



## Conceptual Cylinder Head CAD Project for Assessment

**Mr. Eric Leonhardt, Western Washington University**

I work with primarily undergraduate students in the area of vehicle design and construction. I have been involved with thirty student built vehicles, each named after the school's Viking mascot. We built Viking 32 to demonstrate carbon fiber honeycomb as an impact absorbing material for the Federal Highway Administration. Viking 32 also became the world's first biomethane hybrid as we demonstrated "Cow Power to Horsepower". We used Viking 25 and Viking 32, both hybrid electric vehicles that run on natural gas, to demonstrate technology to utilize Dairy cow derived renewable natural gas (RNG) as a transportation fuel. Viking 40 and Viking 45 were built to demonstrate lower cost and higher rate composite production processes for the body and monocoque chassis. Hybrid electric Viking 45 participated in the Progressive Automotive X Prize as the only U.S. university vehicle and hybrid vehicle to participate in the finals round. The vehicle achieved 172 MPGe for 100 km at 95 km/hr. The latest full size vehicle is Lyn Okse (Norwegian for "Lightning Ox"), a 1/4 ton electric pick-up truck with 300 mm of off-road ground clearance for campus grounds crews. The vehicle demonstrates the future of lower cost, more powerful electric motors and battery packs.

The Vehicle Research Institute operates as a technology development center that provides undergraduate students with opportunities for career specific training and research. Funding comes from a variety of sources including the Department of Energy, Department of Transportation, EPA, Paul Allen Family Foundation, BP, Washington State Department of Agriculture, Whatcom Public Utility District, Boeing, Janicki Industries, Northwest Porsche Club, Danner Corp. and Fluke. Past supporters include the Department of Defense, Fuji Heavy Industries (Subaru), PACCAR, Mazda, Ford, Bentley (parent company Audi), Alcoa, Conoco-Phillips, CNG Fuels of Canada, Chrysler, and DaimlerChrysler.

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## Abstract

A cylinder head design project is used to assess 3D prismatic modeling skills during a capstone course sequence. The capstone course sequence features a large, multi-year project that may not have 3D modeling components of similar complexity for all students. The project ensures that all students are assessed using a similar project. The geometric model is designed to support the creation of a physical prototype that may be used for airflow development models. Models are printed using filament deposition printing techniques. The solid model also supports the use of virtual airflow analysis using computational fluid dynamics. The project progressed from being primarily geometry creation focused to using parametric design tables from an exterior spreadsheet. During one capstone series, students designed and cast engine blocks in addition to prototype cylinder heads for a natural gas long haul trucking and marine application. Students also use engine simulation tools to predict the performance of the conceptual engine. The cylinder head design project allows program graduates to be assessed and to ensure that their CAD skills are marketable as they graduate.

## Introduction

A challenge with a complex, multi-year capstone design project is that it offers different types of design and development experiences as the project matures to completion. The type and level of 3D modeling experience during the conceptual design phase is different than the computer aided design (CAD) tools used during manufacturing and testing phases. Systems assigned to students have different requirements for design and integration as the project matures. Students involved early in the design of an electric vehicle were focused on overall chassis, exterior body design, and suspension design studies. The first cohort involved in the vehicle design project had a primary focus to meet with end users and stakeholders to determine requirements, develop budgets, and submit a grant proposal to secure funding. These students utilized computer aided design tools significantly for conceptual 3D modeling. Later cohorts became more focused on fabrication and construction of the vehicle chassis and testing the electric drivetrain. Each cohort became focused on different systems within the project and each system had a greater or lesser need for a significant 3D modeling experience. As a result, a common 3D modeling experience was added so that the ability of senior students to perform 3D modeling could be assessed.

This paper describes the specific steps used in a 3D prismatic modeling assessment exercise utilized for a capstone design course series, so that other instructors might utilize or modify the CAD exercise. Student learning outcomes—whether students were able to complete the design exercise and what challenges they faced—were tracked for a limited number of courses. Other modeling assessment approaches have looked at tracking student's spatial visualization development [1], using Concept Inventory approaches to 3D modeling [2], or other types of 3D modeling such as surface and free-form modeling [3]. The 3D prismatic modeling assessment experience outlined in this paper involves the conceptual design of a cylinder head for a four-valve, pent-roof spark ignition engine. The modeling approach was briefly used to assess the ability of prospective faculty hires to think about 3D modeling, independent of a particular CAD system. The author adapted the process for students for a course focused on internal combustion design and testing. Later, the process was used within a senior project. The senior project

required the design of a cylinder head to help study the benefits of a natural gas, spark ignition engine for long haul trucks and high-speed marine applications [4].

### Detailed Project Steps

The entire assignment takes three to four weeks, so students complete the task while working outside scheduled class time. The process is broken into three segments. During the first segment, students generate the basic geometry of the combustion chamber. The second segment involves building the intake and exhaust ports following area scheduling guidelines for port flow development. Students use an initial approach featuring port cross sections that are round. Later, they create port cross sections that allow more control over detailed port parameters. More recently a third segment was added to drive the cylinder head parameters and port flow areas from an external spreadsheet.

### Phase One

During phase one, students participate in discussions on cylinder head design and port flow over the course of six one-hour course segments. Key parameters, identified in [5], are included valve angle, intake and exhaust valve size, valve seat geometric design, and port area scheduling. An additional three hours per week are dedicated to the initial design process with students actively generating CAD geometry.

Students are provided handouts containing data on intake and exhaust valve dimensions, valve seat dimensions, and valve spring dimensions. Table 1 below shows representative data. They are also able to utilize their own data for a different engine size. Hand drawn, isometric sketches of the various steps of the process are provided. A series of screen shots, displayed below, are available to the students as well.

Table 1. Sample component data provided to students [6]

Component	Diameter, mm	Length, mm	Margin, mm
Intake Valve Big Block P/N 14011076	55.626	132.59	0.51
Intake Valve Seat Big Block P/N 14011076	58.166	6.35 Depth	
Exhaust Valve Big Block P/N 14011076	47.752	135.9	1.02
Exhaust Valve Seat Big Block P/N 14011076	49.4	6.35 Depth	
Valve Spring P/N 3916164	37.77	47.752 @ 516 N installed height	

### Phase One: Detailed Modeling Process

The specific steps begin with a block with the longest dimension sized to accommodate the cylinder bore diameter, water jacket, and cylinder head fasteners. Initially this dimension can be sized to roughly 110% of the target bore size and then adjusted later as detailed design work and calculations are completed. Figure 1. shows an example. The width dimension is roughly 110% of the half bore. For this project, the bore sizes were selected based on available cylinder sleeves and piston ring packages that were then machined for the desired stroke and deck height of the prototype engine. Both 137.2 mm and ~145 mm bore diameters were modeled to accommodate the available valves and sleeves. The height isn't critical at this stage, although it can be used to generate a rough water cooling box around the intake and exhaust ports. This approach is suitable for a flow box model to position valves and ports. More detail work would be required to develop a state of the art cooling system.

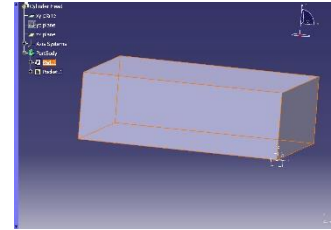


Figure 2. Initial Block

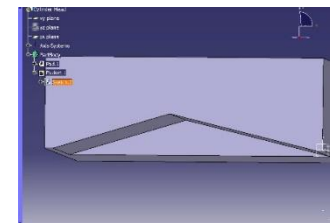


Figure 1. Pentroof Combustion Chamber

One face of the block represents a mirror plane that bisects the cylinder head between the adjacent intake and exhaust valves. This approach uses symmetry to reduce design time so that the intake and exhaust port are each modeled once. The next step involves cutting a triangular projection or relief into the mirror plane. This represents the pentroof surfaces of the combustion chamber. Figure 2. features a 29 degree included valve angle with a 16 degree angle from horizontal for the intake valve surface and a 13 degree angle from horizontal for the exhaust valve surface.

A projection of the cylinder bore is now extruded onto the deck face of the cylinder head. The projection maybe constrained to the edges of the block so that changes in the bore size parameter can propagate through the model without requiring a complete reconstruction. Figure 3. and 4. show the sketch outline and the resulting extruded geometry.



Figure 3. Project Bore Outline

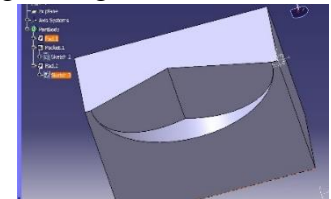


Figure 4. Combustion Chamber Half

The area above the cylinder head deck may now be removed. This action determines the thickness of the cylinder head in Figure 5.

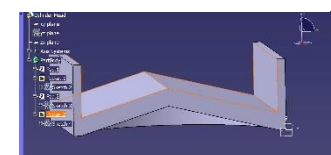


Figure 5. Cylinder Head Water Jacket

## Phase Two: Port Modeling

The next steps involve setting up the port geometry. Holes for the intake and exhaust valve seats are now positioned on the roof of the combustion chamber as shown in Figure 6. These holes are positioned away from the cylinder wall edge roughly 3-4% of the original bore diameter for which the valves were designed. This is to reduce the potential for the cylinder wall to shroud or cause asymmetric flow around the opened valve. This is a starting point and may need to be adjusted after flow bench testing or computational fluid dynamics analysis. An additional area of concern is between the exhaust valves where the cylinder head will face significant stress, heat, and a corresponding drop in yield strength. This is a common

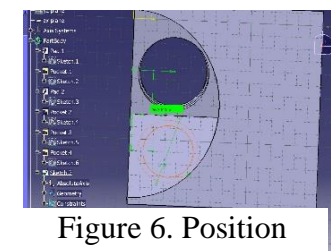


Figure 6. Position Valve Seats

location for cracks to form as discussed in [7] and [8]. The distance between the exhaust valve seat and the mirror plane maybe as large as feasible without shrouding the valve. Since students are provided a variety of valve sizes, they decide which valve package and bore size they wish to design and validate whether the chosen bore size will accommodate their chosen valve sizes.

A series of temporary construction lines are positioned to represent the valve spring diameter, location, and the valve length. The purpose of the valve spring cross section is to identify how close the intake and exhaust ports come to the valve spring seat. This is limited by the material thickness between the valve seat and the port after machining the port and the valve seat. The valve spring cross section represents the closest tangent of the valve spring to the port geometry.

The valve length line originates at the center of the valve seat diameter on the combustion chamber face as in Figure 7. A plane is created that contains the valve centerline and is angled from the mirror plane that bisects the combustion chamber. This plane is used to control how the two intake and exhaust ports join into the intake and exhaust manifolds. A five- or ten-degree angle is a starting point for the port design. The port centerline and valve spring cross section are then drawn on this plane. This plane is most clearly represented below in Figure 7. towards the lower left hand corner.

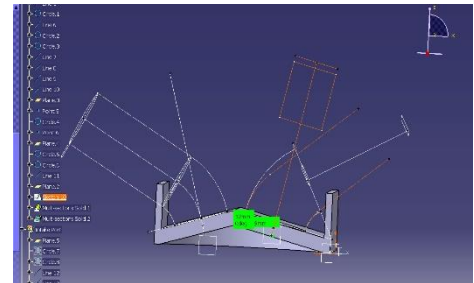


Figure 7. Temporary Construction Lines on Port Centerline Plane

A rectangle representing the cross section of the installed height of the valve spring is drawn from the tip of the valve. The installed height is a compressed spring state when the valve is in the closed position. Allowances are made for the valve retaining method as this alters the spring location. This may not be necessary for the construction of a flow box model.

Construction lines for the port geometry begin with a three-point arc, drawn from the water jacket side at the center of the valve seat. This arc represents the centerline of port geometry. A line drawn tangent to and connecting the arc end represents the remaining centerline of the port. This apparently simple approach seems consistent with cross sections of existing racing engine cylinder heads within our possession and with discussions of CAD designers for other four valve racing cylinder head port designs. Later planes will be drawn perpendicular to both end points of the arc and the line segment with an additional plane perpendicular and along the line segment.

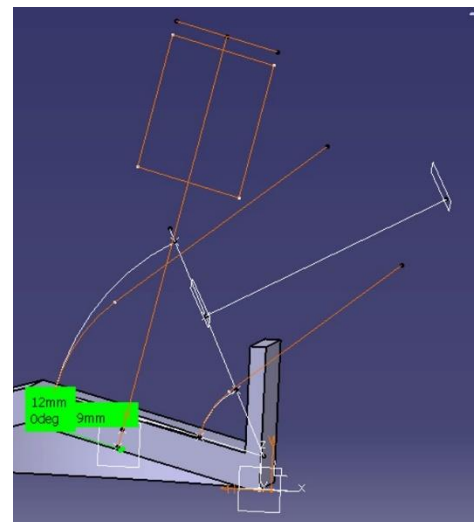


Figure 8. Valve Spring Clearance with Two Prospective Port Outlines

After completing the port centerline, lines and arcs representing the port wall are offset from the port centerline. Figure 8. shows the valve spring cross section with two versions of the cross section of port geometry. These construction lines are constrained to the port centerline. This allows the minimum distance between the outer port and the spring cross section to be adjusted by varying the arc length and radius of the arc at the port center line. Intake port airflow benefits from having the straightest possible port, especially for naturally aspirated designs. A compromise must be reached between the valve length, valve spring diameter, and the intake port angle. Longer intake valves allow the valve spring to move away from the valve seat and therefore a straighter intake path at the expense of valve mass and therefore the maximum engine speed. The offset construction lines representing the port cross section are initially sized to represent 100% of the valve seat area—the area through which all intake or exhaust flows.

Once the port centerline is established, sketches of the inner and outer port are created on planes perpendicular to the port centerline. The planes are established at the beginning of the centerline arc, at the junction of the arc and straight line and at the end of the port as pictured in Figure 9 above. Additional planes may be placed near the center of the arc length and along the straight portion of the port centerline.

For the initial portion of port design, the ports are circular in cross section. This enables students to achieve a completed model more quickly and reduces errors in the model creation process.

Later during the process, the port designs are improved by using four arc segments for each cross section. Within CATIA V5, students are encouraged to generate the arcs from the same relative starting location on each plane, at say the top of the arc at 0 degrees, and then to repeat the arc creation around the circle. At each plane this process is repeated with the same relative arc starting position. The outer port geometry is generated to follow the centerline spline and incorporate the outer cross sections of port geometry at each plane as shown in Figure 10. In CATIA V5 a Multi-Section Solid command is used. Ideally, the command can be controlled so that the generated solid follows the vertex points from one arc cross section to the next arc cross section on the adjacent plane along the port centerline without twisting the solid geometry. In practice it is more reliable to generate each port cross section from the same relative arc starting point for each plane. It is also important to have the same number of active vertices on each sketch being joined. If one port cross section is generated with four arcs, all of them should be generated with four arcs. The software is capable of creating solids from multiple cross sections with different numbers of vertices, but the process is not always repeatable or reliable. Figure 10. above shows the outer port geometry. Figure 11. shows

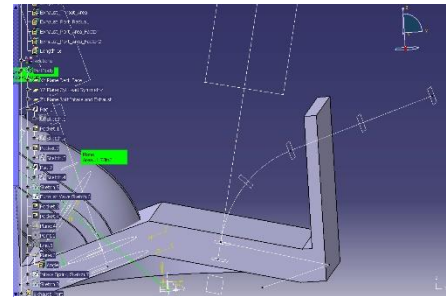


Figure 9. Port Centerline and Planar Cross Sections

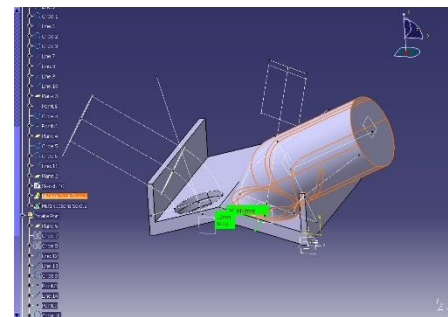


Figure 10. Outer Port

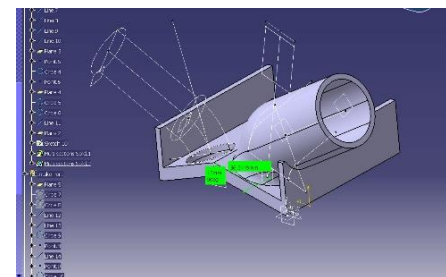


Figure 11. Boolean Subtraction for Port



a Boolean subtraction performed to create the inner port geometry. By using cross sections to specify the geometry of both the inner and outer surface, the port thickness is carefully controlled. Students attempting other methods to generate the port geometry may find that inconsistent surfaces are generated. The process for creating the intake port are repeated for the exhaust port. During engine operation, the higher pressure exhaust is able to follow a curve with much less impact on port flow. Spacing between the exhaust spring perch and exhaust port may be more dependent on structural and cooling issues.

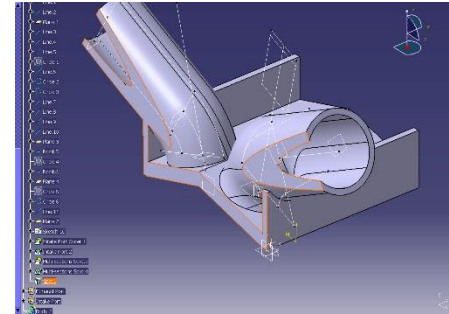


Figure 12. Slicing Cylinder Head at Mirror Plane

Because the port centerline is angled to converge on the centerline of the combustion chamber mirror plane, the ports must be sliced before the product is mirrored. Other geometry, such as spring perch, may be added as well before the half-model is mirrored. Figure 12. displays the sliced geometry. Students often mirror the combustion chamber without slicing the model at the mirror plane.

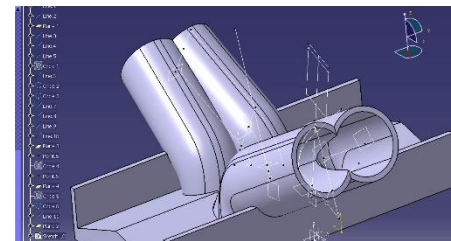


Figure 13. Mirror Geometry for Complete Combustion Chamber

The final step in the first segment of the CAD design is to mirror the combustion chamber half about the center of the combustion chamber mirror plane. The result is depicted in Figure 13.

During the second phase of the project, students focus on creating port cross sections that allow greater control over the final geometry. This involves creating the port cross sections using four arcs for each corner of a rectangular port, separated by four line segments as highlighted in Figure 14. Near the valve seat, the port begins with a circular cross section using eight vertices so that the number of vertices remains the same throughout the solid. In CATIA V5, the Multi Section Solid command is used to link the cross sections while following the port centerline to generate an exterior port solid. The port inlet is created by a Boolean operation or in CATIA V5 a Multi Section Solid Removal command. The advantage of this process is that port height, width, corner radii, and wall thickness maybe altered to control cross sectional area and improve flow around a corner.



Figure 14. Port Cross Section from Four Arcs and Line Segments

Students manage the area of each cross section. One solution uses interior port cross sections to generate solids. The solids may be measured for area. This is depicted in Figure 15. Initially, the valve seat area sets the 100% area value. For our designs the student's target a 100 m/s flow rate at the valve seat opening. As

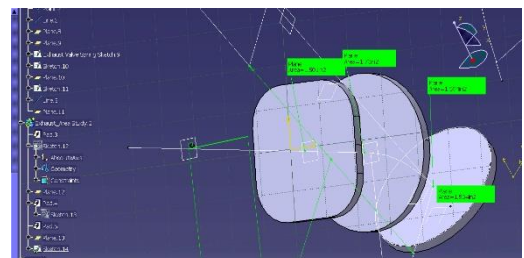


Figure 15. Port Area Measurement

the port transitions from a round opening to a rectangular opening at the end of the centerline arc, the port cross section may grow to 115% of the valve seat opening area. At some point along the straight portion of the port centerline, the port area decreases down to the 100% area value. At the port opening on the intake manifold interface, the port cross section area is dropped to 90% of the valve seat opening area. The exact position of the 115% area and 100% areas are to be confirmed by altering the model and testing the ports on a flow bench. An example port is displayed in Figure 16.

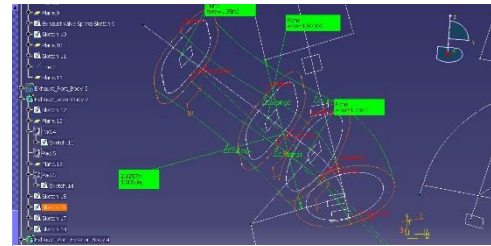


Figure 16. Port Cross Sections Featuring Coupling Between Vertices

### Phase Three: External Parametric Modeling Tables

The final segment of this CAD design project involves controlling the parameters of the cylinder head design using an external spreadsheet. Parameters controlled include bore, included valve angle, wall thickness, and port geometry. Students developed parametric controls to manage the port cross-section areas. Table 2. below controlled the port geometry shown in Figure. 17. These were based on the valve seat opening set at 100% and then varying the cross-section areas as a fraction of the valve seat area. The author performed demonstrations of design tables on unrelated components. Later, students developed design table presentations that were provided to the peer group and subsequent classes This process allowed students to demonstrate their ability to learn new skills.

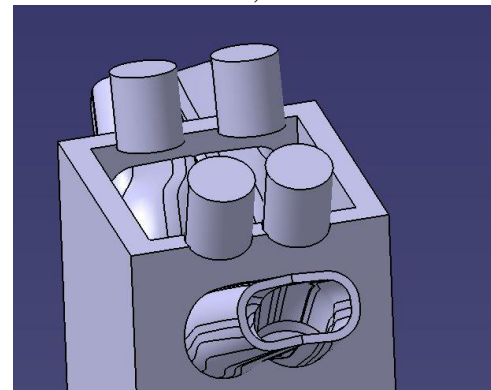


Figure 17. Sample Port Geometry Driven by External Spreadsheet

Table 2. Port Cross-Section Areas Driven by External Spreadsheet

Exhaust Port	Area %	Shape	Fillet radii (in)	Area Actual (in^2)	Valve Radius (in)	Valve Dia. (in)	Aspect Ratio w/h	Port Height (in)	Port Width (in)
1	100	circle		3.801	1.1	2.2			
2	115	circle		4.372	1.18	2.359			
3	100	square	0.5	3.801			1.2	1.829	2.195
4	90	square	0.5	3.421			1.5	1.557	2.335

### Student Learning Outcomes

The rubric for the cylinder head CAD design project changed significantly during its use and was less detailed than rubrics used for fundamental 3D modeling courses [9]. When used for a course focused on internal combustion engine design and operation, students were expected to model the cylinder head geometry. Meeting expectations meant that the basic geometry was created using parameters. Exceeding expectations meant that the geometry was more complete



or more detailed. Students created support material for valve springs, sometimes they modeled the valve springs in three dimensions, and they might have generated a 3D prismatic model with cylinder heads designed for V-8 or V-12 version of the engine.

As the project was applied to the capstone course sequence, the minimum standard changed to demand a less detailed 3D model, while more emphasis was placed on model structure and how the model was parameterized. Exceeding expectations meant driving the port geometry with an external spreadsheet. Results of these changes are displayed in Table 3. below.

Table 3. Results of Changing Rubrics: Number of Students Meeting Expectations

	# of Students	Needs Improvement	Meets Expectations	Meets Expectations	Exceeds Expectations
Rubric for Capstone Course Series		CAD Model Incomplete	Complete Parametric CAD Model	Exterior Spreadsheet Attempted (Model Update May Not Function)	Exterior Spreadsheet Controls Parametric CAD Model
2019-2020	7				100%
2017-2018	11		27.3%	27.3%	45.5%
		Needs Improvement		Meets Expectations	Exceeds Expectations
Rubric for Internal Combustion Engine Course		CAD Model features round ports and a pentroof combustion chamber. Valve spring support is non-existent. Insufficient detail.		CAD model could be FDM printed and used for flow bench testing	Multiple cylinders modeled, details for valve seat and guides, cylinder head bolt pattern
Spring 2014	9	2		2	5
Spring 2013	15*	2		8	2
Spring 2012	20	4		9	7
Fall 2011	24	2		8	14

\*Three models were incomplete; one due to data loss and two were well below standard

The first students to participate in the year-long capstone project were in academic years 2014-2015 and 2015-2016. Due to significant changes in program course sequence and content, these students participated in the cylinder head design project while they were taking an internal combustion engine design course. They are captured in the Spring 2012-2014 data. The 2014-2015 cohort designed, machined, and cast cylinder liners and engine blocks for a V-twin test engine. The 2015-2016 students marked the first cohort who worked on the multi-year electric vehicle project. Since that cohort, the cylinder head model project has been used twice.

The number of students participating in the CAD project since the multi-year, capstone project is rather low to draw quantitative conclusions from the data. The author suspects that the primary improvement from 2017-2018 to 2019-2020, is that better materials were available to explain the Design Table process within CATIA V5. New material was developed following the 2017-2018 experience.

Prior to the 2014-2015 year, the program added a competitive entry process to reduce the teaching load impact of the program on the department. This impacted the program by cutting the number of entered students from roughly 20-24 down to 12. Since part of the selection process was based on academic grades, the mix of students in the program changed. A small snap shot of this effect may be seen in the data where prior to 2015 data shows a certain percentage of substandard or near to substandard work. In the Spring 2013 data, almost a third of the class has low outcomes. Following the move to a competitive program entry process, the below standard performers were essentially eliminated from the program.

Another significant change in the assessment data is that prior to 2014-2015, students working on this CAD project were most likely third year students and might possibly be second year students in the program. After the addition of the year-long capstone project, all of the students were either fourth year or beyond. The combination of the changing student mix and that students used the 3D modeling project later in their academic career helps to explain why project outcomes improved, even though the technical challenge of the project increase. None of the models after 2014-2015 were below standard.

Comments made about the project by students from 2019-2020 are included below:

*“Modeling a cylinder head for this project was very different than most CAD modeling I had done previously. While many projects are designed to be a finished product, the design intent of the cylinder head was that it would be modified extensively to achieve the best flow. Using Catia's parameters, and referencing them to an external spreadsheet, allowed us to easily change most aspects of the head geometry quickly and easily. This is something that would have been laborious using the methods taught in the introductory CAD class.”*

*“Using multi-section solids, we were able to easily alter much of the port geometry. The entry angle, and split angle were altered from our spreadsheet, and it is easy to see how they can effect flow. I also used multi-section solids to control area scheduling of the ports. I designed the sketches to have certain ratios of the valve area, in order to alter the speed of the intake air as it went through bends and around obstacles. This was a new concept for me, as previously I had assumed that the area should remain constant throughout the head.”*

*“For the first question I wasn't sure if it's asking how it demonstrated \*your\* or my own CAD skills. To address both however, my own experience in CAD made me confident and knowledgeable enough to take the project on, while still have a few things about multi-section solids to figure out. Without your demonstrations and help though, I might not have figured everything out nearly as well.”*

*“This project thoroughly challenged my skills as shaping the ports in three dimensions really took a lot of brainpower to get right. This really had me learn how hard it is to balance ideal*

*port design with the packaging of springs and valves, not to mention water passages and holes for fasteners.”*

*“This project was my real first use of editable parameters in CATIA, which undoubtedly is going to be useful. I also got a better sense of how to design things in such a way that they won't all break the second I change a little detail up in the design tree.”*

*“I had a basic understanding of port flow characteristics, but had no idea about tapering the cross-sectional area towards the valve or how important the shape of the bottom edge of the runner meeting the valve seat was. Also, how the shape is ideally a D sort of shape and how often car manufacturers throw that out of the window (looking at you, LS cathedral-port heads).”*

Student comments reflect improvements in student understanding of how to structure a parametric model, how to develop geometry using cross sections that change through out their length, and how to drive parametric models using external spreadsheets. The comments also reflect a growth in understanding of cylinder head design. Some of the cylinder head design knowledge was assessed separately in short answer quiz questions, outside the focus of this paper. The use of external spreadsheets to drive the parametric design seems a useful addition to the project. This provided an additional challenge to the last two cohorts and helped keep them engaged in the modeling process.

The last comment above provided an opportunity to talk with students about General Motors-Chevrolet cathedral port LS engines and how these engines still follow the best practice design guidelines provided to the students. This comment provides a hint at an additional benefit of the assessment project. Course objectives for both the capstone design project and the earlier courses featuring internal combustion engine design shared some internal combustion engine knowledge objectives. By requiring students to 3D model conceptual cylinder heads, they became more engaged in the cylinder head design best practices and became more knowledgeable about engine development issues. This is reflected in the open-ended quiz questions that are outside the intended scope of this paper. The broader take-home lesson is that the whatever 3D modeling assessment is performed, ideally it can be tied to other subject matter content that enables students to develop their own knowledge through practice.

Although our graduates may not design cylinder heads, some of them are involved in engine development, port flow development, and the manufacturing of engine components, including cylinder heads. The parametric design skills are also applicable to our graduates involved in electric motor and drivetrain development. This project may also be valuable for programs that feature 3D modeling training and have students broadly interested in internal combustion engine design.

## **Conclusion**

A cylinder head 3D modeling project was implemented in a capstone project course featuring a multi-year, multiple-system design project. The development cycle of the project meant that students from year to year were not able to have a consistent 3D modeling assessment process for their final courses. In addition, the multiple system requirement of the project meant that

students within a cohort had significantly different 3D modeling experiences. The cylinder head design project provides students with a more consistent experience that is easier to assess. The project has also been useful to grow student's capabilities of analysis and 3D modeling proficiency. A challenge that is not well addressed here is considering whether this 3D modeling approach is too prescriptive and not suited to a senior level design project. On the other hand, students are using higher level skills to determine how to parameterize the model, how to make design choices, and in learning a new skill for spreadsheet driven design. The author would like to incorporate a functional water cooling jacket that could be used to demonstrate student's understanding of thermodynamics. The author would also like to tie the port flow development back into flow coefficients derived from flow bench data and then modeled in the computational fluid dynamics software. Ideally the paper provides other instructors an additional 3D modeling project to provide students.

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