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Development of a Survey Instrument to Evaluate Student Systems Engineering Ability

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Development of a Survey Instrument to Evaluate Student Systems Engineering Ability

Systems engineering skills are difficult to teach in a university setting. As a result, new graduates may require significant on-the-job-training and experience before they and their employers are confident in their systems engineering skills. For example, NASA developed the Systems Engineering Leadership Development Program (SELDP) to provide "development activities, training, and education" to more quickly cultivate systems engineers. We need better ways of teaching systems engineering, so that engineers require less on-the-job training before taking on their roles at their respective engineering companies. A first step in improving systems engineering education is identifying and assessing the strengths and inadequacies in systems engineering education. Here, we propose an approach based on an analysis of the types of errors systems engineers make in practice. In our previous work, we analyzed a large set of systems engineering failures and identified "decision errors" in systems engineering—decisions made before the accident that accident investigators identified as contributing significantly to the accident. We developed eight survey questions based on failures in our dataset, including the Challenger launch decision, the Alaska Airlines flight 261 crash, and the Piper Alpha oilrig fire. We received 47 responses in the Fall 2016 semester and 101 responses in the Spring 2017 semester from undergraduate and graduate students enrolled in Purdue's Aeronautics and Astronautics department. Our initial statistical analysis indicates that there may be a correlation between a student's performance in and exposure to systems engineering-related classes and the student's performance on our survey.

1 Introduction

As the complexity of the systems we build increases, so does the demand for systems engineers [Hutchison et al., 2016; SERC, 2013; Chaput & Mark, 2013]. 23% of all engineers in the U.S. are over the age of 55, which means there may be a labor shortage in the near future as these engineers begin to retire [Wright, 2014]. Retiring systems engineers, specifically, are a major concern in the defense industry [SERC, 2013; Charette, 2008] as well as at NASA [Bagg et al., 2003]. One obvious solution is to train more undergraduates in systems engineering skills. However, there is a pervasive belief that successful systems engineers can only be made through experience [e.g. Armstrong & Wade, 2015; Squires et al., 2011; Davidz et al., 2005]. This belief may partially be due to the previous generation of systems engineers not receiving much systems engineering-specific training in their university engineering education, as noted by Armstrong & Wade [2015] in their interview-guided study on how systems engineers develop their expertise. Additionally, many systems engineers have an integrative role, "requiring a deeper understanding of a wide range of areas than provided by a focused education" [Ross et al., 2014]. Anecdotally, many university faculty agree that successful systems engineers can only be made through experience, as evidenced in part by the relatively few programs in systems engineering, especially at the undergraduate level[1]. As Adcock et al. [2015] note: "current undergraduate engineering education

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[1] A brief note on terminology is appropriate here. While there are many graduate engineering programs that address the problems posed by complex engineering systems, these programs tend to focus on the science of engineering

lacks systems education in key areas". In aerospace engineering in particular (many graduates of which are hired to the defense industry), "teaching SE [Systems Engineering] is not a significant part of our undergraduate aerospace engineering design course objectives" [Chaput, 2010]. Currently, most systems engineers start out as engineers in more traditional engineering areas, like structures or flight testing. Despite the interdisciplinary and integrative nature of many systems engineering efforts in practice, "if SE is taught at all, it is taught as a separate subject" [Chaput, 2016]. As a result, newly-graduated engineers from these traditional engineering disciplines often do not have the necessary systems engineering skills to help projects succeed and "need to be grown via in-house training or experience" [Adcock et al., 2015]. For example, NASA developed the Systems Engineering Leadership Development Program (SELDP) to provide "development activities, training, and education" to more quickly cultivate systems engineers [Ryschkewitch et al., 2009].

Universities have responded to the growing market demand for systems engineers in a range of ways, from adding or further emphasizing elements of systems engineering to existing courses (e.g., capstone design courses; see Chaput [2016]), to creating entire programs in systems engineering (e.g., Stevens Institute of Technology). How effective are these efforts, how can they be improved, and, can we identify a set of best practices in doing such training [cf. Squires et al., 2011]? Here, we address, in part, the first question. Our approach is based on assessing how well students can identify and address problems that have resulted in previous system development or operation failures.

There are several standardized tests intended to gauge critical thinking ability, such as the Watson-Glaser Critical Thinking Appraisal, the Cornell Critical Thinking Test, and the California Critical Thinking Skills Test [Jacobs, 1999], but these tests do not gauge systems engineering-specific abilities. Researchers in engineering fields, such as chemical engineering, have created and deployed tests called "knowledge-base evaluation" designed to evaluate students' mastery of primary foundational topics in these fields [Farand & Tavares, 2017]. These researchers are trying to address a problem in chemical engineering education: their students are able to resolve complex problems but have difficulty explaining the concepts underlying their calculations, such as basic fluid mechanics and heat transfer concepts. The researchers deployed their test to students taking a mandatory fourth-year course on a computer in an exam scenario. They collected and analyzed data from 4 years' worth of testing, and now use their tool to not only assess student ability to learn key concepts in chemical engineering, but also to collect feedback on courses and improve their educational program. We want to take a similar approach to testing the knowledge base for systems engineering for students in Purdue Aeronautics and Astronautics.

Our test of systems engineering skills is inspired by the idea of foundational concepts. In our case, we base the foundational concepts on the errors that frequently lead to failures in complex engineered systems. This approach allows us to circumvent some of the potential "motherhood and apple pie" aspects of systems engineering (e.g., most students know that stakeholder needs should be considered during development—fully and appropriately doing so in practice is much more difficult). The remainder of this paper is laid out as follows. Section 2 describes how we developed the survey questions and what each question tests. Section 3 describes how we

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systems, and generally do not claim to produce systems engineers, rather, they produce graduates skilled in aspects of system development and operation.

distributed the survey and summarizes the nature of the responses we received. We then detail our initial statistical analysis of the results in Section 4, and describe the range of responses we received in Section 5, using examples from our study. Section 6 concludes this paper.

2 Survey Development

Research in accident causation has shown that accidents, as well as failures more generally, are almost always caused by a complex interaction of good decisions, poor decisions, and other factors [Saleh et al., 2010]. For example, the Space Shuttle Challenger accident resulted from the decision to launch on a cold day, despite available evidence suggesting potentially catastrophic damage to the vehicle given the extremely low temperatures and doubt on the wisdom of a launch from experts on the program [Rogers, 1986]. Behind this decision was a complex web of decisions, many of which were locally or temporally rational. For instance, in the Space Shuttle Columbia accident, the Investigation Board stated that they "considered it unlikely that the accident was a random event; rather, it was likely related in some degree to NASA's budgets, history, and program culture, as well as to the politics, compromises, and changing priorities of the democratic process" [Gehman, 2003, p. 11]. There is also a plethora of discussion, ranging from detailed anthropological analysis to press punditry, on why the launch managers "should have known better". Many failures contain one or more such "should have known better" decisions.

In related research, we compiled and classified the causal findings of 63 systems engineering-related failures across a variety of industries. We coded each finding as an actor-causal action-object structure (e.g., "development management – conducted poor requirements engineering – requirements (safety)"). The "causal actions", or "causes" are of particular interest in the context of testing skills, since they refer to the errors engineers made, and, hence, allude to missing skills or abilities. Table 1 shows examples of findings and the resulting causal actions.

Table 1: Findings from Our Study of Systems Engineering Failures

Finding(s)	Causal Action	Discussion/Explanation
Pike River Mine explosion: "The original mine plan specified two main fans located on the mountainside next to a ventilation shaft. Two planning changes were made. Pike decided to relocate the fans underground in stone at the bottom of a ventilation shaft. […] The decision was neither adequately risk hazards assessed nor did it receive adequate board consideration. A ventilation consultant and some Pike staff voiced opposition, but the decision was not reviewed. Putting the fan underground was a major error." [Panckhurst, 2012, p. 19]	Poorly managed risk	The mine operator decided to change an aspect of the ventilation system design, did not assess the risks associated with this decision, and thus did not consider how a potential explosion could be disastrous for the ventilation system.
Fukushima nuclear meltdown: "When the Fukushima Daiichi station was constructed, the emergency diesel generators and emergency batteries were installed on the floor inside the plant building to afford protection against earthquakes. Ventilation ducts in the compartments where this equipment was located were not waterproofed. Moving this emergency power equipment to higher ground, safety experts said, would not have increased its vulnerability to seismic shock, provided it was fixed to a platform designed to resist earthquakes." [Action& Hibbs, 2012, p. 17]	Conducted poor requirements engineering	Similarly, the nuclear reactor designers, while designing safety systems for a reactor susceptible to earthquakes and tsunami flooding, did not consider how these disasters might affect the safety systems themselves.

Finding(s)	Causal Action	Discussion/Explanation
SOHO spacecraft mission interruption: "Multiple ground operations procedures were modified. Each change was considered separately, and there appears to have been little evaluation performed to determine whether any of the modifications had system reliability or contingency mode implications; or whether the use of this modified procedure set should have been accompanied with operational constraints." [ESA & NASA, 1998] **Piper Alpha oilrig fire:** "Some of these additions [to the rig] apparently interfered with the proper functioning of safety features: external reinforcements on module C, for example, prevented adequate functioning of the blast relief. […] The result was that safety features that may have been adequate in the beginning became inadequate for this new layout, with new couplings and higher risks of accident that may not have been realized (or sufficiently questioned) at the time when the additions were made." [Paté-Cornell, 1993] "Although the structure itself was reinforced in 1979, the deck surface was fixed and the result of unpreplanned additions was an extremely packed space. Not only additional components were stacked, thus creating new couplings, but also, the recordkeeping of these additions was inadequate." [Paté-Cornell, 1993]	Failed to consider design interactions	For these failures, designers did not assess design changes for harmful interactions to the existing system.
Aloha Airlines flight 243 aircraft crash: "Aloha Airlines airplanes were accumulating flight cycles at twice the rate for which the Boeing MPD [Maintenance Planning Document] was designed. Even with an adjustment for partial pressurization cycles on short flights, and thus partial loading of the fuselage, the accumulation of cycles on aloha Airlines airplanes remained high and continued to outpace the other B-737 airplanes in the world fleet and Boeing's assumptions in developing the MPD." [NTSB, 1989, p. 51]	Failed to consider customer needs	The aircraft manufacturer did not consider how its maintenance intervals would affect each specific customer; in the case of Aloha Airlines, the operator used the aircraft for frequent, short trips between the Hawaiian Islands.

Next, we identified a subset of these causes that involve scenarios that do not have an obvious "correct" response, lead to questions that students can answer in a short period of time[2], and have sufficiently detailed supporting information to provide a firm basis for creating a narrative. Many of the causes we identified did not fit these criteria, such as "failed to train" and "conducted maintenance poorly". The first cause describes poor training, like in the Texas City Refinery accident, in which operators did not follow procedures because they were not adequately trained in the plant's policies and procedures [Baker, 2007, p. 120]. The second cause describes poor maintenance efforts, like in the Three Mile Island accident, in which investigators found that the plant had a history of poor maintenance activities without adequate corrective action [Kemeny 1979, p. 47]. Both of these causes have obvious but simplistic answers: simply train personnel better and perform maintenance better. An adequate answer to a question framed around either of these causes is much more complex and requires comprehension of ideas like company

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[2] To help ensure that we obtained a useful number of complete responses, we aimed for an average completion time of 45 minutes.

management and company culture beyond that of an undergraduate engineering student, as opposed to comprehension of how systems work. Seven of the causes we identified did meet the criteria we described, so we used these causes to develop our survey questions. Table 2 contains these causes and their descriptions.

Table 2: Causes We Based the Survey Questions On

Cause	**Definition**	**Back story example**
Created inadequate procedures	Actor(s) in the organization developed a deficient procedure, for instance maintenance, manufacturing, or emergency procedures.	Alaska Airlines flight 261 crashed because the maintenance personnel consistently did not lubricate the jackscrew assembly in the horizontal stabilizer properly, so the threads wore down over time. Since there were no threads holding the horizontal stabilizer in place, the pilots were unable to maintain pitch and the aircraft nosedived into the ocean. Among other causes, the procedures for a malfunctioning flight control system gave pilots unclear guidance and led to them improvising troubleshooting measures that could worsen the issue [NTSB, 2000, p. 140].
Conducted poor requirements engineering	Actor(s) in the organization did not lay out the needs, attributes, capabilities, characteristics, or qualities of the system well.	The V-22 is a unique aircraft that uses tilt rotors to take-off vertically, like a helicopter, and travel horizontally through the air like a turboprop aircraft. It was developed to fill a need to replace aging Marine helicopter transports, but can travel faster and farther than any helicopter used previously by the Marines. The program is over budget and behind schedule, however. Among other problems, the contract for the program had vague requirements, including not specifying an engine service life [Gertler, 2009, p. 9].
Failed to consider design aspect	Actor(s) in the organization failed to consider an aspect in the system design. In many cases, this causal action describes a design flaw, such as a single-point failure, improper system interactions, or component compatibility.	An explosion in a fuel tank shortly after takeoff brought down TWA flight 800. The NTSB concluded that a combination of a nearly-empty fuel tank and delaying the flight in July and having to run the air conditioning for the aircraft while it waited on the taxiway caused an explosive atmosphere to form. Once in flight, a short in the electrical system that measured the fuel levels in the tank ignited the atmosphere. It was common practice for aircraft to be flown with nearly-empty fuel tanks, which investigators thought was an avoidable risk. Among other causes, the placement of heat-generating equipment (e.g. the air conditioning system) under a fuel tank unnecessarily increased the amount of time the airplane was operating with a flammable fuel/air mixture [NTSB, 1996, p. 308].
Failed to consider human factor	Actor(s) in the organization failed to consider a human factor in system development. This causal action describes, for example, failing to consider human factors in specifying procedures or physical design.	The in-flight entertainment system was improperly installed on Swissair Flight 111, and as a result wires from the system chafed against metal components in the attic area of the aircraft. A spark started a fire on the aircraft while it was flying, and because it propagated in unoccupied parts of the aircraft, it went unnoticed and eventually brought the plane down. Among other causes, the standby instruments pilots used in an emergency were of a size and location that made them difficult for pilots to use, especially in a smoke-filled environment [TSBC, 1998, p. 254].

Cause	**Definition**	**Back story example**
Failed to form a contingency plan	Actor(s) in the organization failed to form a contingency plan to implement if an unplanned event occurred.	The Exxon Valdez oil ship ran aground on the Prince William Sound in Alaska and because of the rocky bottom of the sound, many of the ship's cargo tanks were torn open and caused millions of gallons of crude oil to spill into the ocean. Among other causes, most of the emergency plans for an oil spill did not assume a spill of the magnitude of the Exxon Valdez spill. The plan that did prepare for the magnitude of the spill did not provide sufficient detail to guide the response [Skinner & Reilly, 1989, p. 8].
Managed risk poorly	Actor(s) in the organization failed to identify, assess, formulate, or implement a proper mitigation measure.	The Imperial Sugar refinery converted raw cane sugar into granulated sugar. The sugar was transported via a series of conveyors and elevators, which spread sugar dust throughout the plant. The sugar dust eventually ignited and caused an explosion. Among other causes, the facility's management were aware of sugar dust explosion hazards, but did not take action to minimize these hazards [CSB, 2008, p. 63].
Used inadequate justification	Actor(s) in the organization used inadequate justification for a decision.	Vioxx, made by Merck, is a non-steroidal anti-inflammatory drug that had widespread use to treat arthritis pain and inflammation. The drug was withdrawn from the market when a comprehensive study showed that people taking the drug had a significantly increased risk of heart attack. Among other problems, Merck attempted to explain away findings that Vioxx had a five times greater heart risk attack than a similar drug by claiming that the similar drug had an unproven protective effect, instead of acknowledging the risks and performing more studies or pulling the drug [Topol, 2004].

Using these back stories, we created a series of scenarios along with questions. We framed each question so as to obscure its origin while potentially allowing the student to draw out and discuss a decision error of systems engineering. Why not simply give students descriptions of the failures and the findings we discussed and have the students evaluate them? First, we wanted to eliminate bias due to students being familiar with a particular failure. For example, the Space Shuttle Challenger accident is a frequent topic in engineering ethics lectures. A learned, in-context, response from a previous exposure would not give us an indication of their abilities in systems engineering. Second, the point of framing a question around a decision error is not to, for example, discuss whether they would launch Space Shuttle Challenger, but instead discuss what else they would consider in the launch decision. The more open-ended question may give us more insight into the student's thought process. Table 3 contains descriptions of the two survey questions we discuss results from in Section 5 and what aspect of systems engineering we expected each question to test. Refer to the Appendix for the same descriptions of the remaining 6 survey questions.

Table 3: Survey Question Descriptions

Survey Question/ Accident	Description	What it tests
Flood Wall Question New Orleans levee collapse [ASCE, 2007]	**Cause:** Used inadequate justification for project design, Conducted poor safety requirements engineering **Decision error:** designers did not consider the interaction of the sand substrate, water, and wall design that caused the wall to easily tip when the water saturated the substrate. **Question format:** the question prompts students with design principles such as "absorbs damage" and "contains functional redundancy" from Jackson & Ferris [2013] and asks the students which design principles the flood wall design satisfies.	This question presents students with a flawed design and gives them tools to criticize it as well as improve it. The student must determine a design principle the flood wall satisfies, and then improve the design by selecting a single best design principle to incorporate into the flood wall design.
Boat Race Question Challenger Space Shuttle explosion [Rogers, 1986]	**Cause:** Managed risk poorly, Used inadequate justification for quality issue **Decision error:** The crew decided to launch the Challenger Space Shuttle, despite evidence suggesting potentially catastrophic damage to the vehicle because a crucial component was vulnerable to below-freezing temperatures and doubt on the success of the launch from experts on the program **Question format:** The question describes an imaginary scenario about a boat racing team experiencing various failures all season and presents a decision point on whether to continue racing despite cold temperatures on the day of the race. The question asks the student what other factors the crew should consider when deciding whether or not to race—what could be contributing to the failures the crew is experiencing.	This question gives very little detail and this allows students to consider the system as widely as they wish (e.g. the engine, the boat as a whole, the driver and the boat, the humans interacting with the boat and the boat). The students are not simply rewarded for making a decision on whether to race, but rather on how deeply and broadly they thought about the system.

3 Survey Deployment

To date, we have distributed our survey in four semesters (Fall 2016, Spring 2017, Fall 2017, and Spring 2018), and analyzed the responses from two of those distributions (we are now grading the Fall 2017 responses and waiting to receive the results of the Spring 2018 responses). We distributed the survey online using the Qualtrics survey platform through email to Purdue students in Aeronautics and Astronautics. For each distribution the survey was available for two weeks. We incentivized the students to participate in the survey each semester by offering them an opportunity to enter a random drawing for a $100 Amazon gift card.

Along with the survey responses, we also collected student demographic data (gender, age, ethnicity, and student classification), responses to personality-type questions relating to systems engineering ability and academic performance, and academic data (overall GPA, and what grade they received in specified systems engineering-related courses at Purdue). "Systems engineering related courses" are all courses designated as "design" or "systems" in the School of Aeronautics and Astronautics. These courses contain systems engineering-related tasks, such as writing requirements, designing, and design verifying. Courses such as senior-level design-build-test courses and the sophomore-level introduction to aeronautics and astronautics course are thus included in our data. We received a total of 148 responses to the survey, and Table 4 describes these responses. The Purdue Aeronautics and Astronautics department has approximately 1,000 students (~400 graduate, ~600 undergraduate) enrolled in each semester. That means that the first semester had a 5% response rate, and the second semester had a 10% response rate.

Table 4: Breakdown of the 148 Responses

Group	**Subgroup**	**Number of responses**
Student classification	Graduate	73
	Undergraduate	75
Distribution Semester	Fall 2016	47
	Spring 2017	101
Completeness	Complete responses (all 8 survey questions)	88
	Incomplete responses (fewer than 8 survey questions)	60

We created a grading rubric and graded each survey question as an “A”, “B”, or “C” response. Since we anticipated short essay responses, we used a limited-resolution grading scale that is widely used by faculty. We verified the validity of these grades by performing an inter-rater agreement, in which two people graded the responses independently and compared the results afterward. If both graders gave a response a “B”, we considered that to be in agreement. However, if one grader gave a response an “A” and the other gave the response a “B”, or any other mismatching, that was not in agreement. For example, of the 106 student responses for the boat race question, the graders assigned the same grade to 98 responses, so the inter-rater agreement for the boat race question was 98/106=92%. Overall, the inter-rater agreement was 93%.

4 Statistical Data Analysis

Does performance on the survey correlate with how many systems engineering-related courses the student has taken or student performance in systems engineering-related courses? To determine the answer to this question, we analyzed the results of the survey using the proportional odds model for ordinal logistic regression (ordinal data) and logistic regression (binary data) with the polr function and the glm function in R, respectively[3]. The proportional odds model is detailed in McCullagh [2013] and described by equations (1) and (2).

$$\text{logit}\left(\gamma_j\right) = \log\left(\frac{\gamma_j}{1-\gamma_j}\right) = \alpha_j - \beta^T x \tag{1}$$

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[3] We used the glm function because the empennage question in the undergraduate data contained no responses we graded as “C”. As a result, the responses all only had a grade of “A” or “B”, which makes the data binary and not ordinal.

Where

$$\gamma_j = P(Y \leq j \,|x) \tag{2}$$

We want to know whether the student's survey performance is affected by variables such as the number of systems engineering-related courses the student has taken (NSE) and performance in those systems engineering-related courses (PSE). Applying the equations to that concept, in words (2) becomes: γ_j is the probability of receiving a survey grade (Y) less than value j (i.e. "B" or "C"), given the presence of variable x (i.e. NSE or PSE). Equation (1) relates the proportional log-odds of variable γ_j to a linear equation with intercept α_j and slope β of variable x (i.e. PSE or NSE). The slope (β) indicates what effect the variable has on the logit equation. **Positive** β values indicate that as x increases, $\text{logit}(\gamma_j)$ decreases, meaning that the probability of getting a survey grade (Y) less than "B" or "C" (j) decreases; thus, there is a **higher** probability of the student getting a better survey grade. To illustrate, Equation (3) contains the values for the regression on the undergraduate responses to the boat race question.

$$\text{logit}\left(\gamma_{B|A}\right) = \log\left(\frac{\gamma_{B|A}}{1-\gamma_{B|A}}\right) = 0.37 - 0.02 * \text{x}_{\text{PSE}} - 0.04 * \text{x}_{\text{NSE}} \tag{3}$$

Equation (3) expresses: the proportional log-odds of the probability of receiving a B or C on the boat race question instead of an A on the boat race question decreases as x_{PSE} (the variable describing student performance in systems engineering-related courses) increases and as x_{NSE} (the variable describing the number of systems engineering-related courses the student has taken) increases. The slope value for x_{NSE} is twice as large as the slope value for x_{PSE}, thus x_{NSE} has twice the effect that x_{PSE} does on the linear equation.

Table 5 contains the results of the regression analysis using R on the undergraduate data, and it reports the slope of the linear equation and the P-value (the statistical significance of the variable within the regression model).

Table 5: Regression on Survey Questions for Undergraduate Data

Question	**Variable**	**Undergraduate**	
		Estimate (β)	**P-Value**
Flood Wall	x_{NSE}	0.13	0.51
	x_{PSE}	1.96	0.01 *[4]
Oil Rig	x_{NSE}	0.19	0.37
	x_{PSE}	1.47	0.13
Empennage[5]	x_{NSE}	0.26	0.46
	x_{PSE}	1.39	0.32
	x_{NSE}	-0.004	0.98

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[4] "*" Indicates significant p-value (<0.05); "." Indicates marginally significant p-value (0.05< and <0.1)

[5] The glm function was used to analyze this survey question because it contained only "A" and "B" grades.

Question	**Variable**	**Undergraduate**	
		Estimate ($\boldsymbol{\beta}$)	**P-Value**
Aircraft Maintenance	x_{PSE}	0.97	0.36
Boat Race	x_{NSE}	0.04	0.75
	x_{PSE}	0.02	0.98
Off-Road Vehicle	x_{NSE}	-0.01	0.96
	x_{PSE}	0.45	0.66
Toothbrush	x_{NSE}	0.11	0.60
	x_{PSE}	2.43	0.01 *
Vehicle Repair	x_{NSE}	0.16	0.42
	x_{PSE}	1.58	0.07 .

Most of the β values in Table 5 are positive, indicating that these variables have the same effect on the logit equation regardless of the survey question. This indicates that undergraduate student's performance in systems engineering-related courses and the number of systems engineering-related courses they have taken are positively correlated with survey performance. Additionally, for most of the survey questions x_{PSE} has a bigger effect than x_{NSE}. This indicates that the undergraduate student's performance in systems engineering-related courses is a better indicator of survey performance than the number of systems engineering-related courses the undergraduate student has taken. There are some P-values in Table 5 that indicate statistical significance. A P-value less than 0.05 indicates that the result is statistically significant with 95% confidence. The variable for the grades a student received in systems engineering-related courses in Table 5 has a statistically significant p-value (<0.05) for two survey questions (with another having a "marginally" significant p-value of 0.07). We expect that the addition of more survey data will strengthen these results: that all of the slopes will become positive and that more P-values will become statistically significant (<0.05).

We had to take a different approach to analyzing the graduate student data, since only 17 of the 73 graduate students who responded to the survey had taken a systems engineering-related course at Purdue. We thus consider using overall GPA as a variable in our regression analysis in place of average systems engineering course grade. Figure 1 compares the GPA and average systems engineering-related course grade for the undergraduate data. This plot indicates that there is some validity in substituting these values for the graduate data because the regression line has a positive slope. To confirm this result, we conducted a hypothesis test for the Pearson's correlation coefficient. The resulting P-value is 9.3E-06 (less than 0.05) and the sample estimates of the correlation is 0.4 (positive, and between 0—no association and 1—perfect positive linear association), indicating that there is a moderate positive correlation between the overall GPA and the average grade in systems engineering-related courses for undergraduate students who participated in the survey. We thus considered that replacing average systems engineering-related course grade with GPA in our regression may also be valid for graduate students.

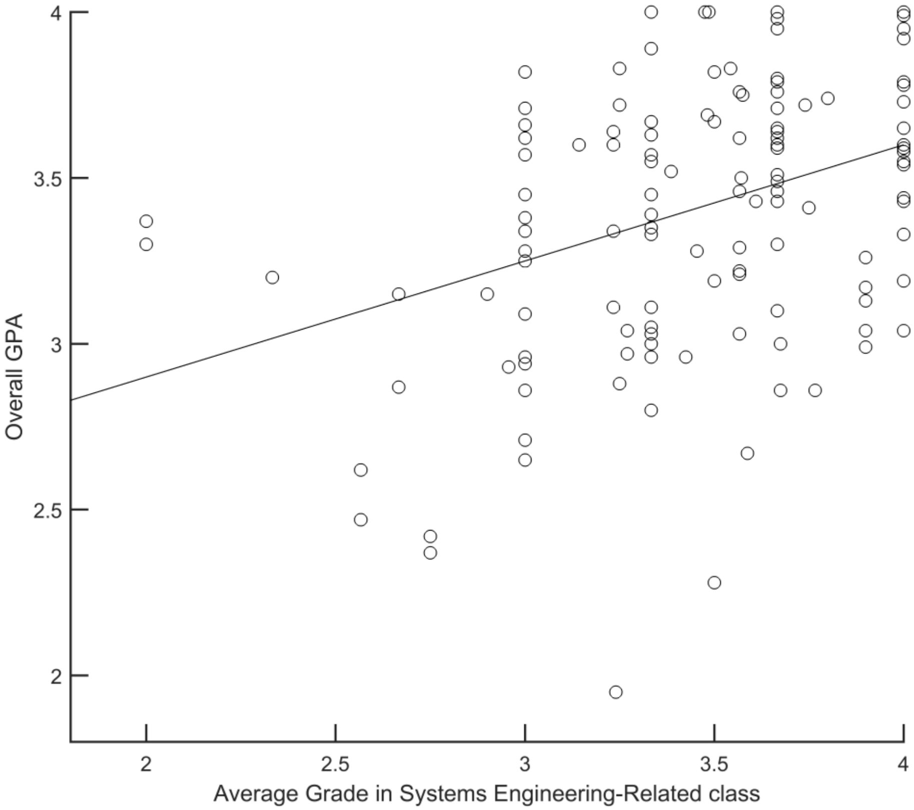

Figure 1: Undergraduate Data Comparison (Grades on a 4.0 Scale)

Table 6 contains the results of the regression analysis on the graduate data and the undergraduate data for x_{NSE} and the overall GPA (x_{GPA}).

Table 6: Regression on Survey Questions for Graduate and Undergraduate Data

Question	**Variable**	**Graduate**			**Undergraduate**		
		Estimate ($\boldsymbol{\beta}$)	**P-Value**		**Estimate ($\boldsymbol{\beta}$)**	**P-Value**	
Flood Wall	x_{NSE}	0.10	0.27		0.14	0.43	
	x_{GPA}	-0.50	0.54		2.14	0.02	*
Oil Rig	x_{NSE}	0.09	0.31		0.29	0.15	
	x_{GPA}	-0.002	1.00		0.85	0.32	
Empennage	x_{NSE}	3.59	1.00		0.02	0.94	
	x_{GPA}	0.53	0.56		-1.89	0.24	
Aircraft Maintenance	x_{NSE}	-0.13	0.08	.	0.29	0.18	
	x_{GPA}	2.29	0.01	*	0.77	0.40	
Boat Race	x_{NSE}	0.07	0.26		0.04	0.74	

Question	Variable	Graduate		Undergraduate	
		Estimate ($\boldsymbol{\beta}$)	P-Value	Estimate ($\boldsymbol{\beta}$)	P-Value
	x_{GPA}	0.80	0.27	0.27	0.69
Off-Road Vehicle	x_{NSE}	0.03	0.60	0.13	0.50
	x_{GPA}	-0.56	0.45	0.65	0.45
Toothbrush	x_{NSE}	0.10	0.14	0.15	0.53
	x_{GPA}	-0.80	0.29	0.02	0.98
Vehicle Repair	x_{NSE}	0.10	0.14	0.10	0.54
	x_{GPA}	1.83	0.02 *	0.11	0.88

Fewer of the β values in Table 6 are positive than in Table 5, and fewer of the undergraduate P-values are statistically significant than when we performed the regression with x_{PSE}. Since the correlation between x_{PSE} and x_{GPA} was not very strong, x_{GPA} was not able to perfectly replace x_{PSE} in the model and thus may have weakened the model. This may explain the presence of more negative β values and fewer statistically significant P-values in Table 6. As mentioned earlier, we asked students to self-identify their systems engineering "ability" (such as requirement writing). We are currently determining whether this self-identified data would be a suitable comparison to performance in systems engineering-related classes and may help us analyze the graduate student data using a better-fitted statistical model.

5 Survey Response Range

There were some aspects of student responses that could not be captured with our "A", "B", or "C" grading scheme. This section qualitatively describes the range of responses we received, using examples of survey responses. Table 7 displays a range of responses from two questions: flood wall and boat race, respectively. The responses have been lightly edited for spelling errors. Refer to the Appendix to see the Flood Wall and Boat Race survey questions in the manner they were presented to the students.

Table 7: Response Range (FW: Flood Wall Question; BR: Boat Race Question)

Response	Grade	Student response	Discussion
FW	**Flood wall:** Choose a design principle that could improve the design.		
FW-1	C	"I'd pick a back-up system. In the event of a flood you want somewhere for the water to go"	The student did not select a design principle, or elaborate on their idea of a back-up system.
FW-2	B	"Beneficial interaction. This system will fail because the sand substrate is vulnerable. If the wall can help to protect it, the system will work." "I would include beneficial interaction into the system. The added subsystem could counter the saturated water on the weak side of the barrier."	Both students chose the "beneficial interaction" design principle but did neither demonstrate that they understood what that meant in the context of this question nor how it could be applied.
FW-3	A	"I would set a second wall behind the first to have physical redundancy."	The student demonstrated that they understood what "physical redundancy" meant in the context of this question, but chose a low-effort solution of simply putting another wall in.
FW-4		"Physical redundancy. Relatively low cost in terms of additional design time, can be integrated easily with current design."	While the student chose a low-effort solution of simply putting another wall in, they demonstrated why that may be an acceptable choice (design time and system integration).
FW-5		"I would choose to include a type of layered redundancy first. This is because a levee is usually a very large system, and if any part of the levee partially fails (regardless of how structurally sound the rest of the levee is), the system as a whole fails. Therefore, a layered redundancy, such as a water pump, could prevent propagation of localized spill water or, at the worst case, prolonged water damage."	The student thought about the system as a whole, noting that if a single part of the levee fails, the system fails.
BR-#	**Boat Race:** consider what factors may be contributing to a boat engine failure		
BR-1	C	"Humidity could be a factor"	The student had one idea but did not elaborate at all, using minimal language.
BR-2	B	"I feel that the engineers are looking only at one factor which might be causing a problem. They kept focus on one thing leaving the other things behind. They should reconsider the decision by looking out for other possible errors"	The point of the question was to discuss what factors could be contributing to the failure and what that would entail for the mechanic's decision to race or not. It is implicit that the mechanics are not considering enough factors.
BR-3	A	"Time between beginning of use and failure. Any non-failure "symptoms" which may exist such as performance deficits or odd sounds."	The student thought of how the engine could be failing, as well as ideas for other "symptoms" to investigate, but did not elaborate.

Response	Grade	Student response	Discussion
BR-4		"Type of engine failure, such as oil leak, pump malfunction, poor combustion, etc. This info can narrow down the cause of the failure."	The student suggested many ideas of how the engine could fail, but did not discuss any other aspect of the system.
BR-5		"They should consider who the opponents of the race are and how likely they are to win with no engine failures. Try to put a money value on how devastating another loss on television would be. Hire a third party mechanic to take a look at the engine. Other weather conditions in the past can be considered too such as humidity, wind, rain, etc."	This student considered aspects at different levels of the system (e.g. the opponents in the race (likelihood of winning) and the weather conditions) and had a positively-phrased criticism of the maintenance crew.

For the flood wall question, many students chose to include redundancy in the system by putting another flood wall behind the primary wall (e.g., FW-3 or FW-4). We graded these types of responses as A because they followed the directions of the question, namely by selecting a design principle the flood wall did not satisfy and describing their choice in a way that made it apparent they understood how this design principle applied to this system. However, this choice does not solve the underlying problem of the flood wall; a second wall would still be susceptible to tipping if the sand substrate gets too saturated with flood water. The creative responses, such as FW-5, discussed design principles that helped to mitigate the primary failure mechanism.

For the boat race question, many students focused on the boat's engine. This open-ended question left room for creative responses by asking "what else the mechanics should consider", not for example "what could be wrong with the engine". An example of this type of response is BR-4. Creative responses like BR-5 considered factors outside of the engine, such as the likelihood of failure, how severe the failure was (considering the safety of the pilot), and which mechanic was working on the boat.

Each survey question received a range of responses similar to the ones described in this section. Future work will be to capture these subtleties in our grading scheme and include that data in the statistical analysis so we can compare them to student demographic data. We will consider how the "following the directions but not displaying creative thinking"-type responses affect how systems engineering students perform in their courses and the implications for performance on project susceptible to failure.

6 Conclusions and Future Work

In this paper we described how we developed 8 survey questions based on decision errors in systems engineering, how we distributed this survey, and the responses we received. We conducted a statistical analysis on the data using the proportional odds model for ordinal logistic regression (ordinal data) and logistic regression (binary data) on our initial results, which hinted that survey performance may be impacted by coursework in systems engineering-related courses, but also indicated that further data collection and analysis may be useful. We then described the range of survey responses we received using illustrative examples.

Does survey performance relate at all to systems engineering course performance? Our results will benefit from further data collection. We are continuing to collect survey responses every semester and expect these additions to strengthen our results. One weakness is that the two populations of students who took the survey, undergraduate and graduate students, require different analysis methods because the graduate student population do not have as much systems engineering-related course data from Purdue. We are investigating other avenues of analyzing and comparing these differences, such as by using other data we collected like self-reported systems engineering ability.

We are currently investigating other means of analyzing our data, including incorporating other data we already have, such as self-reported confidence in systems engineering abilities, instructors for certain systems engineering-related courses, and other indicators of performance on the survey questions. We also plan to expand our statistical analysis by incorporating concepts to strengthen our model, such as by including interaction variables. We also want to capture the subtleties in student responses that could not be described by “A”, “B”, or “C” grading and consider how the “following the directions but not displaying creative thinking”-type responses affect how systems engineering students perform in their courses and the implications for performance on project susceptible to failure.

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Appendix

Descriptions of Remaining 6 Survey Questions

Survey Question/ Accident	**Description**	**What it tests**
Oilrig Question Piper Alpha oil spill [Cullen, 1990]	**Cause:** Failed to consider design interactions **Decision error:** the personnel quarters were not designed with access to emergency controls or equipment such as life boats, and subsequently personnel, who were instructed to wait there during an emergency, were trapped. **Question format:** As in the levee wall question, the question prompts the students with design principles and asks them which design principles the oilrig design satisfies.	As with the flood wall question, the oilrig question presents students with a flawed design and gives them tools to criticize it as well as improve it. The student must determine a design principle the flood wall satisfies, and then improve the design by selecting a single best design principle to incorporate into the flood wall design.
Empennage Question Alaska 261 aircraft crash [NTSB, 2000]	**Cause:** Failed to consider human factor (equipment design), created inadequate procedures **Decision error:** the t-tail configuration of the aircraft's empennage required specific maintenance, which was difficult to perform because it was not easily accessed/visible, causing the component to wear out and fail during flight. **Question format:** The question provides the students with a diagram of an aircraft empennage configuration as well as a table comparing two common empennage configurations. The question asks the students to rank three categories: "maintenance", "performance", and "safety" in terms of what they think are the most important, then discuss the designs based on their ranking judgement and compare the designs in a short paragraph.	The question presents advantages and disadvantages for each empennage design and the student must weigh the trade-offs in deciding between the two designs and justify why they selected that design.
Aircraft Maintenance Question Aloha 243 aircraft crash [NTSB, 1989]	**Cause:** Failed to consider design aspect (customer needs) **Decision error:** Aloha Airlines used their aircraft to travel between Hawaiian islands, which is a relatively short trip. The maintenance intervals for the aircraft were not tailored to the needs of the airline, and were based on flight hours instead of number of flights, causing the fuselage to fatigue faster than usual. **Question format:** The question describes an imaginary scenario in which an aircraft that was previously used on long flights is not being considered for short flights. The question provides the students with a description of five aircraft systems (landing gear, engine, fuselage/cabin, landing flaps and spoilers, and electronic systems) and asks the student to identify and discuss which systems may require different maintenance programs with this different application.	The students must discuss which systems are affected by the change and why. The students have to think about the difference the two types of routes and the implications of those differences for the aircraft and its subsystems.

Survey Question/ Accident	**Description**	**What it tests**
Off-Road Vehicle Question Ford Explorer vehicle quality issues [Bradsher, 2000]	**Cause:** Used inadequate justification for quality issue **Decision error:** The car manufacturer's decision to make insufficient post-design modifications to the vehicle when they found the vehicle was unstable during testing. **Question format:** The question describes an imaginary scenario about an off-road vehicle that failed a stability test and presents the student with four solutions to this problem: (1) adding a large plate under the vehicle, (2) lowering the cabin by replacing the suspension system, (3) redesigning the entire vehicle, or (4) changing the tires to slightly increase stability. The student then must rank each solution in terms of safety, cost, marketability, and time to complete, rate each of these categories on a scale of relative importance, choose a solution, and discuss why they chose that solution.	Students must consider trade-offs in the design and clearly articulate their priorities. The student has to discuss their decision and ensure their discussion matches their trade-off choices. Systems engineers frequently use tools to rank systems and then make their decisions based on the ramifications of the outcomes of using those tools, not on their "gut instinct".
Toothbrush Requirement Question Requirements engineering problems noted throughout our study [Aloisio & Marais, 2017]	**Cause:** Conducted poor requirements engineering **Decision error:** we identified problems with requirements engineering throughout our study of systems engineering failures. For example, in the Pike River coal mine collapse the requirements for ventilation system were not adequately defined; the main fan was placed underground and was not explosion-protected, and thus immediately failed during the initial methane gas explosion [Panckhurst, 2012]. **Question format:** The question provides students with four requirements for a toothbrush and asks them to specify two "terrible" features for the toothbrush (i.e. features that make the toothbrush unusable) that fit within these requirements. The students must then write a requirement that prevents at least one of the features from being incorporated into the toothbrush.	This question reverses the students' typical requirement-writing process by having them imagine the worst design and write requirements to prevent that, rather than having an ideal design in mind while writing requirements to supplement that. An important aspect of the question was prompting the student to write an adequate requirement.

Survey Question/ Accident	Description	What it tests
Vehicle Maintenance Shop Question Piper Alpha fire [Cullen, 1990] SOHO communication loss [ESA & NASA, 1998]	**Cause:** Conducted poor requirements engineering, Failed to consider design interactions, Failed to form a contingency plan **Decision error:** The Piper Alpha oilrig design was significantly modified decades after it was put in service to incorporate additional equipment, living quarters, and crew amenities. These design modifications interfered with the functions of some safety features included in the original design, and there were unforeseen design couplings. **Question format:** The question provides students with a scenario in which a maintenance shop is considering providing transmission repair services. The students are asked to consider the impact of making this change on employee training cost/time, shop resources cost/time, eliminating the "middle man" cost/time, and marketability profits. The students must rank each of these aspects in terms of importance to the shop's success and discuss whether offering transmission repair is worth the modification	This question challenges the student to consider what may occur to an existing system when significant structural changes are made.

Flood Wall Question (As Presented to Students Taking the Survey)

The figure below shows a simplified diagram of a flood wall that prevents water from overtaking a levee. The flood wall is built in a sand substrate, which may become saturated with flood waters and lead to the flood wall tipping. Of the design principles, which do you think this design satisfies?

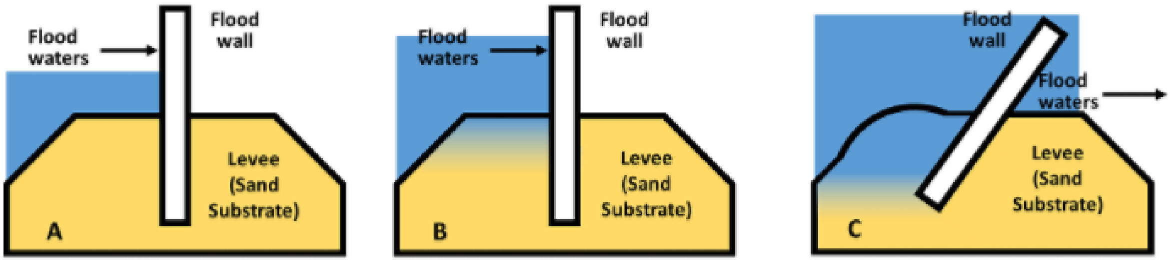


Figure 2: Flood Wall Diagram

Use the following safety design principles (taken from Jackson & Ferris [2013]) to answer the following questions.

Absorbs damage: the system shall be capable of absorbing the magnitude of the disruption that it encounters (e.g. a phone case absorbs shock damage if you drop your phone).

Contains physical redundancy: One or more independent components of a system may fail and the system will still function (e.g. a car has a spare tire in case of a flat tire).

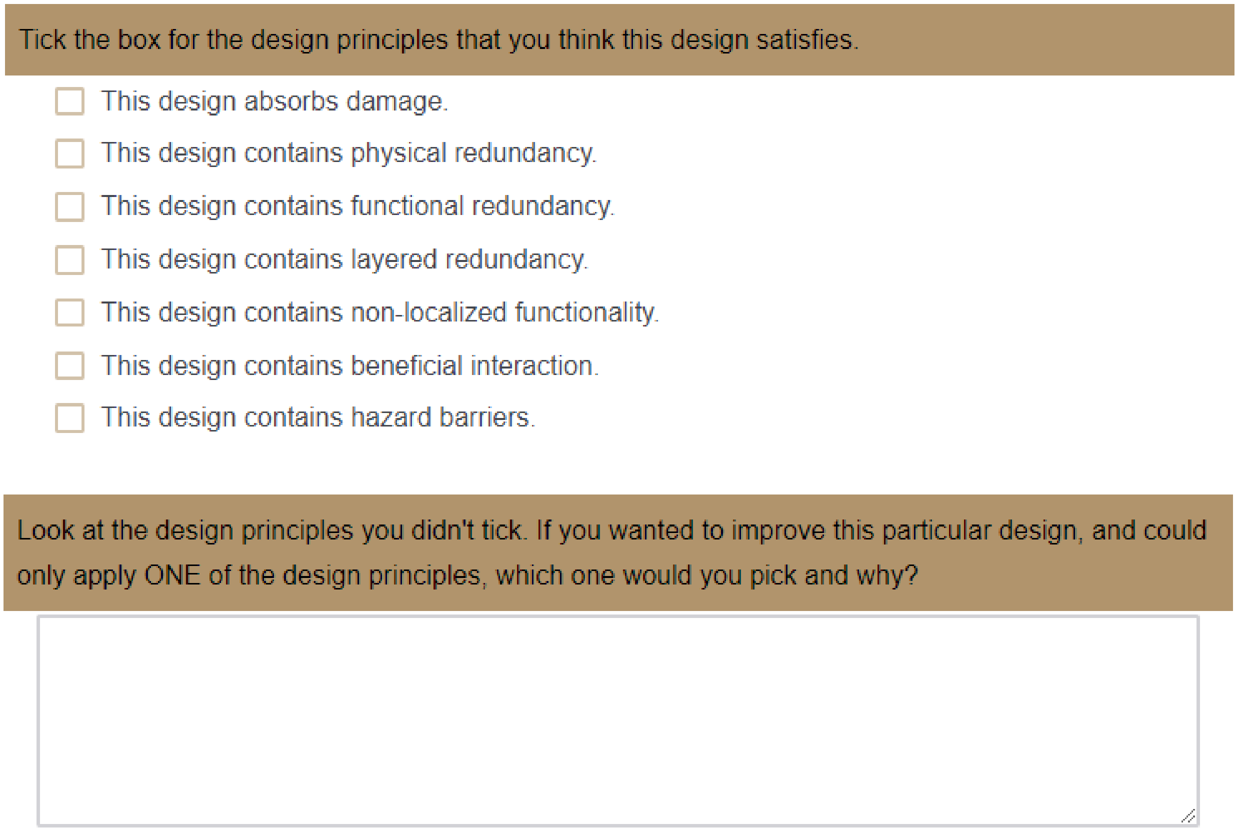
Contains functional redundancy: There should be two or more different ways to perform a critical task (e.g. to prevent sunburn you could apply sunscreen or wear more clothing).

Contains layered redundancy: More layers leads to more resiliency (e.g. if your car breaks down, you can take the bus, rent a car, or ask a friend for a ride).

Contains non-localized functionality: The functionality of a system is not contained to a single node (e.g. if an airport shuts down, other airports nearby accept rerouted traffic).

Contains beneficial interaction: Two or more subsystems interact in a way that actively prevent damage (e.g. elevator safety systems work together to prevent them falling down the elevator shaft).

Contains hazard barrier(s): A system is protected from a hazard by a barrier (e.g. wearing safety glasses prevents debris from getting in your eyes).



Tick the box for the design principles that you think this design satisfies.

- ☐ This design absorbs damage.
- ☐ This design contains physical redundancy.
- ☐ This design contains functional redundancy.
- ☐ This design contains layered redundancy.
- ☐ This design contains non-localized functionality.
- ☐ This design contains beneficial interaction.
- ☐ This design contains hazard barriers.

Look at the design principles you didn't tick. If you wanted to improve this particular design, and could only apply ONE of the design principles, which one would you pick and why?

Boat Race Question (As Presented to Students Taking the Survey)

 [6]

Figure 3: Boat Race Picture

A boat racing team is attempting to decide whether to participate in a lucrative race. However, the team has been experiencing engine failures ranging from minor to debilitating all season and another loss on television would be devastating, but not racing would lose their sponsorship for the rest of the season. So far the mechanics have been unable to pin down exactly what is causing the failures. Since they store their boat outside in the water, one mechanic suggested that cold temperatures may be a factor in engine failure, but the other mechanics are skeptical. The next race would take place on a morning where the ambient temperature is 40°F. The mechanic provided the following graph of engine failures:

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[6] Public domain photo—Wikimedia Commons, courtesy Joe Schneid

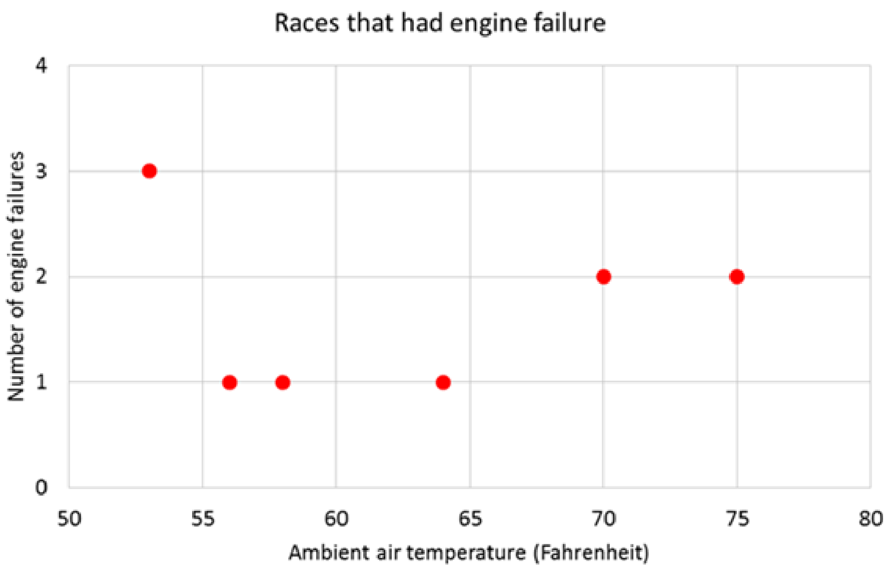

Figure 4: Boat Race Graph

What other data or factors should the crew consider when making this decision?