Formula SAE as a Capstone Design Course at the U.S. Air Force Academy

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Abstract: The U.S. Air Force Academy (USAFA) uses the intercollegiate Formula SAE (FSAE) competition as a year-long capstone mechanical engineering course project. This student design competition has become the preeminent international test of engineering prowess for students. The authors are currently FSAE capstone team advisors and have previously participated in FSAE as students at military and civilian institutions. The FSAE student design competition and the capstone program in the Department of Engineering Mechanics at USAFA are summarized. Historical performance comparisons are made between the FSAE teams from the only two U.S. military academies that participate in the competition (Air Force and Navy). This paper discusses factors and behaviors related to effective participation in national student competitions and team projects. Best practices, recommendations, and challenges are described from the perspective of the USAFA team advisors. Topics such as resources, schedule, continuity, motivation, grading, and mentoring are individually addressed. Of importance is properly choosing the scope at the beginning of the project to promote student motivation, efficacy, and overall project experience. Two tools are highlighted that may be applied to FSAE and other team projects, one to gauge student motivation, and the other to offer peer feedback to the students. The perspective is from authors in established FSAE team advisory roles with ongoing institutional support, although many of the topics apply to newly formed teams and new faculty advisors as well. The specific recommendations and discussions that are presented are program management centric and thus non-technical.

INTRODUCTION

Academic projects centered on intercollegiate competitions are a challenge for students, and project success depends heavily on student motivation. This paper discusses factors and behaviors related to student motivation and effective participation in collegiate design competitions and provides recommendations for faculty advisors. The perspective of this work is from faculty advisors at the U.S. Air Force Academy (USAFA), whose team attends the Formula SAE competition (FSAE) in Michigan, an annual event so popular that it has a waitlist and is capped to 120 teams. This international engineering design competition organized by the Society of Automotive Engineers (SAE) has grown into organized events in the U.S., Europe, Australia, Japan, and India. In addition to sponsoring much of the event, private companies actively hire and recruit new employees from the competition. FSAE is an engineering design competition where a prototype vehicle must be designed, manufactured, and presented at competition for a series of static events that are evaluated by industry professionals (design judging, costing, marketing presentations, etc.). After passing a safety and technical inspection that verifies rule compliance, the competition also includes timed dynamic driving events where the students compete against each other. Using FSAE as part of an engineering curriculum is a well-accepted practice [1, 2]. The most important factors influencing team success and measurable learned outcomes include resources, schedule, continuity, motivation and mentoring. These factors are discussed individually after a summary of the USAFA FSAE program.

USAFA FSAE PROGRAM

The FSAE team is integrated into the capstone curriculum of the Department of Engineering Mechanics at USAFA, with 8-15 seniors participating in the year-long undergraduate course. The FSAE team is one of multiple capstone team projects, and although the technical projects are different, the underlying curriculum for all the capstone projects is the same. The department’s curriculum includes multiple topics: customer needs, functional decomposition, ideation and concept generation, 6-Hats and Myers-Briggs Type Indicator testing [3], transformational design methodology, prototyping, failure modes and effects analysis, preliminary design reviews, and critical design reviews. The U.S. Air Force Academy (USAFA) has competed in the FSAE competition since 1999, but missed the 2000, 2005, 2008, and 2015 year competitions because the vehicle was not completed in time for the competitions.

Figure 1 shows the recent 2017 and 2018 competition vehicles. The designs usually incorporate a steel alloy tube frame, short-long arm (SLA) individual wheel suspension, pushrod shock actuation, a limited slip differential, an all-terrain vehicle (ATV) or motorcycle engine, and custom engine tuning via a programmable engine control unit. Recent designs have included wings to provide aerodynamic downforce and increased cornering performance.

Figure 1: U.S. Air Force Academy Formula SAE vehicles from 2017 (left) and 2018 (right). The 2017 competition was only the second time since 1999 that the team completed all the competition events. Aerodynamic downforce wings were first incorporated in 2018.

The historical USAFA overall competition results are shown in Fig. 2 compared to the U.S. Naval Academy, which is the only other military academy that participates in the competition. As both academies impose additional military time commitments on their respective students, and have similar environments, this was thought to be the fairest comparison for the USAFA team. USAFA is usually in the bottom half of the competition and averages about 80th in the rankings.

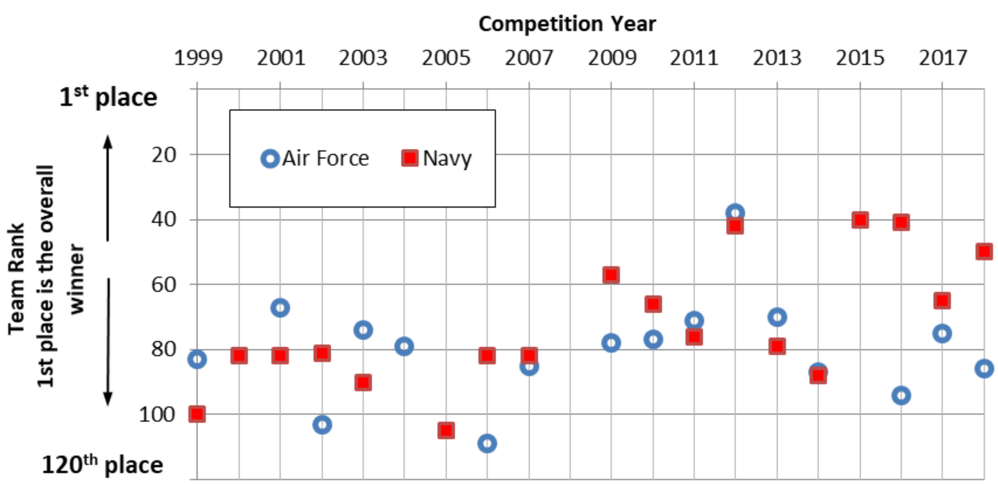

Figure 2: Historic comparison between the U.S. Air Force Academy and the U.S. Naval Academy showing overall Formula SAE team rank by year, from 1999-2018.

Additionally, Table 1 below shows the 2016-2018 scores for the USAFA team by competition category, including both static and dynamics events. USAFA has difficulty completing all the dynamic driving events, especially the 22 km endurance and fuel economy event. Significant points are also lost in the static events. The team arguably has better control and has less risk in maximizing their static event scores, but underperforms because the last minute completion of the vehicle often limits their preparation for the competition judging at the static events. Without a completed and running vehicle the teams will not pass the technical inspection and may not start the dynamic events. It is common for USAFA to start driving the car one to three weeks before the competition begins, which is insufficient time for good reliability testing and driver training. The team also often underestimates the value of driver training for these high-performance automobiles. Only in recent years has the team established a formal simulator and track training program that helps prepare the drivers for the dynamic events.

Table 1: Recent USAFA Formula SAE competition results for all the scored events. Total scoring is out of 1000 points (top ten teams usually score totals above 600 points).

Year	USAFA, Formula SAE results, by year and category									
	Static Events (325 pts)			Dynamic Events (675 pts)						
	Cost Score	Presentation Score	Design Score	Acceleration Score	Skid Pad Score	Autocross Score	Endurance	Economy Score	PENALTY	**Total Score (of 1000 pts)**
Points possible	100	75	150	100	75	125	275	100		**1000**
2018	62	61	50	14	14	17				**219**
2017	65	43	85	47	15	46	25	0	-50	**276**
2016	38	55	60	4	9	41	7			**214**

ADVICE AND RECOMMENDATIONS

Student competitions such as FSAE have many benefits and challenges [4], and are difficult to advise and manage even for established faculty [5]. Resources, schedule, continuity, motivation and mentoring are all important aspects for the FSAE advisor.

Resources

Funding, space, and manufacturing resources must be met in order to enable a successful environment for the team. A practical minimum budget required for the car build (excluding travel) is approximately $15,000-$20,000 depending on how many parts can be reused or donated. Space requirements include at least a welding or work table and floor space for the assembled vehicle. If possible, the work area should be co-located with shop facilities. The USAFA team has a dedicated automotive laboratory with a chassis dyno, flow bench, tube notcher, horizontal band saw, and welding equipment. The student machine shop is in close proximity. A nearby open parking lot without poles, obstructions, or curbs is preferred for vehicle testing. The USAFA team has all of these necessities.

Schedule

One of the most important and difficult tasks for an advisor is to keep the team on schedule. The FSAE project has three distinct phases: design, build, and test. The USAFA team and other comparably ranked teams often run out of time for testing because they are late to finish crucial design and build milestones. It is important to reserve time in the schedule for vehicle testing and driver training. At least four weeks, but preferably six or more weeks should be allotted.

Tools such as Gantt charts and other task planning methods are certainly useful for schedule management, however students typically create these plans for the required academic presentations, but are poor at making continual use of such tools. The initial schedule should be organized around FSAE deliverables (structural equivalency spreadsheet, design report, specifications sheet, cost report, etc.) and around internal university curriculum deliverables. For the USAFA team, the primary academic course deliverables are a generic introductory design project, the preliminary design review (PDR), and the critical design review (CDR), each with their associated engineering analysis reports. Once those minimum elements are scheduled, a useful activity for the team is to critically assess the prior year's vehicle and list needed improvements. Students should then estimate the man hours associated with each potential improvement, and estimate the benefit of each potential improvement. The tasks with the most value for the least effort can then be chosen and prioritized. The team should compare the total number of tasks and total hours required to the hours they have available as part of their class, and are willing to provide outside of class. If the team has an insufficient number of man hours, or the hours are distributed poorly throughout the academic year, the team needs to reduce scope – i.e. simplify the design, use simpler manufacturing, simplify the complexity, and reuse historic parts and solutions. Note that the FSAE competition prohibits "second year" vehicles, thus each year the team must have as a minimum a newly built chassis, but may reuse other parts and assemblies such as suspension components or the engine. Schedule tracking should be emphasized on a regular basis, with tracking of completed weekly tasks and upcoming predicted tasks, and an ongoing tally of individual student performance throughout the year. Students should be encouraged to track their hours spent for various tasks using a spreadsheet or online tool like Toggl (www.toggl.com).

Continuity

The USAFA team formally enrolls only seniors as part of the graded capstone FSAE course, but in the last few years has allowed freshmen through juniors to participate for no credit. The ability to get cadets involved early has been a useful practice as they become much more comfortable with the overall logistics of the project, have a better technical understanding, are better at tool use, and are more likely to undertake leadership roles in subsequent years. Importantly, each year the USAFA team also documents vehicle design data (presentations, drawings) and experiences in "continuity binders" and online files, which are provided to the following year's team. If possible it is important to send younger students to competition as well. Even if not involved directly with the competition vehicle, their time is well spent at the many excellent design seminars or researching the innovative solutions of the other teams. Continuity of the faculty advisor is important as well.

Motivation

Student motivation is particularly important for FSAE teams. Although framed in an academic setting, this real-world project is fraught with challenges that must be overcome throughout the year. The ability to persevere is driven by student motivation, and no amount of advisor motivation is a direct substitute.

Motivation factors that are typical for civilian students are difficult to apply to USAFA cadets. Unlike civilian universities no USAFA cadets can interview or be hired from the competition since they are already committed to military service upon graduation. The cadets have already received their post-graduation Air Force jobs in the fall semester, hence it is natural for students to see less value in their grades and efforts in the following spring semester, which ends right before the competition. Also, the Academy offers many other engaging opportunities for cadets to prioritize over FSAE during their discretionary time (flight training, parachuting, shooting, skiing, etc.).

Indicators of student motivation should be gauged however possible. One method is via a periodic feedback survey where the students are asked to rate the following categories from low to high: supportive environment in the classroom, supportive environment in the department, personal value of their capstone efforts, and their efficacy to produce desired results (where 1 is low and 5 is high, with efficacy having ratings of 1-4). The responses can be shown on a plot similar to that in Chapter 3 of "How Learning Works" [6]. See Figure 3 for examples for how the responses can be used as an indication of individual student motivation. Instead of simply tabulating yes/no responses, the plot from Ambrose et al. [6] has been adapted to offer a range of motivation values, with the numerical values indicating the extent. For the plot, the classroom and department "supportive environment" score would be averaged to provide an indication of overall environment - but the individual values can hint on whether limitations exist at the instructor or the department level. This method is valuable for assessment of team motivation.

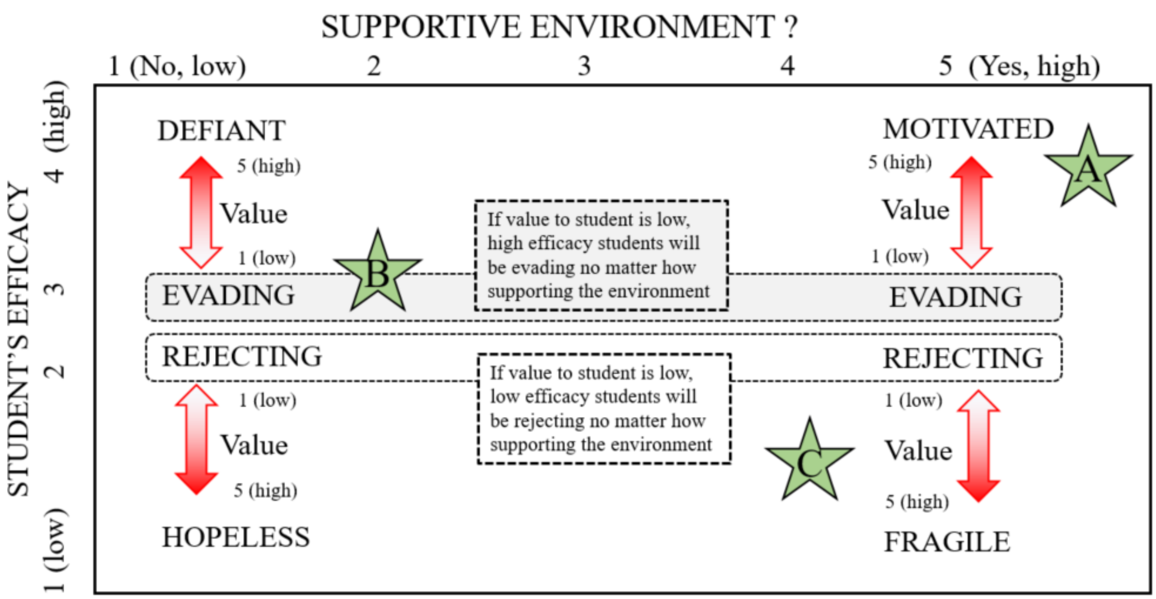

Figure 3: Example motivation feedback results plotted for three hypothetical students shown as stars A, B, and C. Student A, for example, responded that they think the environment is supportive (5), that their efficacy is high (4), and that they are see lots of value (5). Thus, student A falls in the MOTIVATED category. Whereas, student B rated the environment as (2), their efficacy as (3) and the value as poor (1). Student B would be in the EVADING category. Student C would be between the FRAGILE and REJECTING categories. The plot has been adapted from Ambrose et al. [6].

The advisor should seek to provide an environment that creates "Motivated" team members. As Figure 3 shows, the following three factors are needed: (1) students must perceive the environment as supportive, (2) students must see value in their efforts, (3) and the student efficiency must be high. Topic (1) was briefly addressed when discussing funding, space and resources. The environment may also be improved through high team morale that may be boosted through a supportive environment that has fun activities available. Examples may include drive days where existing vehicles are driven, karting track days, simulator nights, and less formal team dinners. The latter two categories, (2) value and (3) efficiency can be controlled by properly scoping the work for the year. If the workload is too high, the perceived efficiency (ratio of accomplishments to expectations) will be low and the students will be "hopeless" or "rejecting". Research has shown that work overload reduces self-efficacy and performance [7]. For scenarios such as FSAE, value is often tied to whether the team succeeds at fielding a car that passes the technical inspection, does well in the static judging, and finishes all the dynamic events. Much of this is associated with the amount of scope the team decides to undertake.

A diminishing returns scenario is proposed in Figure 4, which suggests that if the entire project is properly scoped at the start of the year, the team can sustain high performance at the competition. However, if the team is too aggressive at the start and the project is overly scoped or experiences scope creep, the team may fail the safety inspection, the car may become more unreliable, and other competition deliverables such as the cost report and design judging may be triaged. The extreme right of the figure shows that if the scope is too aggressive (e.g. the team builds its own engine, and manufactures its own tires), failure is almost certain from the competition perspective, as the team will not have a functional vehicle.

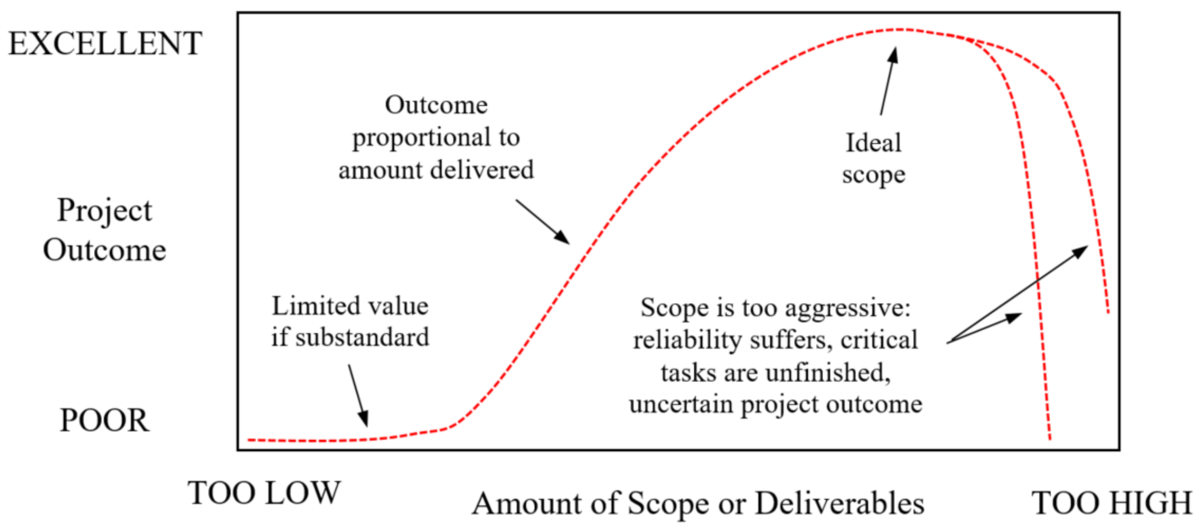

Figure 4: This diminishing returns scenario shows that for a given set of project resources, more scope and deliverables is not always better.

It is important to properly limit the scope of the team at the beginning of the project, and to hold underperformers accountable through constant communication, peer review feedback, realistic grades, motivation indicators, and mentoring. Despite the best efforts of the advisor, performance degradation may occur. A suggested goal for advisors is to help the team limit scope so even if the productivity of, say 15-20%, of the team members goes to zero in the second semester (students leave the team, underperform, are ill, etc.), the balance of the team can still tangibly achieve the project objectives without experiencing a drop in self-efficacy. If the overall project is scoped such that the “motivated” students always need to make up the work of the “rejecter”, “defiant”, or “hopeless” students, it will create conflict within the team even for the students that are completely dedicated to the effort. Those in the middle “fragile” ground may be pulled either way.

Mentorship and Grading

At USAFA at mid-semester and at the end of the semester, all capstone team members are asked to evaluate themselves and their peers on the following seven categories: quality, effort, deadlines, dependability, creativity, cooperation, and attitude. The results can be tabulated in a table and color coded relative to each other. An example with fictitious data is shown in Fig. 5.

The individual students are debriefed in a meeting with the advisor(s) and shown their scores relative to the anonymized scores of their peers. This process and feedback has been well received by the students and is a good opportunity for individual advisor-to-student mentorship.

= LOW
= HIGH

							MAX	AVG	MIN	STDEV
OVERALL AVG	4.24	4.21	3.69	4.62	4.19	3.55	**4.62**	**4.08**	**3.55**	**0.36**
STDEV above/below	0.4	0.4	-1.1	1.5	0.3	-1.5				

Category	**Student 1**	**Student 2**	**Student 3**	**Student 4**	**Student 5**	**Student 6**	**MAX** 5.0	**AVG** 4.08	**MIN** 3.00	**STDEV** 0.54
1: Quality	4.67	4.17	3.67	4.67	4.33	3.50	4.67	4.17	3.50	0.45
2: Effort	4.67	3.83	3.50	4.83	4.50	3.17	4.83	4.08	3.17	0.62
3: Deadlines	4.33	4.50	4.17	4.50	3.50	3.33	4.50	4.06	3.33	0.47
4: Dependability	4.50	4.50	3.67	5.00	4.00	3.17	5.00	4.14	3.17	0.60
5: Creativity	4.00	3.50	3.00	4.33	4.00	3.00	4.33	3.64	3.00	0.51
6: Cooperation	4.17	4.67	4.00	4.67	4.67	4.00	4.67	4.36	4.00	0.31
7: Attitude	3.33	4.33	3.83	4.33	4.33	4.67	4.67	4.14	3.33	0.43

Figure 5: Example peer review results for six students (hypothetical data) to show format and color coding methodology. The students evaluated each other on the seven categories listed on the left and ranked themselves and their peers from 1-5 (with 5 being the best).

For the capstone courses in the department, the grades are divided into the following categories for the fall semester: customer needs research (20%), design and ideation (20%), teamwork and leadership (20%), decision making (20%), and engineering communication (20%). The spring semester uses: design and ideation (20%), engineering tools (20%), experimentation and testing (20%), teamwork and communication (20%), and engineering communication (20%). Much of the grade contribution comes from the department briefings and related documents. Typically the final performance of the team at the Michigan SAE competition is not included in the grades, as it usually occurs too late in the semester to meet grade deadlines, and it is unfair to tie many elements from the competition directly to grades. For example, recent competition weeks had rain, snow, and hail that can impact vehicle reliability and ultimate team rank. It is up to the advisor and department to create meaningful assessment metrics. Published examples have shown merit for FSAE and capstone projects [8, 9].

CONCLUSIONS

A number of best practices are discussed, with a focus on monitoring cadet engagement and motivation via survey tools and methods to visualize the results. These techniques can be applied to any student competition or team project. A case is made that particularly for large annual efforts like FSAE capstone projects, the scope at the start of the project must be properly chosen to align with the available resources. If the FSAE project is part of a larger curriculum, the team should be encouraged to limit scope by choosing only one vehicle subsystem per year to update, and for small teams (<10) preferably the entire focus that year should be to improve only the chosen subsystem. Regarding competition performance and scoring, the team should be encouraged to arrive well prepared for the static judging events, which have less uncertainty and are a good opportunity to maximize scores. The dynamic driving events, however, may depend on the weather, or may be plagued by the reliability of the vehicle, a vehicle which after all is designed and tested by developing student engineers.

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