ENGR 360 Final Report
Team Darley Havidson

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Contents

Executive Summary

¡Executive Summary here¿

Goals and Objectives

Scope

The goal of this project is to collaborate effectively as a team to design an internal combustion engine for the Spartan Motorcycle Company by the year 2020. In addition to considering the current market of existing competitive motorcycle engines, our design will adhere to all of the requirements provided by our project sponsor, Professor Sunniva Collins. Our final design will represent the quality and values of the Darley Havidson team.

All systems within the scope of this project are listed below:

- **Fuel Injection** The fuel injection system should include the valve train, fuel efficiency considerations, and air intake. The fuel tank and fuel rail is not deemed to be in scope.
- **Power train** The power train will include the pistons, cylinders, connecting rods, and crankshaft. The powertrain will not include the clutch, flywheel or any part of the transmission.
- **Exhaust** The exhaust system should also consider noise and emission regulations, as chosen by the target customer requirements. Specifications for a muffler will also be incorporated into exhaust and noise regulations, but the design of the muffler is out of scope.
- **Fluids** The complete cooling system and the complete lubrication system (including the dipstick) will be included.
- **Manufacturing** Material selection, assembly, and minimum cost to produce should be included for all components of the final design.
- **Mounts** The mounting method and vibration damping capabilities will be in scope, the design of the specific mounting system will be out of scope.
- **Bill of Materials (BOM)** A detailed design with a full bill of materials will be included.
- **FMEA** Our scope will include an analysis of various modes in which our system can fail, and mitigation actions to reduce severity and occurrence of failures
- **Electrical Systems** The spark plugs, starter motor, and alternator will be in scope, all other electrical components are out of scope

Assigned and Derived Requirement

Customer	Derived
The system shall have 2 or more cylinders	The system shall be a V-Twin cylinder configuration.
The system shall have a 4-stroke cycle.	The system shall have a 4-stroke otto cycle.
The system shall have a displacement of between 1500-1800cc	The system shall have over 1500 cc of total displacement between all cylinders
The system shall be fuel injection and spark ignition	The system shall be fuel injection and spark ignition
The system shall run on standard gasoline	The system shall run on 87 octane gasoline
The system shall have a compression ratio between 9:1 and 10:1	The system shall have a compression ratio of 10:1
The system shall be capable of 5000 rpm continuous service	The system shall have a max rpm over 5000 rpm
	At 5000 rpm the system shall be able to power a 6 speed transmission
	The system shall be designed to idle at 800 rpm
The system shall be designed to idle at 800 rpm	The system shall be designed to idle at 800 rpm
The system shall be capable of powering a six-speed transmission	The system shall produce at least 80 horsepower and at least 90 ft-lb of torque
The system shall be designed with manufacturing processes equipped to output between 7,500-15,000 units annually	The system shall be designed with manufacturing processes equipped to output 15,000 annually
The system shall be production ready by 2020	The system shall be production ready by 2020
The system shall adhere to all relevant specifications and standards for safety, fuel efficiency, noise, and emissions	The system shall adhere to all EPA standards for safety, fuel efficiency, noise, and emissions for Class 3 motorcycles
	The maximum sound levels permitted are 82dBA (35mph or less) for vehicles manufactured before January 1, 1979; and 78dBA(over 35mph) for vehicles manufactures after January 1, 1979.
	Emissions - (0.8 g/km HC + NOx. 12 g/km of CO)
The system should minimize overall dimensions and weight	The system envelope shall be no larger than 20” x 18” x 12”
	The system shall weigh no more than 275 lbs
The system should maximize fuel efficiency	The system shall have a combustion efficiency of at least 0.9
	At open throttle the system shall have a volumetric efficiency of at least 0.75
	The system shall have a mechanical efficiency of at least 0.75 at max rated speed.
The system should minimize production cost	The system shall cost no more than $3750 per unit to produce
The system should be durable and reliable	The system shall have a factor of safety of at least 6
	The system shall have an operating life of at least 50,000 miles
	The system shall have a maintenance period of 1500 miles

System and Subsystem Design

Relevant Technical Information and Calculations

Combustion Analysis Part 1

Combustion Analysis Part 2

Power Output

Emissions

Fuel Economy

Cylinder Head Design

Piston

Connecting Rod

Crankshaft

Manufacturing and Materials

The crankshaft was forged and machined from Aluminum 4032 to ensure that it has the static and fatigue strength necessary. Additionally, Aluminum 4032 is ductile and has high impact resistance to sustain the combustion forces acting on the piston and pushing through the connecting rod.

Modelling and Balancing

The crankshaft dimensions were found from reference dimensions from "Vehicular Engine Design" by Kevin Hoag. These values were derived primarily from the bore diameter of the cylinder. Then, balancing calculations were performed to make sure that the center of mass (COM) was balanced around the shaft. There are two components of crankshaft balancing: static and dynamic. Static balancing deals with one plane, where all the forces acting on the system are equal to zero. Dynamic balancing deals with 2 reference planes, so the sum of moments must equal zero as well as the sum of forces. The calculation was done using a free body diagram of the mass of the crank pin and respective counterweight. Due to the fact that there was only one crank pin in the design, balancing the crankshaft was fairly straightforward and the reference dimensions given in Hoag balanced the crankshaft very well, with a negligible distance between the COM and the crankshaft axis.

Camshaft

Intake and Exhaust

Cooling

Overview

The engine will be liquid cooled by 50\50 Water\Ethanol–Glycol in a series–flow configuration. The calculated coolant operating temperature range is approximately $298.15K$ to $358.15K$, which takes into account of factor of safety of 1.886. The coolant will be pushed through the engine with a volumetric flow rate of $24.36L/min$, and the achieved rate of heat rejection is $24.392kW$ and the outer surface temperature of the engine block is $373.15K$.

The radiator total surface area required to achieve this rate of cooling is $0.9895m^2$. The radiator dimensions are approximately $250mm \times 700mm \times 50mm$; and because the surface area needs to meet requirement, the radiator needs to have fins and be made out of aluminum. The overall heat transfer coefficient needs to get above $200W/m^2 \cdot K$.

The water pump selected is the Davis Craig EBP®25 Electric Booster Pump, which is capable of outputting $25.02L/min$. A thermostat will be used to regulate the coolant flow rate, and the component of choice is the Fail-Safe thermostat, which operates at $91°C$.

Calculation

Two mathematical models were used in designing the cooling jacket and the radiator.

The cooling jacket design entails modeling the combustion chamber, coolant channel, and the cylinder block as a $1D$ thermal resistance network, with the three components simplified as three concentric cylinders. The equation for the rate of heat transfer inside the cylinder block can be written as

$$\dot{Q} = \frac{T_g - T_{out}}{\frac{\ln(\frac{r_1}{r_2})}{2\pi k_s L} + \frac{1}{2\pi r_2 L h_c} + \frac{\ln(\frac{r_4}{r_3})}{2\pi k_b L}} \tag{5.1}$$

where T_g is the gas temperature, T_{out} is the cylinder block outside surface temperature, r_1 is the bore radius, r_2 and r_3 define the radii of the coolant channel tube dimensions, r_4 is the an average radius of the cylinder block measured from the combustion chamber center. L denotes the stroke length, k_s and k_b denote thermal conductivity of the cylinder sleeve and cylinder block, respectively, and h_c denotes the convective heat transfer coefficient of the coolant. Note that T_g was used to approximate the temperature of the inner wall of the combustion chamber.

To find out the value of h_c, Reynolds number is needed. The model for a concentric annulus was used for the calculation

$$Re_D = \frac{\rho_c \bar{V} D}{\mu_c} \tag{5.2}$$

where D is the characteristic length of the model of choice and it has value

$$D = 2(r_3 - r_2)$$

The resulting Reynolds number is 1058.76, which falls under the laminar flow range, and therefore the Nusselt number and convective heat transfer coefficient can be calculated as

$$Nu_D = \frac{h_c D}{k} = 3.66 \tag{5.3}$$

The $\bar{V}$ term corresponds to the average flow velocity, and we iteratively designed the number so that the desired flow rate as well as the heat transfer coefficient can be achieved. The cooling sleeve was designed so that the cross-sectional area is the same as that of the ring used in the mathematically model.

The overall rate of heat transfer was calculated to be $\dot{Q} = 12.196kW/cyl$. With 2 cylinders, the total rate of heat transfer is then $24.392kW$.

A summary of values used in this set of calculations can be found in Table 5.1.

Table 5.1: Cooling Sleeve Calculation Variables and Values

Variable	Value	Unit	Note
T_g	1768.3	K	75% of highest gas temperature
T_{out}	373.15	K	
r_1	0.0516	m	$B/2$
r_2	0.0616	m	$r_1 + 0.01$
r_3	0.065	m	
r_4	0.0706	m	
L	0.1064	m	
k_s	53.3	W/mK	
k_b	151	W/mK	
ρ_c	1038	kg/m^3	
μ_c	0.001	$Pa \cdot s$	
C_p	3643	$J/kg \cdot K$	
D	0.0068	m	
$\bar{V}$	0.15	m/s	
Re_D	1058.76		
Nu_D	3.66		
h_c	223.37	W/m^2K	

With this configuration, the total volumetric flow rate is then

$$\begin{aligned}\dot{V} &= 2 \cdot \bar{V} \cdot A_c \\ &= 2 \cdot \bar{V} \cdot (r_3^2 - r_2^2) \\ &= 24.36L/min\end{aligned}$$

The water pump can be selected based on the above volumetric flow rate calculation. In this case, the pump selected is Davies Craig EBP® Electric Booster Pump, which is capable of outputting $25L/min$.

Given the fluid velocity in the coolant channel and the stroke length, the time coolant spends in the coolant channel is $t = 0.7091s$, and the total heat transferred to the coolant during this process is

$$Q_{tot} = \int \dot{Q} dt \tag{5.4}$$

and the temperature change in the coolant is

$$\Delta T = \frac{Q_{tot}}{C \cdot m} \tag{5.5}$$

where $C_p = 3643J/kg \cdot K$ and $m = \rho_c \cdot V = 0.14929kg$ for the coolant. $\Delta T = 31.802K$, and with factor of safety $SF = 1.886$, the temperature raise is taken as $60K$.

The radiator was modeled after a cross-flow heat exchanger involving coolant and air

$$q = UA\Delta T_{LM,CF} \tag{5.6}$$

On the coolant side, the velocity needs to reduce to $0.3756 L/min$ ($0.0065 kg/s$) for the most efficient heat transfer,

$$\begin{aligned} q_c &= \dot{m}_c C_{p,c}(T_{c,o} - T_{c,i}) \\ &= 0.0065 kg/s \times 3643 J/kg \cdot K \times (298.15K - 358.15K) \\ &= -1.388 kW \end{aligned}$$

Assuming air comes in at $0.75 kg/s$ at $303.15K$, the air temperature at outlet of the heat exchanger can be calculated as $T_{a,o} = 305.73K$. Therefore,

$$\Delta T_{LM,CF} = \frac{(T_{c,i} - T_{a,o}) - (T_{c,o} - T_{a,i})}{\ln\left[\frac{(T_{c,i} - T_{a,o})}{(T_{c,o} - T_{a,i})}\right]} \tag{5.7}$$

$$R = \frac{T_{c,i} - T_{c,o}}{T_{a,o} - T_{a,i}} \tag{5.8}$$

$$P = \frac{T_{a,o} - T_{a,i}}{T_{c,i} - T_{a,i}} \tag{5.9}$$

The calculated results are $\Delta T_{LM,CF} = 8.7669K$, $R = 0.4885$, and $P = 2.3882$, which gives $F \approx 0.7$. The radiator should be made out of Aluminum and should have fins, which easily give an overall heat transfer coefficient above $200 W/m^2 K$. Therefore the total area required for the radiator is

$$A = \frac{q}{UF\Delta T_{LM,CF}} = 0.9895 m^2 \tag{5.10}$$

Assumptions

A couple of assumptions were used during the modeling process. They are listed as follows:

- Constant material properties
- Constand and uniform surface temperature
- Negligible kinetic and potential energy effects
- Fully developed flow
- Steady-state conditions

Lubrication

Engine Block

Drawings

Detailed Drawings

Assembly Drawings

CAD Models

Bill of Materials

Materials and Manufacturing Methods

Assembly

The assembly for the engine will be split into two primary parts, the drivetrain and the valvetrain, then the two of them will be assembled into the engine to make our end product. The valvetrain assembly will be done after the drivetrain is initially assembled.

Drivetrain

The first step for this assembly would be to put together the piston. The piston will be first press fitted to the connecting rod with the use of a wrist pin bearing. The piston rings will be placed on their respective piston grooves. As its a V-Twin engine, there will be two pistons. This will be then connected to the crankshaft with a sprocket. When this is attached, the powertrain is ready. This crankshaft-piston sub-assembly will then be attached to the flywheel at the bottom of the engine.

Valvetrain

Here, the first step would be to put in the intake and exhaust valves. The valve springs are compressed with a valve spring retainer. Once the intake and exhaust valves are in their appropriate positions, the springs are released to hold these valves in place. Then the camshaft is placed in its position, with a camshaft timing sprocket. Apart from this, the rocker arms and timing chain are assembled and inserted inside the engine block. The engine housing will be screwed on after this assembly. The spark plugs, fuel injector and the starter motor are attached to their respective places.

Overall Assembly

First the drivetrain will be assembled. Then on top of that, the valvetrain will be assembled. After this assembly, the engine goes back to Quality assurance in order to make sure it meets the quality requirements set by Darley Havidson.

Quality Control and Critical Characteristics

The parts used in the engine will go through a series of rigorous tests, both destructive and non-destructive, in order to make sure that the engine meets the quality requirements of the customer. The testing will be split into 3 divisions, Pre-assembly, In assembly, and post assembly. Darley Havidson will adhere to standards set by ISO 9001:2015, and will aim to achieve their certification. In order to make sure Darley Havidson meets these quality requirements, two Defect Prevention Analysts will be hired.

Pre-Assembly

First thing to be checked up is the material that is being used. All the metal alloys and metals used for parts of the engine must be checked for material composition. A simple alloy tester machine shall suffice the requirements for this check. The purchased parts also need to be checked for conformity with their drawings. They will be compared to the manufacturers drawings, and all purchased parts will go through non-destructive tests such as: visual testing, dimension measurements and material testing. One of Fifty (1/50) parts will be used for destructive tests such as: hardness test and tensile strength. The same non-destructive testing will occur on parts manufactured by the manufacturing division of Darley Havidson. Another key aspect that needs to be checked is the surface finish of the parts that will be in contact with other parts in the engine assembly. A subgrade surface finish will significantly hinder the durability and the power generated by the engine. For parts manufactured by forging and casting, crack detection must be carried out, as blowholes are very common with such manufacturing methods. The presence of blowholes will increase the risk of failure and reduce the strength of the engine parts.

Assembly

The assembly stage of quality testing will be primarily based around ensuring the free motion of the parts that will be moving in order to run the engine. First the bearings will have to be checked for correct placement and whether they are the correct bearings. The pistons will have to be checked for free motion, otherwise it will cause severe durability issues. The crankshaft must also be checked for correct connection and free motion. The lubrication and cooling system must then be checked for appropriate fitting and coolant flow, and whether there are any leakages.

Post-Assembly

The post-assembly stage will also pay attention at free motion, but here the motion would be checked as a whole. The working of the engine and free movement must be checked here. The next thing to be checked is whether the engine is meeting its idle and maximum rpm. After that, the emissions such as noise and gas must be compared to the regulations. 100% of the engines produced must meet these emission requirements. The fuel efficiency must be checked, and it should meet the expectations set before production. The last thing to be checked is the torque and power generated by the engine. This should also meet the calculations done prior to production.

Theory of Operations

Failure Modes Effects Analysis

Final Cost Estimate

Design Satisfies Requirements

Project Management

Team Contributions

References

[1] ¡Name of the reference here¿, <urlhere>

[2] ¡Name of the reference here¿, <urlhere>

Appendices

Learning Outcomes Index

Learning Outcome	Example/Response Found on Page	Student(s) Responsible
An ability to apply knowledge of mathematics, science, and engineering		
An ability to design and conduct experiments, as well as to analyze and interpret data		
An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, heath and safety, manufacturability, and sustainability		
An ability to function on multidisciplinary teams		
An ability to identify, formulate, and solve engineering problems		
An understanding of professional and ethical responsibility		
An ability to communicate effectively		
The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context		
A recognition of the need for, and an ability to engage in life-long learning		
A knowledge of contemporary issues		
An ability to use techniques, skills, and modern engineering tools necessary for engineering practice		

Team Charter

Purpose

Formed at Case Western Reserve University in the fall of 2018, Darley Havidson has been tasked with designing a motorcycle engine. This engine will be designed for the Spartan Motorcycle company, with the intent of production beginning in 2020. The new engine design must be unique enough to differentiate the product from the competition. The final design will include technical specifications, bill of materials, theory of operations, risk analysis, and FMEA.

Background

Our team consists of 12 Mechanical Engineering students from Case Western Reserve under the supervision of the program advisor Sunniva Collins. Our team members are coming from various technical backgrounds and have been separated into sub-teams based on individual strengths and weaknesses. Over the course of the 15 week project, there will be multiple project and design reviews, which will act as benchmarks to track the project and receive feedback on the technical decisions that we make throughout the design process. In addition, there will be weekly progress reports in which we will report out the status of the project and express any questions we have to Professor Collins. The outcome of this project will be a commercial engine that can be mass produced by the Spartan Motorcycle Company at a low price. The engine design will be modeled around the given customer requirements and the technical requirements that we establish to ensure safety, reliability, noise reduction, and fuel efficiency. The design must also comply with all legal and market regulations that apply to commercial motorcycle engines.

Scope

The goal of this project is to collaborate effectively as a team to design an internal combustion engine for the Spartan Motorcycle Company by the year 2020. In addition to considering the current market of existing competitive motorcycle engines, our design will adhere to all of the requirements provided by our project sponsor, Professor Sunniva Collins. Our final design will represent the quality and values of the Darley Havidson team.

Given Engine Requirements:

- 2 or more cylinders, 4-stroke cycle
- Displacement 1500 to 1800cc
- Fuel injection, spark ignition
- Runs on standard gasoline
- Compression ratio 9:1 to 10:1

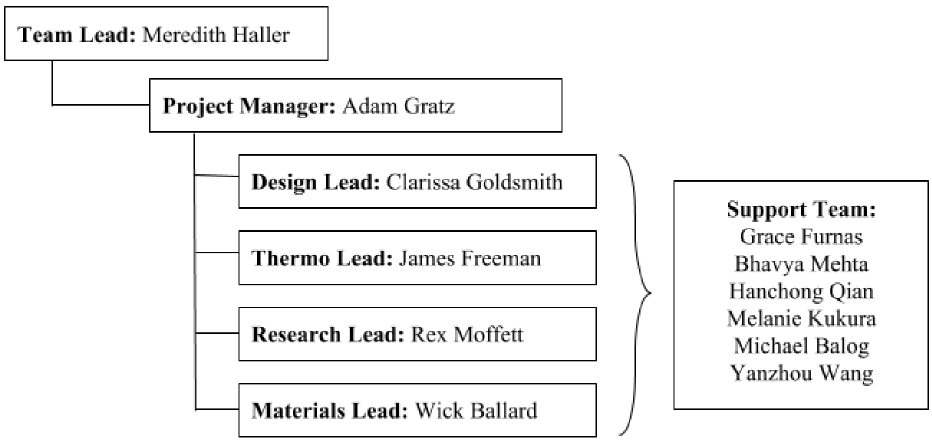
Given Performance Requirements

- Capable of 5000 rpm continuous service, idle at 800 rpm
- Powers a six-speed transmission
- Must meet all relevant specification and standard for safety, fuel efficiency, noise and emissions

Given Design Requirements

- Maximize fuel efficiency, minimize overall dimensions and weight, minimize cost to produce
- Reliability and durability should be considered
- Portfolio should include technical specifications, theory of operations, risk analysis and FMEA, and detailed design with bill of materials
- Associated with each component should be a manufacturing process, mechanical drawing, material of construction, heat treatment (if required), and cost to manufacture or buy
- Assembly and required fluids and lubricants should be covered

Team Composition



Membership Roles

Darley Havidson is composed with twelve CWRU Undergraduate students. All 12 students are expected to spend 2-3 hours a week outside class in order to report progress and come up with new ideas.

Name	Phone	Email	Project Role
Meredith Haller	513-709-1342	mlh146@case.edu	Team Leader
Adam Gratz	715-386-5949	jag256@case.edu	Project Manager
Rex Moffett	585-485-1304	trm79@case.edu	Research Lead
James Freeman	408-761-9330	jpf75@case.edu	Thermo Lead
Michael Balog	919-448-6323	mwb65@case.edu	Support Team
Wick Ballard	216-385-5003	wxb119@case.edu	Materials Lead
Clarissa Goldsmith	614-507-0442	cag111@case.edu	Design Lead
Bhavya Mehta	216-333-3798	bmm95@case.edu	Support Team
Yanzhou Wang	216-816-8959	yxw723@case.edu	Support Team
Melanie Kukura	440-465-2081	mlk122@case.edu	Support Team
Grace Furnas	440-409-1185	gmf45@case.edu	Support Team
Hanchong Qian	216-785-6271	hxq44@case.edu	Support Team

Responsibility Matrix

Team Empowerment

As shown above, our team will have 6 leadership positions. The Team Lead will be the head of the team, and will work very closely with the project manager. Right under the Project Manager, will be the 4 team leaders; Design Lead, Thermo Lead, Research Lead and Materials Lead. These four leaders will be operating at the same level of leadership, and they will be responsible for each of their respective teams. The responsibilities for each position is outlined below.

The **Team Lead** is responsible for team organization and making sure that the team meets all deadlines with major deliverables. Their job is to organize and run team meetings in order to ensure that the team meets all deadlines. The Team Lead will work closely with the Project Manager and continuously check on each sub-group (Materials, Thermo, Design and Research) in order to make sure that the project continues to move along on the right track. The Team Lead also serves as the tie-breaking vote in the event that a normal vote results in a tie. The Team Lead will monitor the progress of each team by checking in with the team leads weekly before each progress report, and managing any problems that may affect submission of project deliverables. They may also act as a floating support member as needed, helping out any team that may need an extra member each week as the project continues. The Team Lead will also be the point of contact with Dr. Collins and act as a mediator in case of a conflict. If the Team Lead cant make a meeting, the team must be informed at least 24 hours before the meeting. In such a scenario, the rest of the team will go through the agenda.

The **Project Manager** is in charge of the four teams. The project manager will act as the mediator between the Team Lead and the rest of the teams. Apart from this, the manager will also act as a support member and be a floater for all of the teams, and act as a line of communication between the teams to ensure parts designed by different teams are compatible. They will also manage accountability for individual team members to ensure assigned work is being completed on time. The manager will move about the teams according to the workloads present.

The **Design team** (led by Clarissa Goldsmith) is responsible for the overall design of the engine, including 3D modeling and the bill of materials, as well as part naming structure, part revisions, and final rendering. The support members of this team will change over the course of the project.

The *Thermo team* (led by James Freeman) is responsible for the thermodynamics systems in the engine. This will involve any sort of combustion or flow calculations that are needed to determine the fuel efficiency and power of the engine.

The **Research team** (led by Rex Moffett) is responsible for the research that goes into designing an engine, and maintaining a thorough bibliography while doing so.

The **Materials team** (led by Wick Ballard) is responsible for selecting materials for each component of the engine based on their individual purpose and requirements. In addition to the physical characteristics, the cost of the materials will also be taken into consideration.

Team Operations

Communication and Data Collection Plan

The team will use Slack as our primary mode of communication, Trello for task tracking and management, and Google Drive for file sharing and editing. The entire team will meet weekly on Sundays 7:30-9:00 in whatever room can be reserved (typically Tink or KSL) where sub team leads will report on progress first, and the Gantt chart will be updated as tasks are completed and assigned. Sub teams will also have meetings as needed, to be organized by their respective team lead. In addition, there will be one specified member in charge of recording team minutes at each full group meeting. Excluding emergencies, team members must give 24 hours notice if they must miss a team meeting via Slack. SolidWorks 2017 and PDM will be used for 3D modeling, LaTex will be used for all final reports, Microsoft Office will be used for presentations, and Google Drive will be used for all document storage.

Risk Mitigation Plan

Loss of team member

- Ensure secondary task owners
- Thorough documentation of decisions

Loss of Team Lead/Project Manager/Supporting Team Lead

- Loss of Team Lead, Project Manager takes on Team Lead Role
- Loss of Project Manager, One of the Sub Team Leads Takes over, determined by vote
- Loss of Sub Team Lead, a team member takes over, decided on by vote

Conflicts between team members

- Team Lead will mediate

Team members not completing assignments on time

- Subteam Lead is primarily responsible
- Group meetings w/Adam if teams are consistently missing deadlines

Loss/neglect of files

- Before each progress report, check integrity of files (weekly basis)
- Ensure one member in charge of minutes for each meeting

Running behind schedule/Scope Creep

- Trello
- Float time worked into schedule

Product Design Specifications

Pugh Charts

MATLAB Calculations

List of Abbreviations

Engine Configurations		Inline 4		Inline 3		Inline 5		V Twin		V4		Boxer 4		Boxer 6			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S		
Vibration propensity/balance	10	3	30	2	20	4	40	2	20	2	20	4	40	5	50		
Reliability	9	3	27	3	27	3	27	2	18	4	36	3	27	4	36	Score System	
Simplicity of Design	8	3	24	3	24	2	16	3	24	2	16	2	16	1	8	1	Unsatisfactory
Fuel efficiency	7	3	21	3	21	3	21	4	28	4	28	3	21	2	14	2	Poor
Ease of Manufacturing	6	3	18	3	18	2	12	2	12	2	12	2	12	1	6	3	Acceptable
Current Market Prevalence	5	3	15	2	10	1	5	5	25	1	5	3	15	5	25	4	Good
Overall dimensions/ergonomics	4	3	12	4	16	3	12	5	20	5	20	4	16	2	8	5	Excellent
Cost	3	3	9	4	12	3	9	3	9	2	6	2	6	1	3		
Overall weight	2	3	6	4	8	2	4	5	10	4	8	2	4	2	4		
Noise	1	3	3	2	2	5	5	2	2	2	2	3	3	5	5		
Total			165		158		151		168		153		160		159		
Uniqueness	1	1	1	5	5	5	5	3	3	5	5	5	5	5	5		
Emotional Total			166		163		156		171		158		165		164		

Figure 13.1: Pugh Chart: Engine Configuration

Valves Per Cylinder Head		2		3		4			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S		
Flow of Intake/Exhaust	6	1	6	2	12	3	18	Score System	
Oil Consumption	5	3	15	2	10	1	5	1	Average
Efficiency at Cruise	4	2	8	2	8	3	12	2	Good
Efficiency at Redline	3	2	6	2	6	3	9	3	Best
Complexity	2	3	6	2	4	1	2		
Cost	1	3	3	2	2	1	1		
Total			44		42		47		

Figure 13.2: Pugh Chart: Valve

Cooling System Pugh Chart		Liquid Cooling		Air Cooling			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S		
Temperature Control	7	4	28	2	14	Scoring System	
Durability of System	6	2	12	4	24	0	Unsatisfactory
Impact on Engine Life	5	2	10	3	15	1	Poor
Effect on Emissions	4	3	12	1	4	2	Satisfactory
Effect on Noise	3	4	12	1	3	3	Good
Simplicity of Design	2	2	4	3	6	4	Excellent
Cost	1	1	1	4	4		
Total			79		70		

Figure 13.3: Pugh Chart: Cooling

Valve Timing		Single OHC		Dual OHC		Free Valve		Variable Timing			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S		
Durability	6	2	12	2	12	2	12	2	12	Score System	
Size	5	3	15	2	10	3	15	3	15	1	Average
Efficiency	4	1	4	2	8	3	12	3	12	2	Good
Complexity	3	3	9	2	6	1	3	1	3	3	Best
Cost	2	3	6	3	6	1	2	1	2		
Serviceability	1	2	2	1	1	1	1	1	1		
Total			48		43		45		45		

Figure 13.4: Pugh Chart: Valve Timing

Injection Cycle		Direct		Port			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S		
Efficiency	6	3	18	1	6	Score System	
Fuel Economy	5	3	15	2	10	1	Average
Simplicity of design	4	1	4	2	8	2	Good
Manufacturing cost	3	1	3	3	9	3	Best
Emissions	2	3	6	1	2		
Flexibility of design	1	2	2	3	3		
Total			48		38		

Figure 13.5: Pugh Chart: Injection Cycle

Combustion Chamber Geometry		Wedge		Bathtub		Pentroof			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score System	
Power Output	6	2	12	1	6	3	18	1	Average
Efficiency	5	2	10	3	15	3	15	2	Good
Emissions	4	3	12	1	4	3	12	3	Best
Cost	3	2	6	3	9	2	6		
Total			40		34		51		

Figure 13.6: Pugh Chart: Combustion Chamber Geometry

Angle		45		52		75		90			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S		
Firing Timing	6	3	18	1	6	2	12	1	6	Score System	
Vibration	5	2	10	2	10	2	10	3	15	1	Average
Size	4	3	12	2	8	2	8	1	4	2	Good
Simplicity of Design	3	1	3	1	3	1	3	3	9	3	Best
Total			43		27		33		34		

Figure 13.7: Pugh Chart: Angle

Thermo Cycle		Otto		Atkinsons		Miller			
Characteristics	Weight (W)	Score (S)	W x S	Score (S)	W x S	Score (S)	W x S		
Complexity	4	3	12	1	4	1	4	Score System	
Efficiency	3	2	6	3	9	2	6	1	Average
Power	2	2	4	1	2	3	6	2	Good
Documentation	1	3	3	1	1	1	1	3	Best
Total			25		16		17		

Figure 13.8: Pugh Chart: Thermodynamic Cycle