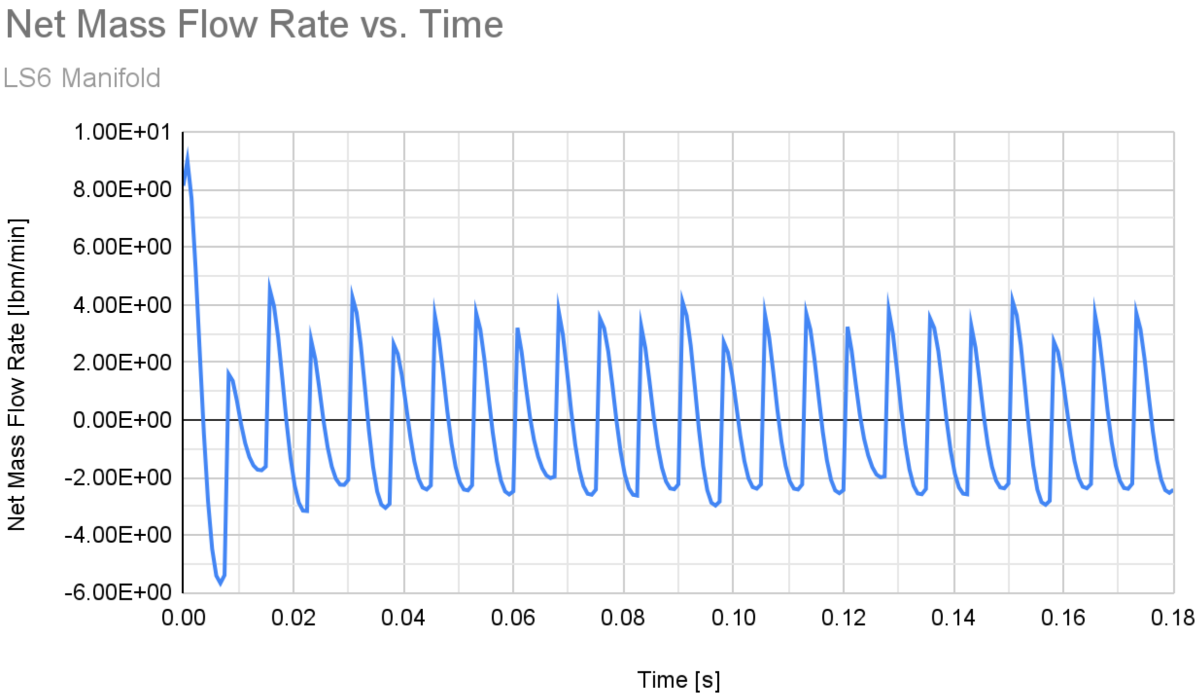


Figure E10: Net Mass Flow vs. Time of LS6 Manifold

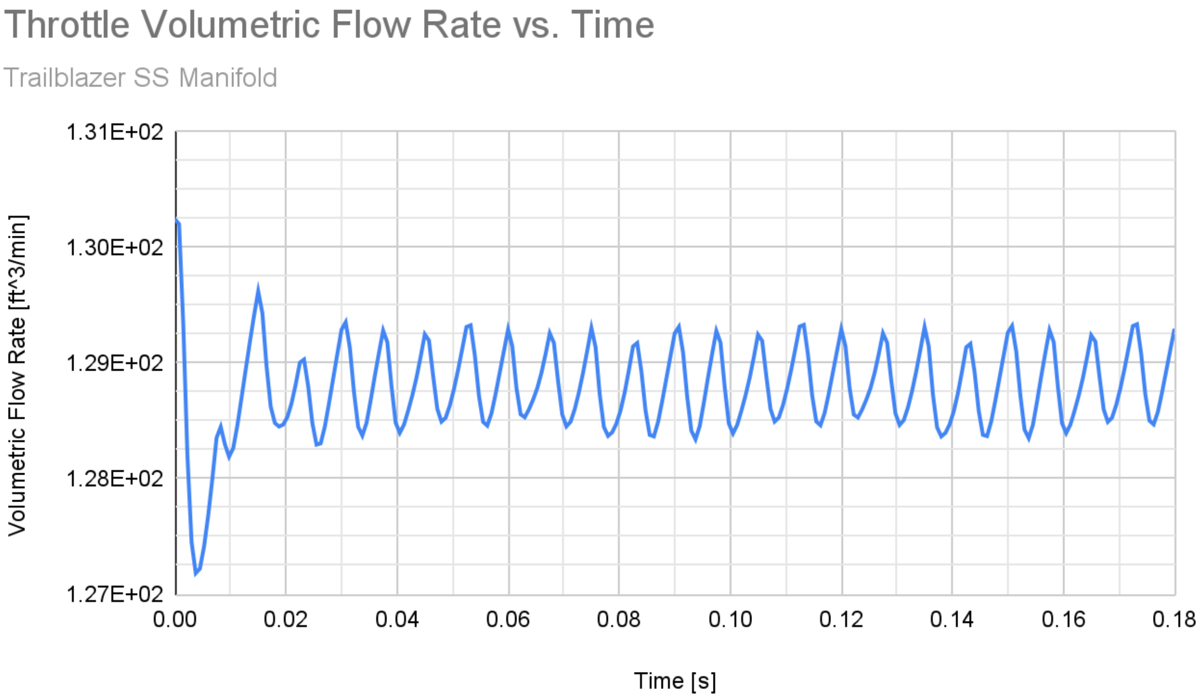


Figure E11: Volumetric Flow vs. Time of Trailblazer SS Manifold Inlet

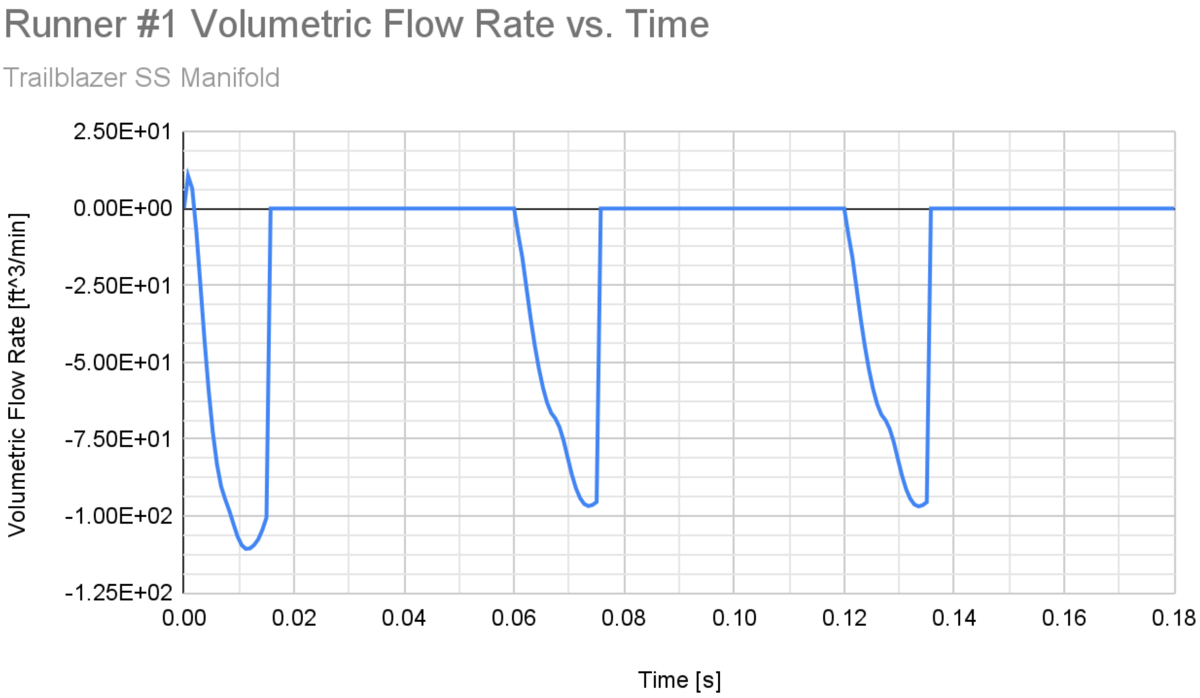


Figure E12: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #1

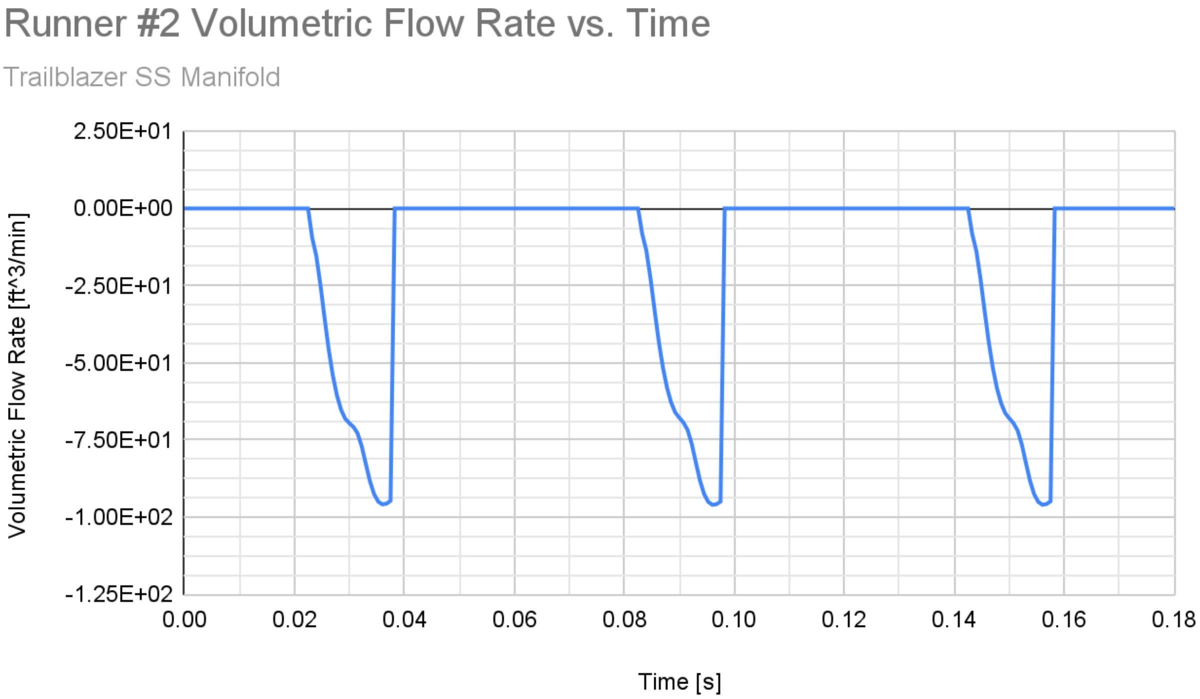


Figure E13: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #2

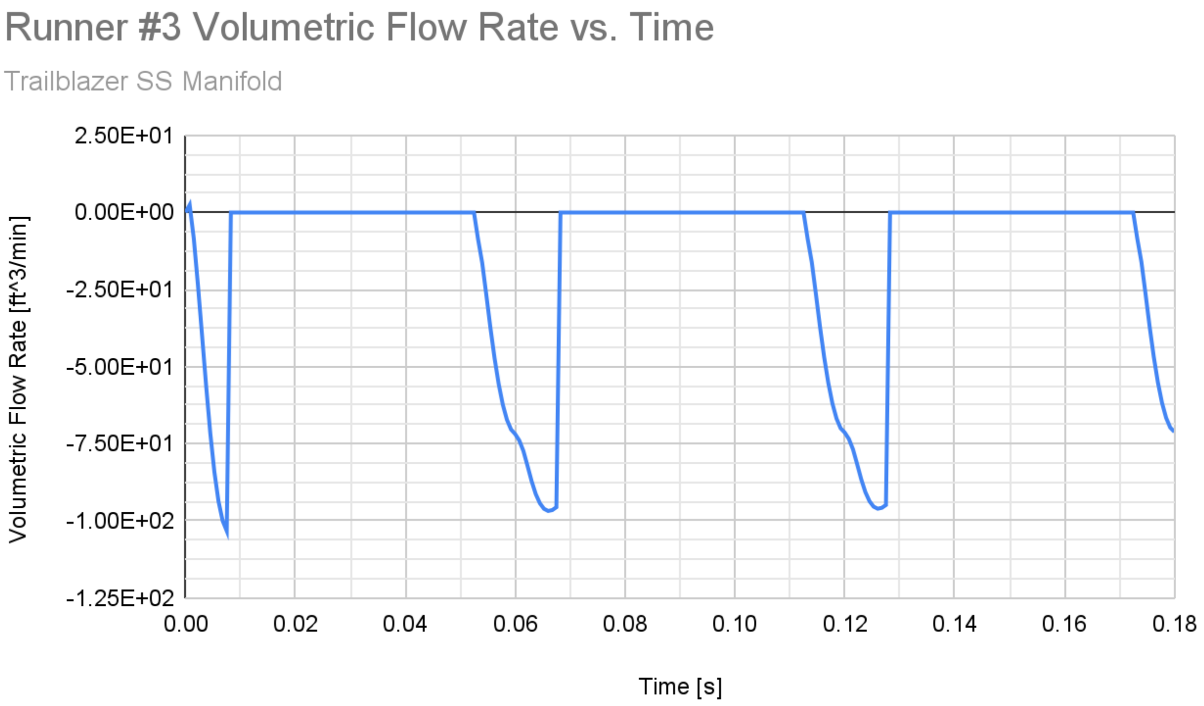


Figure E14: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #3

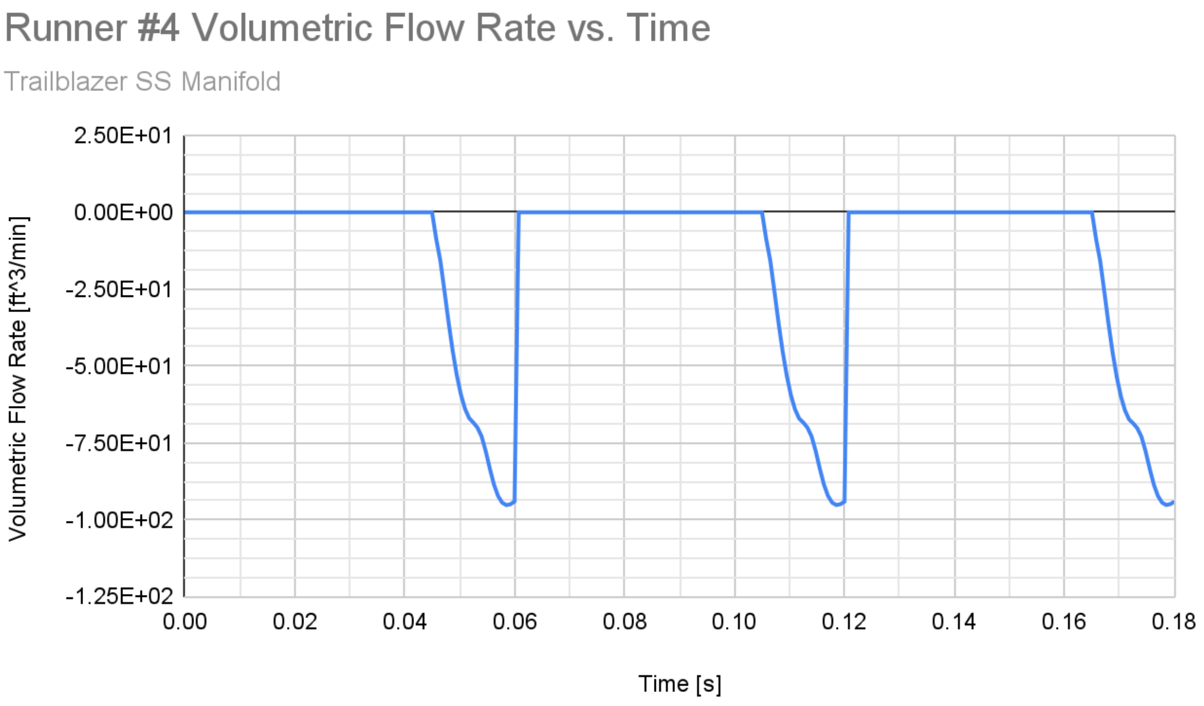


Figure E15: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #4

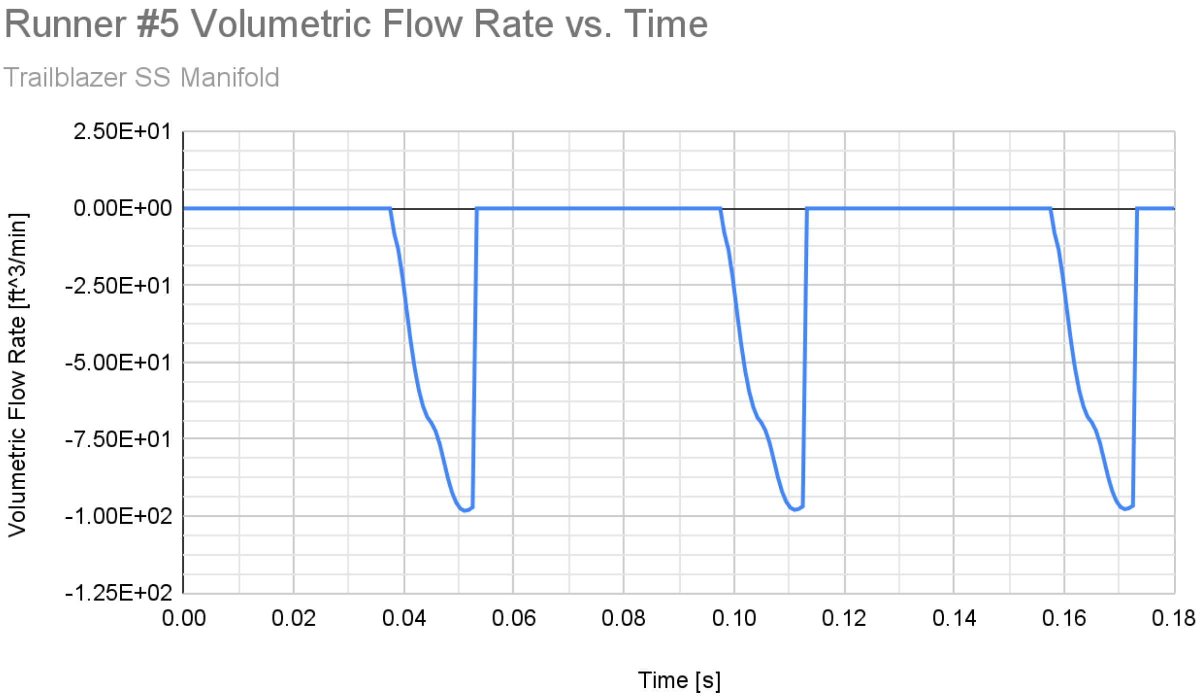


Figure E16: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #5

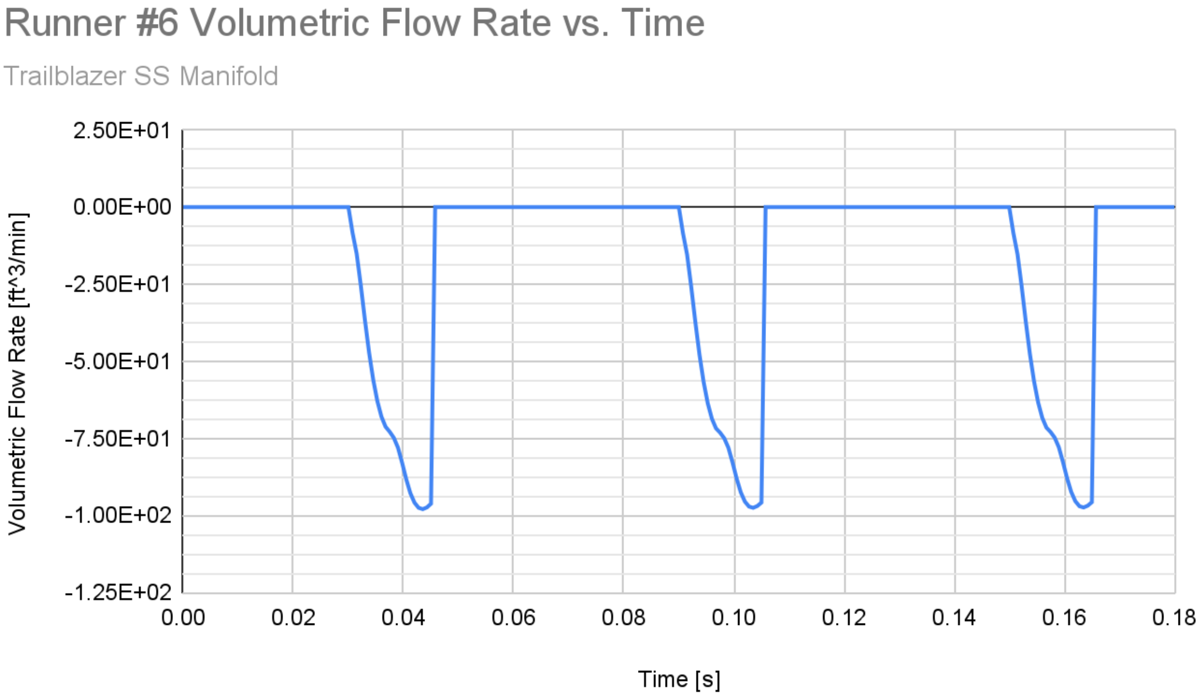


Figure E17: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #6

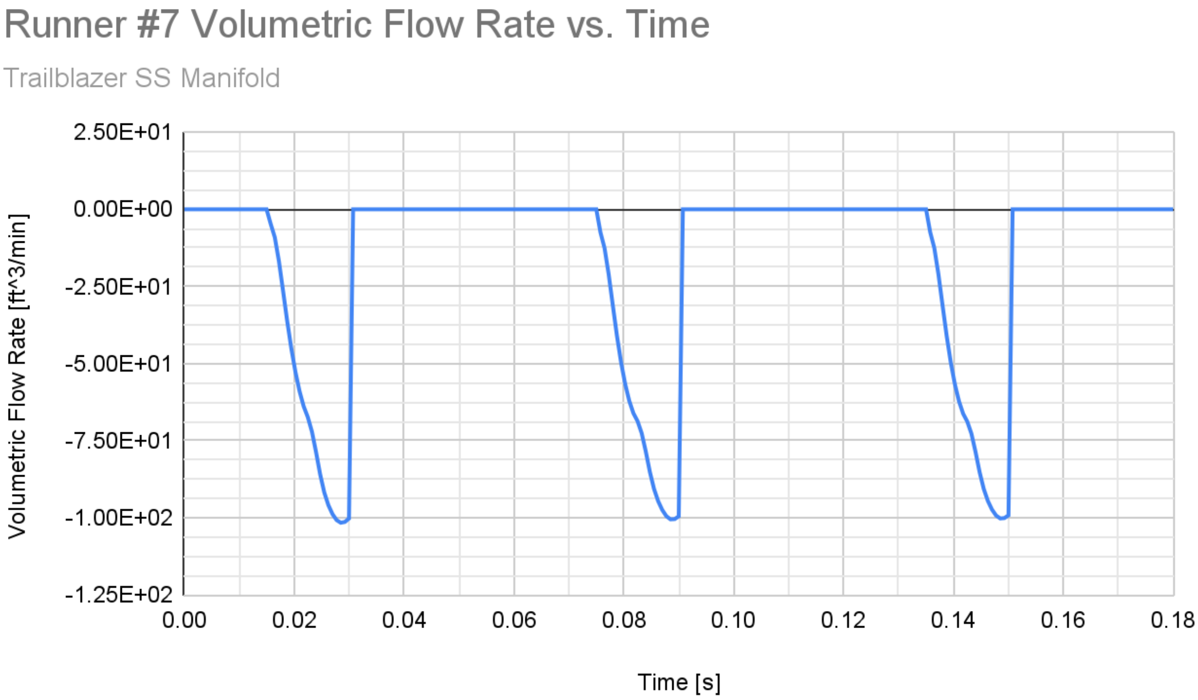


Figure E18: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #7

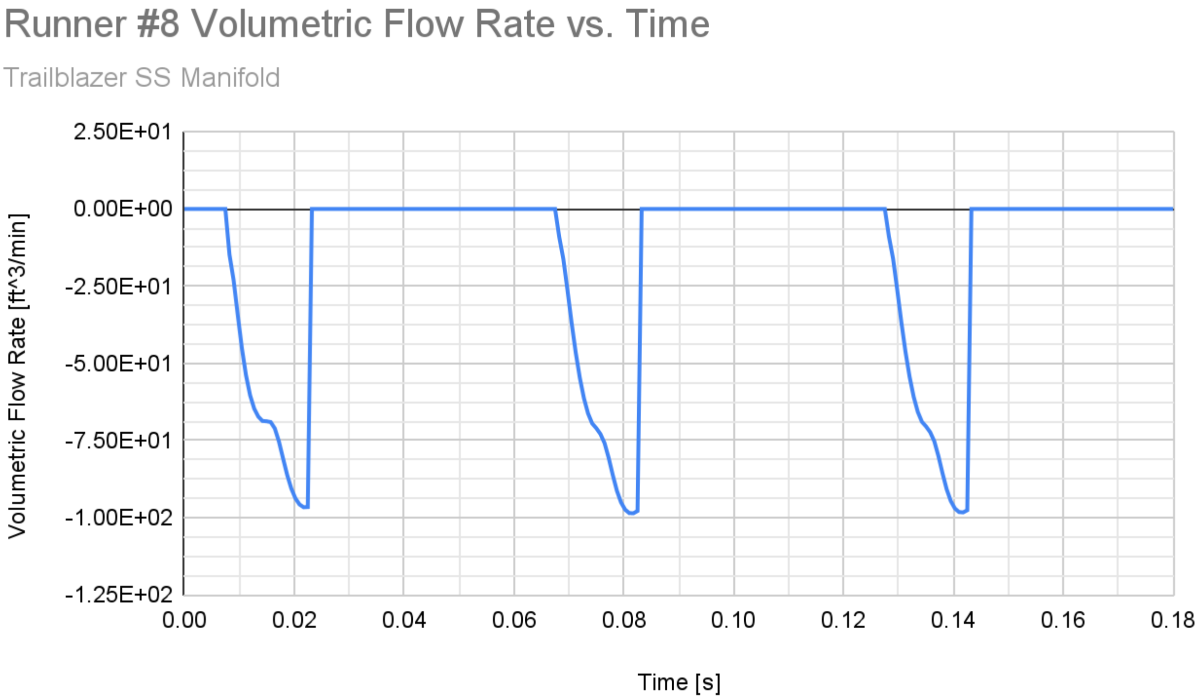


Figure E19: Volumetric Flow vs. Time of Trailblazer SS Manifold Outlet #8

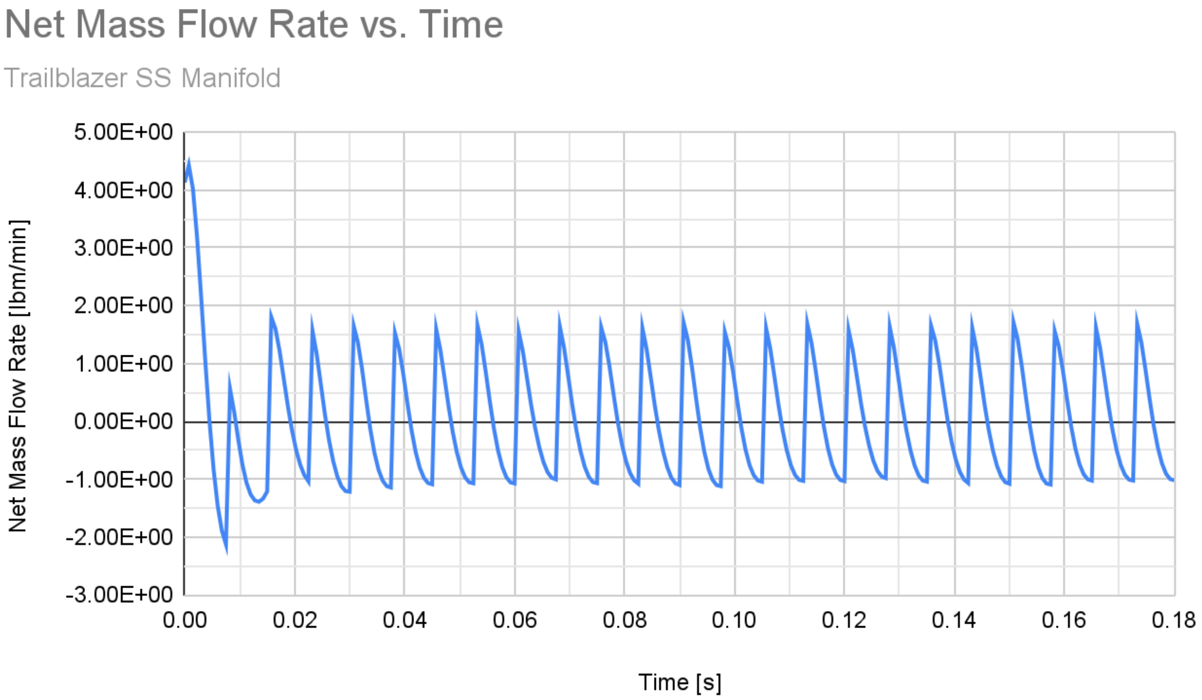


Figure E20: Net Mass Flow vs. Time of Trailblazer SS Manifold