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Revisiting Undergraduate Student Engagement Through Hands-On Laboratory Activities

Dr. Claudia M Fajardo, Western Michigan University
Ghazal Rajabikhorasani, Western Michigan University

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Ghazal Rajabikhorasani
Department of Mechanical and Aerospace Engineering
Western Michigan University
Kalamazoo, MI 49009
Email: Ghazal.rajabikhorasani@wmich.edu
Dr. Claudia M. Fajardo
Department of Mechanical and Aerospace Engineering
Western Michigan University
Kalamazoo, MI 49009
Email: claudia.fajardo@wmich.edu

Abstract

Active learning is a key component of effective engineering education. Within Mechanical Engineering curricula, many courses provide rich platforms to engage students through active learning strategies to promote effective retention of theoretical concepts. Hands-on laboratory activities are one example. At Western Michigan University (WMU), the course Introduction to Internal Combustion Engines is offered every fall semester as a (2-3) laboratory elective to upper-level undergraduate students. The laboratory activities, which comprise at least 25% of the overall course grade, require students to conduct experiments, work in teams to analyze and display data, and prepare laboratory reports.

The course is structured such that the internal combustion engine is used as a platform for students to revisit core engineering topics within the field of thermal-fluid sciences from an application perspective, expanding this foundational knowledge through more advanced concepts. Pedagogical challenges include engaging a student population with diverse academic preparation, limited availability of specialized laboratory equipment, and assessing individual student contribution in team-oriented laboratory activities.

This paper describes efforts to strengthen the engagement of undergraduate students in hands-on laboratory activities in connection to an upper-level mechanical engineering course, with the main objectives of increasing critical thinking, knowledge retention, and strengthen the students' ability to connect theory and application. Strategies to manage the pedagogical challenges previously outlined, as well as post-pandemic adjustments, are described. Feedback from a post-assessment survey indicates that the modifications incorporated into the course assisted students with both preparing for the laboratory activities and developing the laboratory reports. Responses also suggest that the changes motivated the students to think more critically about the technical content, promoted accountability and more effective time management.

Introduction

Laboratories are an integral and essential component of engineering education [1,2,3]. The Mechanical Engineering program at Western Michigan University (WMU) requires undergraduate students to enroll in five elective courses, two of which must satisfy a laboratory requirement. The course Internal Combustion Engines I (IC engines) is a three-credit laboratory elective offered in the fall semesters (September through December) with Multivariate Calculus and Matrix Algebra, Thermodynamics I, and Dynamics as pre-requisites. In addition, it serves as a pre-requisite to Engine Design and satisfies a requirement for students seeking to earn a Concentration in Automotive within the Mechanical Engineering program.

IC engines introduces students to the operating principles of internal combustion engines. The engine is used as a platform for students to see theoretical concepts learned in prior courses at work in a practical device. Students who enroll in this course bring various levels of background knowledge and practical experience. *Figure 1* shows responses to two questions from a survey administered at the beginning of three consecutive semesters. Question 1 (Q1): What is your *primary* reason for taking this course? and Question 2 (Q2): Do you perform engine-related vehicle maintenance? Response rates were 70%, 82%, and 81% in 2021, 2022, and 2023, respectively. Most of the students (2021: 95%, 2022: 63% and 2023: 69%) responded choosing IC Engines over other elective courses due to interest in the subject, whereas the remaining students enrolled mainly based on schedule constraints and the need to satisfy a laboratory elective. At least half of the students reported having some experience with engine related maintenance (2021: 57%, 2022: 63%, and 2023: 50%), which also means a large portion of the students had no practical experience working with internal combustion engines at the time of enrollment. The first few weeks of the course are, therefore, devoted to introducing the fundamental function and key components of internal combustion engines to establish a common baseline and rigorous framework that benefits all students.

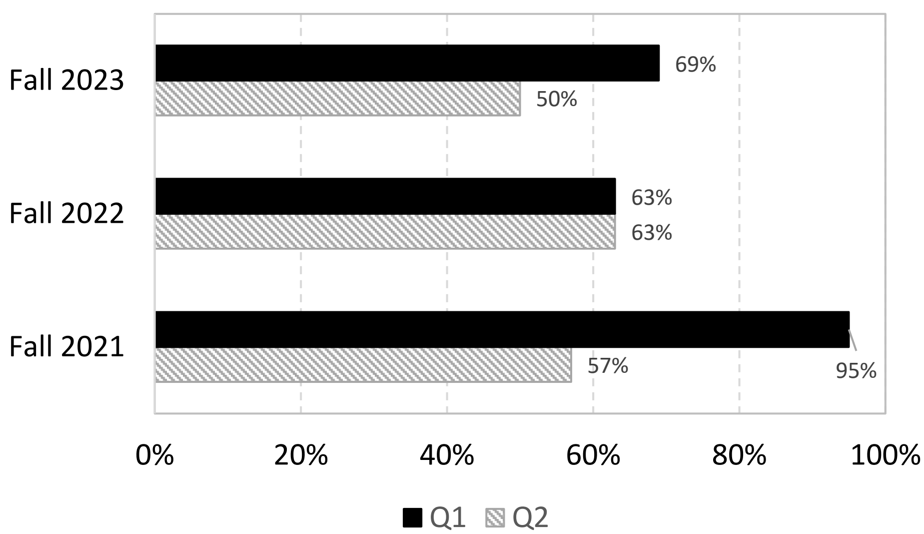

Figure 1: Student responses to two survey questions (Q1 and Q2) in three consecutive academic semesters.

The laboratory activities play a key role enabling the students to understand the connection between theory and application and to appreciate how seemingly disconnected disciplines, which are covered in separate courses, are all needed to analyze a complex engineering system. These activities are structured such that students work collaboratively in teams as they carry out the experiments, process and analyze the data, and develop the laboratory report.

The COVID-19 pandemic forced a switch to online instruction in the IC Engines course in the Fall of 2020. Lectures and laboratories were offered through virtual platforms and assessments were mainly conducted online. For IC Engines, online quizzes, videos of the laboratory activities, and short learning modules on various IC engine topics were created to supplement synchronous lectures.

Although remote and virtual laboratory initiatives have proven at least moderately effective in many disciplines [4-8], strong student interest in physical IC engine laboratories, along with the challenges of implementing virtual or remote options specific to this course, prompted a return to in-person laboratory instruction as soon as it was possible. During the Fall 2021, 2022, and 2023 semesters, the course has been offered in hybrid format, consisting of online synchronous lectures with in-person laboratories. Many of the materials developed for online instruction during the pandemic have been retained, most notably instructor-developed learning (video) modules and online assessment tools. Some of these have been repurposed to complement laboratory instruction and motivate student engagement in the course.

In the Fall 2022 and 2023 semesters, individual and team-focused activities were incorporated into the laboratory requirements. The main goals of this paper are to describe these activities and assess their effectiveness in enhancing student preparation for the physical laboratories and also for developing technically strong laboratory reports. Both challenge students to think critically and connect theory and application as they analyze the experimental results.

Background

This section provides background information about the IC Engines laboratories and describes practices common to the Fall 2021, 2022, and 2023 semesters.

Team Composition

Each team is capped at four students randomly selected from the laboratory section rosters. The scope and anticipated workload for each activity is tailored to this team size. This approach aims to prevent a demonstration laboratory environment, promoting instead a small group setting where students are encouraged to "turn the knobs." As *Figure 2* shows, on average 25 students have taken the course each semester between 2007 and 2023. The average over the past nine years is slightly higher at 30. Two laboratory sections with three to four teams each have typically been scheduled to accommodate enrollment while maintaining the per team cap.

Number of Laboratory Activities

Approximately four laboratory activities are assigned during the semester. Each requires a team-developed laboratory report incorporating quantitative analysis and in-depth explanations connecting the laboratory observations to the theory presented and illustrated in-class through textbook examples. This is a quality over quantity approach which also considers practical limitations. First, there are no multiples pieces of the same equipment for each laboratory. This, coupled with the need to allow sufficient time for each experiment, imposes a scheduling constraint over the 15-week period. Second, there are two university-wide breaks within the semester, which create unbalance between the two laboratory sections. Third, to establish a common baseline, effectively review background material, and introduce new topics prior to the laboratory activities, the laboratory schedule begins approximately three weeks into the semester.

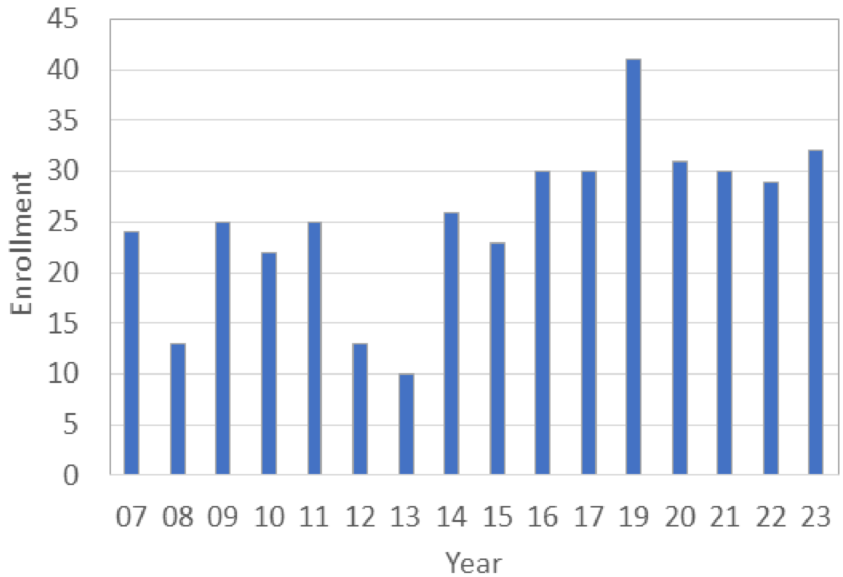

Figure 2: Student enrollment in the Internal Combustion Engine course offered at Western Michigan University as part of the Mechanical Engineering curriculum.

A representative laboratory sequence is shown in *Table 1*. The third column shows a condensed list of topics incorporated into the laboratory activities. Students have been exposed to many of these topics in pre-engineering and pre-requisite courses. The laboratory experience re-introduces these topics from a practical perspective and requires students to reason through challenges not encountered as they solve ideal, textbook problems (e.g., working with discrete data sets and how to handle extraneous data). The majority of the topics discussed in the course require a strong foundation in thermal-fluid disciplines.

Table 1: Sample laboratory sequence for the Internal Combustion Engine course offered at WMU as part of the Mechanical Engineering curriculum. CFR: collaborative fuel research.

Lab	Title	Topics	Hardware
0	Laboratory Safety and Report Preparation Instructions	Technical writing, report structure, data processing and visualization techniques	
1	Analysis of Brake Performance Parameters	Torque-work-power relationships Friction and efficiency	Chassis Dynamometer
2	Effect of Spark Timing on the Output Work and Cyclic Variability of an Internal Combustion Engine	Thermodynamic Cycles and Diagrams Numerical Integration Statistical Analysis	Natural gas CFR engine
3	Intake Flow Analysis in a Spark-Ignition Engine	Pressure (Manometers) Discharge/Flow Coefficients Mass and Volumetric Flow Rates	Flow bench
4	Effect of Design and Operating Parameters on Engine Knock	Combustion Fundamentals Randomization in Data Acquisition	Liquid fuel CFR engine

The hands-on component is emphasized throughout each laboratory. For example, in the first activity shown in table 1, students drive a vehicle on a chassis dynamometer and are also in charge of data acquisition to generate torque and power curves. In the second and fourth laboratories, students change engine operating parameters (e.g., compression ratio, spark timing, fuel-to-air ratio) to explore cause-and-effect relationships on the output work (laboratory 2) and knock (laboratory 4) of a single-cylinder engine. Laboratory 3 expands on the knowledge students gain in the introductory fluid mechanics course by investigating high-speed intake flows and compressibility effects using a flow bench. Students are tasked with measuring valve dimensions and adjusting the valve lift throughout the experiment, as they gather volumetric flow rate data.

A typical semester schedule is shown in *Table 2* for one of the laboratory sections with a four-team configuration. The first activity (week 3) introduces the students to the laboratory space and equipment, details safety requirements, and presents guidelines and expectations for laboratory reports. Due to equipment and time limitations, not all teams can perform the laboratory activity in the same week. The staggered arrangement shown in the table provides teams with an additional week to complete their reports. The schedule works around Week 12: Thanksgiving Break and Week 14: Senior Design Conference Week. Final exams are administered in Week 15. A more detailed schedule is discussed with the students as part of the introductory laboratory meeting.

Table 2: Sample laboratory schedule for one section of the Internal Combustion Engines course for a four-team arrangement (T: 1-4). Week 12-Thanksgiving Break. Week 14-Senior Design Conference Week.

Week	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Lab 0	T: 1-4											
Lab 1		T: 1,2	T: 3,4									
Lab 2				T: 1,2	T: 3,4							
Lab 3						T: 1,2	T: 3,4					
Lab 4								T: 1,2	T: 3,4			

Laboratory Document and Teaching Assistant

A laboratory document prepared by the instructor is made available to the students approximately a week in advance. This document outlines the objectives of the laboratory activity, background technical information, and connection to the theory discussed in class. Also included are the procedure for conducting the activity and a technical section with questions to *guide* the preparation of the laboratory report. Since a laboratory notebook is not mandatory, students are required to bring a physical copy of the laboratory instruction document and take notes throughout the activity. These notes are collected and count towards the overall grade for each laboratory.

A graduate student laboratory assistant is assigned to the course. The laboratory assistant is trained by the course instructor to operate the equipment and guide the students through the laboratories. Prior to each scheduled activity, the laboratory instructor performs the tasks using the same instructions shared with the students to verify that the equipment is in proper working order and identify any necessary adjustments. This minimizes (although does not eliminate) the risk of having to re-schedule the laboratory due to equipment malfunction, which poses logistical challenges due to the condensed scheduled (see *Table 2*). The laboratory assistant monitors attendance and participation and communicates directly with the course instructor on a regular basis. The same laboratory assistant was assigned to the course in the three semesters evaluated.

Grade Allocation

The laboratories account for 25% percent of the course grade. Each laboratory is worth 100 points and is equally weighed toward the final grade. For each laboratory, students earn a maximum of 25 points for attendance and participation and 75 points for the report. The attendance/participation grade is earned individually, whereas the report score is earned collectively. The reports are graded by the instructor, who provides detailed feedback each team, including points earned on each section of the report and specific areas of improvement to address as they prepare the next submission.

Challenges

While the laboratory schedule allows sufficient time for students to produce strong laboratory reports, especially as the semester progresses, some teams postpone the data analysis and report preparation, effectively negating the time benefit afforded by the "additional" week afforded by the schedule. This procrastination ultimately leads to rushed data analysis and generation of visual aids, weak explanations, and a poorly written report. Second, notwithstanding the benefits of collaboration, in the process of a collectively produced report the work may often end up disproportionately distributed among team members. Third, although the laboratory instructions are made available to students in advance, many rush through the reading at the last minute and consequently arrive with deficient understanding of the "big picture" and laboratory activity requirements. While it could be argued that the onus is on the student to address these time-management problems, a few instructional adjustments were implemented in the Fall 2022 and 2023 semesters to motivate student preparation ahead of the laboratory activities, promote active engagement in the experiments, and mitigate procrastination [9] in report preparation. The ultimate goals are to help students better understand and apply technical concepts, connect theory and application, and strengthen executive function skills that will serve them well as they enter the engineering workforce. Some of the ideas described next were identified during the COViD-19 pandemic.

IC Engine Laboratory Modifications

In the Fall 2021, 2022, and 2023, semesters the IC Engines course has been offered in hybrid format, consisting of online synchronous lectures with in-person laboratories. Capitalizing on the materials developed for online instruction and the need to strengthen the engagement of students in the IC Engine laboratory activities, two main changes were implemented in the Fall 2022 and 2023 semesters:

a) Students are required to watch a short video prepared by the instructor reviewing the background theories prior to attending the laboratory activity. Information from this video and from the laboratory instruction document is used to generate a pre-laboratory quiz assigned to all students prior to attending the laboratory. The quiz is not timed, as the main objective is for the students to re-watch and re-read as many times as needed in preparation for the laboratory.

b) A team *check-in* activity with the instructor is mandatory the week after each laboratory is conducted. To earn credit for this portion, students must arrive on time and be prepared to discuss workload distribution and individual contribution to the overall team effort. Students must also demonstrate significant progress in data analysis and report preparation and be prepared to ask questions and seek clarification on pending items. The objectives of the check-in are to: (1) encourage students' questions and technical discussions within each team in a small group setting for the purposes of addressing the needs of the report *and* solidifying understanding of the material discussed in class and (2) gage and encourage individual contributions toward the team effort and (3) motivate the teams to avoid procrastinating as they prepare the laboratory report.

The 25 points allocated to attendance and participation are specifically distributed as follows: punctual arrival to the laboratory activity (5 points), pre-laboratory quiz (10 points), check-in meeting with the instructor (10 points). As a result of these changes, the final grade in each laboratory may be different for each student even if all attend the laboratory activity and a single report per team is submitted.

Results

The following observations capture the instructor's and teaching assistant's perspective and qualitative feedback from students after the check-in laboratory activities.

1) Most teams came to the check-in activity prepared to show substantial progress in report preparation a week in advance of the due date.
2) The small-group setting often prompted discussions among team members and with the instructor. Many of these discussions stemmed naturally from the questions brought forth by the students as they shared their approach and data analysis with the instructor. Some discussions encompassed IC engine topics of specific interest to the students, even if not directly related to the laboratory.
3) Students used the check-in activity to also seek clarification to content discussed during the online synchronous lectures, especially as these related to the assigned homework problems.
4) The TA reported that students asked more questions during the experiments and that, on average, students arrived better prepared to conduct the experiments.
5) The instructor perceived greater individual accountability to the overall team effort.

A post-assessment survey was administered to the students enrolled in the Fall 2023 IC Engines course to gather feedback on the impact of the pre-laboratory assignment and check-in activity. The response rate was 47%. All survey participants indicated that the *pre-laboratory assignment* was helpful (73.3%) or very helpful (26.7%) in enhancing their readiness for the laboratory experiments. In addition, all survey participants indicated that the *check-in activity* was helpful (13.3%) or very helpful (86.7%) as they developed the laboratory report.

As shown in Figure 3, responses also indicate that students drew the most benefit from the check-in activity in connection with data analysis (100%), generating visuals such as graphs and tables (66.7%) and preparing the report conclusions (53.3%). From time management and accountability perspectives, all students agreed (40%) or strongly agreed (60%) that the check-in activity motivated them to avoid procrastination, whereas 80% indicated that the activity made them more accountable to their team regarding their individual contributions to the overall effort. In addition, 80% of the respondents indicated taking advantage of the check-in time to address other course-related items, such as clarifying lecture notes and asking homework questions.

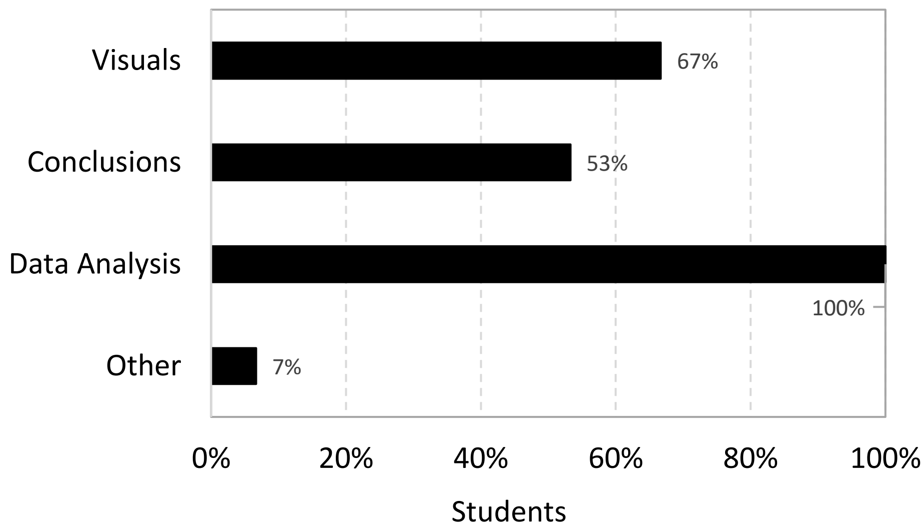

Figure 3: Student responses to the post-assessment survey, indicating portions of the laboratory report where the check-in activity was helpful.

Respondents unanimously indicated that the check-in activity should be kept in future semesters. In the comments section of the survey, some students reported that the check-in activity helped them "think more critically about what each lab was covering", "was very helpful in providing actual feedback," and was also "important in getting a deeper understanding of the laboratory." Also from the survey and as an area of improvement, students suggested for the instructor to be more specific as to what is considered progress toward the final draft of the laboratory report.

Figure 4 shows the average grade for three laboratory reports over the three semesters evaluated. Course enrollments are 30 students (8 teams) in Fall 2021, 29 students (8 teams) in Fall 2022, and 32 students (9 teams) in Fall 2023. The check-in activity was only implemented in the Fall 2022 and Fall 2023 semesters.

A separate analysis considering only the technical section of the report yielded similar results, as the performance in the overall report is highly correlated with quality of the technical section. Given the positive feedback from the post-assessment survey, these results are surprising in that, on average, no significant difference was found in student performance, especially when the standard deviation is considered. This prompted a closer examination at students' background preparation and additional factors prior to enrolling in the IC Engines course.

Since a strong foundation in thermal-fluid sciences is required for the course, an initial evaluation was conducted on the number of students who earned a B or better in Thermodynamics I (a course prerequisite). The aim was to determine whether a significant number of Fall 2021 students had benefited from a stronger foundation in Thermodynamics I at the time of enrollment in IC Engines, consequently mitigating the impact of the small-group check-in laboratory sessions. The results shown in *Figure 5* do not support this hypothesis, as the largest number of students earning a B or better in Thermodynamics I (75%) was found in the Fall of 2023. *Figure 5* also shows the percentage of students earning less than an A in Thermodynamics I who waited at least four semesters after completing the prerequisite to take the IC engines course. For example, in the Fall of 2021, 55% of the students enrolled in the IC Engines course who earned less than an A in Thermodynamics I, waited at least four semesters between Thermodynamics I and IC Engines. This number decreased to approximately 33% and 36% in Fall 2022 and Fall 2023, respectively, indicating that significantly more students in the semesters when the check-in activity was implemented had taken the prerequisite closer to their enrollment in the IC Engines course. This should be a benefit to their performance in IC engines and, therefore, does not suggest the small-group check-in activity providing an advantage in this regard.

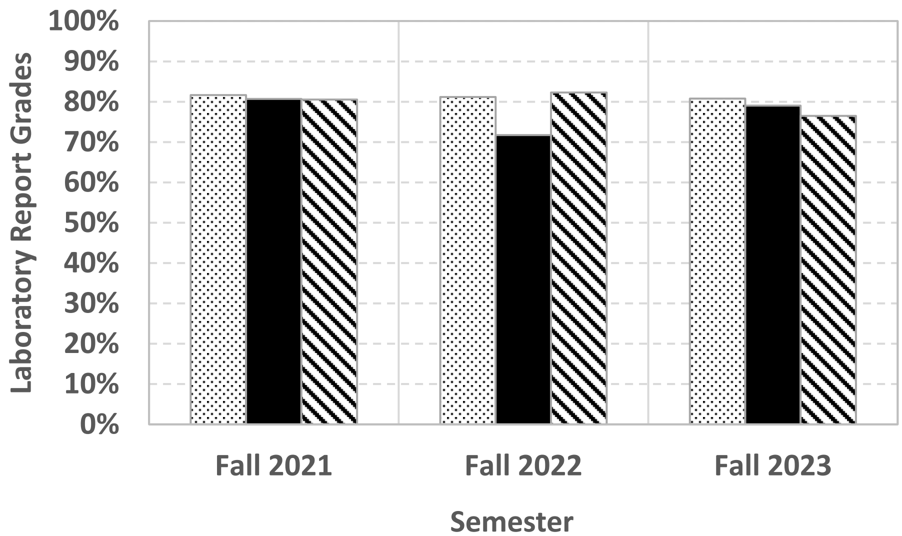

Figure 4: Engineering report grades for the same three laboratory activities. The small-group "check-in" activity with the instructor was only implemented in the Fall of 2022 and 2023.

Upon closer inspection of the data, it was also found that 44% of the students who enrolled in IC Engines in the Fall of 2022 completed Thermodynamics I during the COVID-19 pandemic (Fall 2020). This semester also yields the lower performance in the IC Engine laboratories. In comparison, the numbers are 12% in Fall 2023 and 0% in Fall 2021. Therefore, although the benefit of the in-person check-in laboratory activity cannot be conclusively ascertained based on a statistically significant increase in laboratory scores or Thermodynamics I grades, it is plausible that students who completed pre-requisite topics relevant to the IC engines course during the COVID-19 pandemic benefited from bi-weekly, small-group interactions with peers and the instructor, helping them develop comparatively strong reports. Evaluating the activity over a longer time span may yield additional insights with regards to its value in addressing knowledge gaps in background material, especially post pandemic.

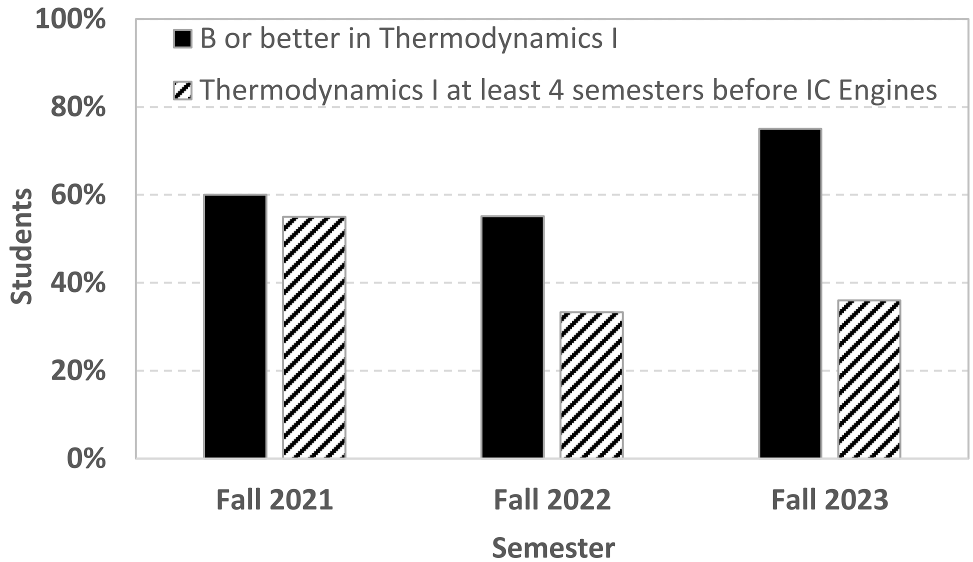

Figure 5: Percentage of students with at least a B in Thermodynamics I and number of semesters lapsed between Thermodynamics I and IC Engines.

Conclusions

This paper describes pedagogical efforts to enhance student engagement in an undergraduate Mechanical Engineering laboratory course. Student performance over three semesters (Falls 2021, 2022 and 2023) was evaluated. The course was offered in hybrid format, consisting of online synchronous lectures and in-person laboratories. In the Falls 2022 and 2023 semesters, two laboratory modifications were implemented: a pre-laboratory activity and an in-person, small-group check-in meeting with the instructor as the teams prepared the written laboratory reports. This was done with the goal of increasing the students' motivation to better prepare ahead of the laboratory activities and strengthen the quality of the submissions.

Qualitatively, the check-in activity implemented in the Fall of 2022 and 2023 motivated students to make substantial progress toward completing the report a week in advance of the due date, which enabled opportunities for small-group discussions and content-related clarifications during the small-group meetings. In the Falls of 2022 and 2023 semesters, students also arrived to the laboratory activities with improved background preparation and readiness to conduct the experiments. A comparison of the average grade in the same three laboratory reports, however, did not reveal a grade improvement in the Fall 2022 and 2023 semesters compared to the baseline, Fall 2021 group. Student performance in a critical pre-requisite course (Thermodynamics I) does not point to a background knowledge gap in the subject that the small-group check-in activity could have helped mitigate in the Fall 2022 and 2023 semesters. It was found however, that 44% and 12% of students enrolled in the IC engines course in the Fall 2022 and 2023 semesters, respectively, completed the pre-requisite during the height of the pandemic, suggesting that these groups might have benefited from the bi-weekly, small-group interactions with peers and the instructor, helping them develop comparatively strong reports. Evaluating the activity over a longer time span may yield additional insights with regards to its value in addressing knowledge gaps and supporting a deeper understanding of course-related content.

Feedback from a post-assessment survey is encouraging. Students indicate that the modifications incorporated into the course helped them prepare for the laboratory activities and think critically through the development of the laboratory reports. Responses also suggest that the changes increased students' accountability to their team in regards to individual contributions to the laboratory report and motivated more effective time management. Overall, the check-in activity and pre-laboratory assignment were both well received by the students and recommended for future semesters.

1. Abdulwahed, M., and Z. K. Nagy. 2009. Applying Kolb's Experiential Learning Cycle for Laboratory Education: *Journal of Engineering Education.* 98 (3): 283–294.
2. Sheppard, S. D., K. Macatangay, A. Colby, and W. M. Sullivan. 2008. Educating Engineers: Designing for the Future of the Field. Book Highlights. Stanford, CA: Wiley.
3. Feisel, L. D., G. D. Peterson, O. Arnas, L. Carter, A. Rosa, and W. Worek. 2002. Learning objectives for engineering education laboratories. Paper presented at the 32nd Annual Frontiers in Education.
4. Koretsky, M., Amatore, D., Barnes, C., and S. Kimura. 2008. Enhancement of Student Learning in Experimental Design Using a Virtual Laboratory: *IEEE Transactions in Education*. 51 (1): 76-85.
5. Nedic, Z., Machotka, J., & Nafalski, A. 2003. Remote Laboratories Versus Virtual and Real Laboratories. In Frontiers in Education Conference, Vol. 1, Westminster, CO, USA. T3E-1eT3E-6.
6. de Jong, T., Linn, M. C., & Zacharia, Z. C. 2013. Physical and Virtual Laboratories in Science and Engineering Education: *Science*. 340. 305e308.
7. Brinson, J. R. 2015. Learning Outcome Achievement in Non-Traditional (Virtual and Remote) versus Traditional (Hands-On) Laboratories: A Review of the Empirical Research: *Computers and Education*. 87: 218-237.
8. Climent-Bellido, M. S., Martinez-Jimenez, P., Pontes-Pedrajas, A., and J. Polo. 2003. Learning in Chemistry with Virtual Laboratories: *Journal of Chemical Education*. 80 (3): 346.
9. Serrano C, Danya M., Lindt, S. F., and P. Williams. 2021. Effects of Positive College Classroom Motivational Environments on Procrastination and Achievement: *Learning Environments Research* 24: 299-313.