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## Implementing NGSS Engineering Disciplinary Core Ideas in Middle School Science Classrooms: Results from the Field

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# Implementing NGSS Engineering Disciplinary Core Ideas in Middle School Science Classrooms: Results from the Field

## **Cover Page Footnote**

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## Implementing NGSS Engineering Disciplinary Core Ideas in Middle School Science Classrooms: Results from the Field

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### Abstract

With the inclusion of engineering disciplinary core ideas (DCIs), the Next Generation Science Standards (NGSS) position engineering as a new priority in K–12 science classrooms. This paper reports findings from the implementation of SLIDER, a problem-based learning 8th grade physical science curriculum that integrates engineering and physical science core ideas. As a culminating engineering design challenge, the SLIDER curriculum asks students to apply their understanding of energy, motion, and forces to design an automatic braking system for a robotic truck. The paper describes the curriculum and synthesizes findings from an array of data sources including student design interviews, written design recommendations, engineering notebooks, pre- and post-assessments, and teacher interviews to address two research questions: (1) To what extent and in what ways do students participating in the SLIDER curriculum engage in NGSS engineering DCIs: defining problems, developing solutions, and optimizing solutions? (2) To what extent and in what ways do students draw upon their understanding of science concepts as they engage in engineering design? Findings indicate variations in the degree to which students participating in the SLIDER curriculum engaged across the three NGSS engineering DCIs, with students generally demonstrating competency with regard to identifying and delimiting the engineering problem (ETS1.A) and, to varying degrees, developing solutions (ETS1.B) but experiencing more challenges engaging in the optimization of design solutions (ETS1.C). Findings also illustrate the degree to which students were able to apply their knowledge of relevant physical science core ideas (e.g., friction, force) as they developed and communicated their solutions. Implications of the findings for instruction, curriculum development, and assessment are discussed.

*Keywords:* middle school engineering, STEM integration, problem-based learning, design-based implementation research

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### Introduction

The Framework for K–12 science education (National Research Council [NRC], 2012) and subsequent Next Generation Science Standards (NGSS Lead States, 2013) articulate an expanded definition of science education that, for the first time, includes engineering. The Framework defines engineering broadly as “any engagement in a systematic practice of design to achieve solutions to particular human problems” (p. 11) and specifies engineering design as a core idea (ETS1) comprised of the following components:

- ETS1.A—Defining and delimiting an engineering problem: identifying the problem to be solved in terms of criteria and constraints.
- ETS1.B—Developing possible solutions: generating possible design solutions and evaluating potential solutions to determine which best meet criteria.

- ETS1.C—Optimizing the design solution: testing and refining solutions; comparing the advantages and disadvantages of design solutions and making decisions about trade-offs among competing criteria.

The Framework suggests grade band endpoints defining expectations for each of these engineering competencies. For example, regarding optimization (ETS1.C), the Framework suggests that by the end of 5th grade, students should recognize that “different solutions need to be tested in order to determine which of them best solves the problem, given the criteria and constraints” and by the end of 8th grade, students should understand that systematically evaluating solutions to determine how well they meet criteria and constraints requires iteratively testing and modifying designs to optimize the most promising design solutions. Although these grade band endpoints provide useful guidance for curriculum developers and educators implementing the NGSS, empirical studies exploring how engineering design unfolds in the science classroom remain scarce within the science education literature.

As part of a research agenda to elucidate these issues, Science Learning Integrating Design, Engineering, and Robotics (SLIDER), an NSF-funded DRK-12 project, developed a multi-week 8th grade physical science curriculum that integrates engineering design, as specified by ETS1.A, ETS1.B, and ETS1.C of the NGSS, into core science instruction (Ryan, Gale, & Usselman, 2017). The curriculum, described in detail below, presents an authentic challenge rooted in engineering and physical science. Students then spend eight to ten weeks developing fluency in physical science disciplinary core ideas (DCIs) that they apply to design, prototype, test, and attempt to optimize a solution to the problem.

### *NGSS and Engineering Design*

Researchers have begun to explore the implications of engineering within the NGSS, particularly for instruction, learning, and assessment in K-12 science classrooms. This work has identified potential benefits of integrating engineering instruction into core science instruction including the development of 21st century skills (NRC, 2013), increased achievement in mathematics and science (Cantrell, Pekcan, Itani, & Velazquez-Bryant, 2006; Wendell & Rogers, 2013), and increased interest in STEM fields and careers (Guzey, Moore, & Morse, 2016; Moore, Tank, Glancy, & Kersten, 2015). Engineering experiences also provide a real-world context for mathematics and science learning and can help prepare students who are adaptive and ready for an ever-changing society (Brophy, Klein, Portsmore, & Rogers, 2008). The introduction of engineering into core science classrooms also brings new challenges. As many teachers do not have an engineering background or specialized training in engineering education, they require professional development experiences in

which they learn how to facilitate the engineering design process in their classrooms and assess engineering competencies (Brophy et al., 2008; Cunningham & Carlsen, 2014; Moore et al., 2015). Although engineering challenges have the potential to showcase the “iterative, product-oriented, material features of engineering problem solving” (Cunningham & Carlsen, 2014, p. 202), teachers do not necessarily highlight the overlapping conceptual areas of science and engineering.

Moore et al. (2015) call for additional research to “help shape the scope and sequence of engineering design and engineering thinking, as well as classroom assessment practices, in the K-12 science curriculum” (p. 315). Similarly, Cunningham & Carlsen (2014) discuss the “small but growing literature on science learning in the context of an engineering activity,” suggesting that “this new research emphasis will offer new perspectives and new opportunities for science education, with implications for both curriculum and—critically—teacher education” (p. 203). This paper represents one curriculum development project’s effort to explore these “new opportunities” for science education in the age of NGSS.

### **Research Questions**

Drawing from results of the SLIDER project, in this paper we explore the possibilities and limitations of engaging science students in engineering design, as defined by the NGSS. The paper addresses the following research questions:

1. To what extent and in what ways do students participating in the SLIDER curriculum engage in NGSS engineering DCIs: defining problems, developing solutions, and optimizing solutions?
2. To what extent and in what ways do students draw upon their understanding of science concepts as they engage in engineering design?

### **Framework**

In addition to the articulation of the components of engineering design as a core idea within science education (ETS1.A, ETS1.B, and ETS1.C defined above), this study was informed by the tenets of design-based implementation research (DBIR) (Fishman, Penuel, Allen, Cheng, & Sabelli, 2013; Penuel & Fishman, 2012). In the tradition of “practice-embedded research” (Snow, 2015), this study takes place at the nexus of research and practice. As such, the study is motivated not only by theory and the aims of basic research to address gaps within the science and engineering education literatures, but also by the need to address urgent problems of practice and to understand innovations and their implementation in diverse school settings (Donovan, Wigdor, & Snow, 2003; Snow, 2015). Snow (2015) affirms

this practice-inspired approach to educational research, stating that “knowing what aspects of a new program or practice are easy or hard to implement, which ones are adopted after minimal versus only after intensive professional development, which are embraced by teachers, and which rejected is crucial to designing new innovations that are likely to take” (p. 462).

Fishman et al. (2013) describe four core principles of DBIR that inform the current study. The first principle, alluded to above, is an emphasis on “problems of practice” and the consideration of such problems from multiple stakeholders’ perspectives. It is this principle that guides the study’s effort to explore the integration of engineering in various classroom settings and to incorporate the perspectives of both students and teachers participating in the curriculum project. The second principle is a commitment to an iterative, collaborative design process. As described further below, the SLIDER curriculum was developed and refined iteratively over the course of several years, in close collaboration with participating teachers. The third principle, which is evident in the study’s data collection and analysis, is the concern with using systematic inquiry to develop theory and knowledge related to learning and implementation. The fourth principle highlights concern for developing capacity for sustaining change at the systemic level. Although the current study does not examine sustainability of the innovation directly, this tenet of DBIR serves as a lens for considering potential implications regarding the capacity and the necessary conditions for implementing engineering disciplinary core ideas in the science classroom.

**Curriculum Context**

The SLIDER project, funded through the NSF DRK–12 program in 2010, investigated the use of robotics and design to develop conceptual understanding among 8th grade physical science students. The curriculum has roots in multiple problem- and project-based learning frameworks, most notably Kolodner et al.’s (2003a) Learning By Design™ (LBD) and Project-Based Inquiry Science (PBIS) curriculum (2009), in which design challenges and driving questions facilitate the learning of content and skills

(later described by NGSS as Disciplinary Core Ideas and Practices). LBD and some PBIS curriculum units situate learners in engineering-design or design-based challenges, where students iteratively develop a solution to a problem or challenge over the course of 3–5 weeks. LBD, PBIS, and the SLIDER curriculum are all grounded in problem-based learning (PBL). Research in PBL and project-based learning over the last 20 years reveals that, relative to traditional lecture-based instruction, PBL promotes more active learning of content, the development of problem-solving skills, increased ownership of learning, greater understanding of the nature of science, more flexible thinking, improved collaboration skills, and opportunities for students to become “STEM experts” (Barrows, 1986; Boaler, 1998; Bransford & Donovan, 2005; Hmelo-Silver & Pfeifer, 2004; Kolodner et al., 2003a, 2003b; Krajcik et al., 1998). These advantages are also consistent with the science learning goals promoted in the Framework for K–12 science education (NRC, 2012).

Central to the LBD curriculum philosophy is a fluid movement, back and forth, between engaging in the practices of science and engineering while addressing the problem or challenge (Figure 1). For example, 8th grade students beginning a multi-week PBIS unit on force and motion first encounter a challenge to build a better version of a self-propelled model vehicle that can climb many obstacles and travel far. Thus, students start atop the cycle on the left in Figure 1. As they create and consider design options, the need to identify a well-suited wheel emerges. This shifts their work over to the cycle on the right, where they design and run experiments with surfaces of different coefficients of friction. Through this inquiry into friction, the teacher is able to target core ideas and practices. Armed with their new physics knowledge, students shift back into the left cycle where they apply their knowledge to iteratively build and test prototypes, present their new design, and evaluate it against the challenge criteria. This back and forth occurs throughout the unit, covering a wide range of force and motion concepts that govern the various features and elements of the model vehicle (Koloder et al., 2003b).

The SLIDER project adapted the LBD/PBIS approach and set out to explore the use of robotics and design in a

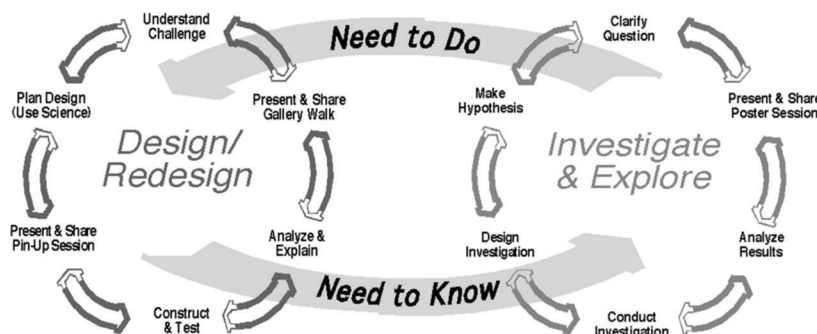


Figure 1. LBD activity cycles (from Kolodner et al., 2003b).

similar learning experience to understand their affordances for learning physical science. From 2010 to 2014, the curriculum team iteratively developed and pilot tested units that incorporated LEGO NXT Mindstorms™ robotics. Students would develop understanding of energy, motion, and forces as they engineered a solution to an authentic traffic accident problem and designed an automatic braking system to help prevent traffic accidents. Though the curriculum was developed from the beginning of the project to guide students as they define the problem, iteratively design prototypes, and ultimately settle on a solution to recommend, the release of the Framework in 2012 and subsequent NGSS standards further encouraged the explicit integration of science and engineering within the curriculum.

The curriculum promotes inquiry learning through what Bell and Banchi describe as *guided inquiry*—i.e., the curriculum materials guide which questions students ask, but the students develop their own experimental procedures, collect and analyze data, look for trends, and support design decisions using evidence and scientific reasoning (Banchi & Bell, 2008). The curriculum consists of two units that, over approximately eight school weeks, target multiple standards in middle school physical science. Unit 1 focuses on energy core ideas (e.g., the relationship between kinetic and potential energy, transfer of mechanical energy, the law of conservation of energy); Unit 2 focuses on force and motion core ideas (e.g., force, balance of forces, changes in motion, speed, acceleration, the mass and inertia relationship). The overarching challenge asks students to address a serious issue affecting the (fictitious) town of McFarland. Students learn that during the past year, a widely used intersection in McFarland has been the site of numerous dangerous vehicle accidents that have resulted in deaths, extensive injuries, and property damage. The curriculum guides students to understand why the accidents are causing more damage, investigate the factors

that lead to such accidents, and design possible solutions to decrease the accidents and injuries. They do this by building, testing, and gathering data using LEGO Mindstorms™ robotics kits. These kits offer two desirable features. First, LEGO pieces are well known to students and well suited for design purposes. Second, the LEGO Mindstorms™ robotics kits contain a number of sensors and parts that can make difficult physics concepts more explicit and evident. For example, the kit's light sensor detects variations in visible light and can initiate varying behaviors by the robot based on light waves reflected to the sensor. This allows students to learn more explicitly about, and create models of, wave behavior.

SLIDER units can generally be organized into three phases. In Phase 1, students try to understand the specifications of the problem or challenge; they ask questions about traffic accidents and the vehicle behaviors involved and identify possible investigations or models that would help answer their questions. In Phase 2, students iteratively develop and conduct investigations that attempt to answer Phase 1 questions. They analyze and explain the data they collect to find causal effects, explore physics core ideas, and iteratively construct explanations, arguments, and recommendations to justify possible solutions. Students may, in some units, cycle through Phase 2 multiple times before moving on to Phase 3. Finally, in Phase 3, students continue to explore additional core idea knowledge and collect more data to propose their ultimate solution to the challenge. Tables 1 and 2, adapted from Usselman and Ryan (2015), provide a summary of each unit. The SLIDER curriculum materials can be accessed at [slider.gatech.edu](http://slider.gatech.edu).

The curriculum culminates in students attempting to design an emergency braking system that meets all the criteria and constraints introduced along the way. Specifically, the challenge asks students to design a brake system using one of three types of LEGO brakes (small, large, and rake) and various non-LEGO surface materials (e.g., brillo,

Table 1  
Summary of SLIDER curriculum Unit 1: The accident challenge.

| Curriculum units/components description |                                       |   |
|---|---------------------------------------|---|
| Phase 1                                 | Organize the challenge                | Identify criteria and constraints from the challenge and determine the questions they wish to ask of a model that could simulate the accidents at the intersection.   |
|   | Explore modeling                      | Build the model to simulate trucks hitting cars at the intersection, develop a procedure and the types of tests to run the model consistently and usefully, and record and compare data from each set of tests.           |
| Phase 2                                 | Investigate accidents with model      | Design investigations and collect data on different variables that affect kinetic and potential energy in a system. Use digital simulations to adjust variables similarly to and beyond their test model.                 |
|   | Share investigation results           | Create presentations to share data collected and review trends. Review the procedures and analysis of each other's work to identify errors and discuss sound scientific practice and measurement.                         |
|   | Add to their understanding            | Define and practice with the concept of energy transformation. Use simulations to identify variables that can affect the type, amount, and transfer of energy in a system.  |
|   | Create an argument: new traffic rules | Review design solutions made by fellow town citizens and search their data to find evidence in an argument for/against those claims. Connect various claims and evidence to the science content knowledge learned so far. |
| Phase 3                                 | Answer the challenge                  | Address and evaluate citizens' ideas through the eyes of a traffic engineer, using evidence from model and science content knowledge to support or refute ideas.  |

Table 2  
Summary of SLIDER curriculum Unit 2: The brake challenge.

| Curriculum units/components description |   |  |
|---|---|--|
| Phase 1                                 | Organize the challenge                  | Identify criteria and constraints from the challenge. Determine questions to investigate that would determine how varying brakes make vehicles stop differently.   |
|   | Explore modeling                        | Briefly compare how various surfaces affect the motion of a coasting vehicle. Generate an operational definition of forces and how they affect moving objects  |
| Phase 2                                 | Investigate accidents with model        | Design investigations and collect data on different variables that affect forces acting on the truck as it starts, accelerates, slows, and then stops. Students investigate the amount of friction generated by different materials.                   |
|   | Share investigation results             | Groups present data collected and review trends, informing each other of the performance of different materials and basic brake assemblies tested, and, again, identify errors and discuss sound scientific practice and measurement.                  |
|   | Add to your understanding               | Define and practice with the concepts of forces, net force, and balance of force, and changes in speed and acceleration.   |
|   | Create an argument: best brake material | Draft arguments about various materials tested, supporting the claims with evidence collected during investigations and with reasoning discussed during class. Review claims made by other groups about the performance of other materials.            |
| Phase 3                                 | Answer the challenge                    | Iteratively design, build, and test truck brake solutions that account for multiple criteria and constraints and optimize a solution. Draft a written recommendation for a final brake design using evidence from tests and science content knowledge. |

balloons, plastic wrap, foil, string), with each brake type and each material assigned a price. In order to be considered a successful design, the braking system must stop the LEGO truck short of a predetermined threshold distance and the total cost of the design (including brake and materials) must not exceed a predefined budget. Students detail this 3- to 5-day design-and-build experience in the curriculum's engineering notebook. The engineering notebook was designed to be an educative resource intended to guide students through the design and build of a solution to the brake challenge. The notebook includes instructions; information text; multiple planning, design and data sheets; discussions of engineering; and a set of pages for a final written design recommendation in which students detail the rationale for their final recommendation.

## Method

The participants, data sources, and procedures are described below.

### Participants

#### School sites

The findings presented in this paper are drawn from the implementation of SLIDER at two middle schools: Hickory Road Middle School and Sycamore Lane Middle School (school and teacher names are pseudonyms). Hickory Road is a historically high-performing school located in a relatively affluent suburb of a major southeastern city. It serves approximately 1,300 6th–8th grade students, with a student body that is majority white (58%), 17% African American, 12% Hispanic, and 11% Asian. Sixteen percent of Hickory Road's students qualify for free or reduced lunch.

Sycamore Lane Middle School is located in a small rural town in the same state. It has historically struggled academically, with below-state-average scores on standardized tests. Sycamore Lane serves approximately 700 6th–8th grade students, 44% of whom are white, 46% African American, and 8% Hispanic. Eighty percent of students at Sycamore Lane qualify for free or reduced lunch.

Data reported in this study were gathered during the fifth and final year of the project, at which point each of the schools had implemented versions of the curriculum for three years. In spite of the differences between the two school sites described above, in many respects, teachers at each school implemented the curriculum under relatively similar conditions. At both schools, administrators were supportive of the project, allowing teachers to devote sufficient time to curriculum implementation and professional development associated with the project. Although the two schools had slightly different class schedules that fluctuated over the course of the project, class periods at both schools equated to approximately 50–60 minutes of daily science instruction. The duration of implementation at each school varied somewhat depending on a range of local factors (e.g., school and district calendars, testing). However, at both schools, teachers devoted four to six weeks to each of the two curriculum units, implementing the units sequentially during the same part of the school year, without other intervening science or engineering content. The school sites varied somewhat with regard to class size, with an average class size of 20 students at Hickory Road and 25 students at Sycamore Lane. Teachers at both schools implemented the curriculum in each of their 8th grade physical science class periods, which included five class periods at Hickory Road and four class periods at Sycamore Lane.



### *Teacher participants*

This study focuses on data gathered in classrooms led by two teachers: Sydney, from Hickory Road, and Alex, from Sycamore Lane. Although both Sydney and Alex were experienced teachers, they came to the project with markedly different teaching backgrounds. Sydney had a strong background in science, a working knowledge of LEGO robotics, and substantial prior experience teaching using PBL curricula. In contrast, Alex was a self-described “traditional teacher” with a background in home economics. Alex began the project with little experience in PBL or inquiry teaching methods and only a moderate understanding of science content. Alex and Sydney participated in the same array of project-sponsored professional development activities including annual week-long summer institutes during the three years of curriculum development, professional development days throughout the school year, instructional videos aligned with particular sections of the curriculum, and weekly coaching from curriculum developers. Summer institutes included opportunities for teachers to provide feedback and reflect on their experiences implementing the curriculum the previous year, review and ask questions related to the curriculum, and work through curriculum investigations they would be facilitating in their classrooms. As the curriculum was iteratively developed, additional sessions focused on deepening teacher understanding of relevant physical science content and the engineering design process.

In order to provide additional teacher perspectives, we also include interview data from three additional teachers participating in the project during its final two years. These teachers were a second teacher at Sycamore Lane and two additional teachers from a third school site.

### *Student participants*

This study reports analysis of interview, assessment, and artifact data for 8th grade students in each teacher’s physical science classes. The sample includes all students for whom parental consent and student assent forms were obtained ( $n = 189$ ). This sample includes over 90% of students in each of the participating classrooms. The demographics of the student sample are generally representative of the school-level demographics described above.

## **Data Sources and Procedures**

To triangulate and contextualize the findings, the study synthesizes results drawn from five data sources: student design interviews, student written recommendations, student engineering notebooks, a pre–post assessment, and teacher interviews.

### *Student Design Interviews*

Each “design group” of three to four students participated in short, videotaped design interviews after each

iteration of designing and building their brakes. As the brake challenge was the culminating engineering activity at the end of the curriculum’s second unit, all interviews took place within a three-day time-span in each classroom. We collected and analyzed a total of 144 interviews from 52 groups including 28 groups in Sydney’s classes and 24 groups in Alex’s classes. Each group participated in at least two and as many as four interviews, depending on the number of design iterations completed by the group. The majority of groups ( $n = 34$ ) participated in three design interviews. Fifteen groups participated in two design interviews and three groups participated in four design interviews.

Interviews were conducted by one of two research assistants and followed a short semi-structured protocol including one primary question and follow-up prompts. The primary question referenced each group’s specific brake design and asked students to provide rationale for their design decisions (e.g., “I see you’ve made a brake with the rake and the balloon. Tell me about why you chose this design.”). Follow-up prompts were intended to elicit additional details regarding students’ design decisions in relation to the challenge (e.g., “What about using the rake and the balloon do you think will make the truck stop faster?”). With few exceptions, all students in each group appeared in the design interview videos; however, in 41% of the interviews, just one of the group members responded to the interview questions on behalf of the group.

Student design interviews were coded by two members of the research team. The coding scheme included codes aligned to each engineering DCI as well as codes that identified instances where students applied relevant science concepts. Because students made gestures as they described their designs, coding was completed using videos rather than transcripts, and each video was watched at least three times and sequentially coded. Researchers also noted emergent patterns or themes for both individual videos and across all videos for a particular student group. The videos were divided equally into four batches. The first batch was coded jointly by the two coders, with any disagreements reconciled through discussion and refinement of the code definitions. A second batch was then coded by both coders independently with an inter-rater reliability of 92%. After resolution of remaining coding discrepancies, the remaining two batches of videos were divided between the two coders.

### *Written Design Recommendations*

The design recommendation writing exercise was conducted as a culminating in-class assignment. Students were asked to write a letter describing which model brake design they recommended along with an explanation detailing why they believed their recommendation was the best design. Students were informed that they could recommend their design or a design built by another group in their class. Curriculum materials also included guidance for teachers,



indicating that the design recommendations were intended to serve as a final assessment for the unit and, as such, students should complete the exercise independently and be given adequate time to do so.

A total sample of 96 design recommendation letters were coded, including 48 randomly selected letters from each teachers' classroom. Initial analysis of the letters indicated that this was a sufficient sample to achieve saturation (Bowen, 2008). This sample represented approximately 50% of the design recommendations submitted. A researcher with subject matter expertise coded all letters with frequent consultation with the research team to discuss code definitions and preliminary findings. The letters were read multiple times to identify instances in which students' recommendations referenced engineering DCIs and the application of relevant science concepts.

### *Student Engineering Notebooks*

Students' engineering design notebooks ( $n = 182$ ) were reviewed as a secondary data source to provide context for the analysis of engineering design videos and recommendation letters. The notebook was created as a supplemental resource to the student edition of the curriculum to guide students as they worked through the engineering design challenge. Data sheets within the engineering notebook (Figure 2) provided space for students to describe and record test results for three brake designs. Each student submitted their own engineering notebook documenting their group's brake designs. Engineering notebooks contained a total of 141 individual brake designs, corresponding to each of the designs discussed in group interviews. Note that the three groups completing a fourth, optional design did not document this additional design in their notebooks. The data sheets and design descriptions were cross-referenced with interview data to explore the nature of each group's design iterations and to determine whether each design satisfied the stopping distance and cost criteria of the challenge. The data were also cross-referenced with student letters to determine whether students recommended a brake they designed and tested, or a brake designed by another group in their class.

### *Engineering Design Process Assessment*

Students ( $n = 183$ ) completed an Engineering Design Process (EDP) assessment before and after implementation of the SLIDER curriculum. The EDP assessment consisted of multiple items aligned with each of the engineering DCIs adapted from pre-existing engineering assessment items or developed for the project through subject-area-expert review. The majority of items were scenario based, presenting students first with an engineering-focused scenario followed by several multiple-choice DCI-related test items. Distractors were carefully constructed to reflect common

student misconceptions in engineering design. For a full description of the development of this assessment, see Wind, Alemdar, Lingle, Gale, and Moore (2017).

The analysis of assessment results is based primarily on Rasch measurement theory (Rasch, 1960/1980). Rasch models use students' responses to items to estimate achievement levels for each student and difficulty levels for each item on a linear continuum that represents the construct. Researchers and practitioners frequently use Rasch models to develop measurement instruments in the social, behavioral, and health sciences (Bond & Fox, 2015; Engelhard, 2013). For example, researchers and practitioners use Rasch models to develop and evaluate attitude surveys (e.g., Armstrong, Morris, Tarrant, Abraham, & Horton, 2017; Waugh, 2002), diagnostic scales for psychological conditions (e.g., Shea, Tennant, & Pallant, 2009), and physical functioning scales (e.g., Gross, Jones, & Inouye, 2015). The Rasch approach is also a popular choice among educational researchers and practitioners for developing, evaluating, and maintaining educational achievement tests. Beyond assessment development, Rasch modeling has been applied extensively within education as an approach for analyzing and interpreting student learning outcomes in various disciplines, including science education (Liu & Boone, 2006; Wind & Gale, 2015).

Analyses included separate applications of the many-facet Rasch model (Engelhard, 2013; Linacre, 1989/1994) to student responses on the pre- and post-administrations of the assessment. Average student achievement measures were compared between administrations, teachers, schools, and across items grouped by the DCIs. Analyses based on differential item functioning techniques were used to explore the degree to which student achievement and item difficulty changed across the two time points. Rasch analyses were conducted using the Facets computer program (Linacre, 2014).

### *Teacher Interviews*

Data collected during the implementation of the brake challenge have been supplemented by interview data collected during the final two years of the project. Five teachers were interviewed by one member of the research team following implementation of the curriculum. These semi-structured interviews lasted approximately 60 minutes and included questions intended to gather teachers' general impressions of how the curriculum worked in their classrooms as well as specific questions related to engineering design activities.

Interviews were audio-recorded and transcribed for analysis. Transcripts were subjected to sequential analysis (Miles, Huberman, & Saldana, 2014). A provisional start-list of codes was generated, with codes added or refined over two rounds of iterative coding. The initial coding scheme included codes pertaining to each of the engineering

## SLIDER Engineering Notebook

**Brake Design Data Sheet #1**  
Part 2 of 5 Explore

*Instructions: Use this space to record information about the design and performance of your brake design. Record the data from the investigation and whether it collides with the car. Complete the analysis of your design on the back of this sheet.*

| Design #1:       |   |
|------------------|---|
| Shoe option:     | Materials:                              |
| Labeled Drawing: | Why did you select this design to test? |

Threshold distance/car placement: \_\_\_\_\_ cm

| Trial      | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|------------|---|---|---|---|---|---|------|
| Distance   |   |   |   |   |   |   |      |
| Collision? |   |   |   |   |   |   |      |

**Design #1 Analysis**

|   |  |
|---|--|
| 1. Was the mean distance less than the threshold distance?                        |  |
| 2. Calculate the difference between the threshold distance and your mean distance |  |
| 3. Design cost  |  |
| 4. Optimization Index (Distance x Cost)   |  |
| 5. What were the advantages to using this design?                                 |  |
| 6. What will you change about your design and why?                                |  |

Figure 2. Engineering notebook data sheets.

DCIs. After applying this coding scheme, teacher responses were subjected to a second round of evaluative coding in which teacher attitudes and self-reported enactment were coded as positive, negative, or neutral with respect to the integration of NGSS engineering DCIs in teachers' science classrooms. The NVIVO software program was utilized for all interview coding.

**Findings**

*Research Question 1: Student Engagement in NGSS Engineering DCIs*

Findings pertaining to Research Question 1 are presented in three sections: EDP assessment results, SLIDER implementation findings, and teacher interviews. As the focus of this study is student engagement in the engineering design process rather than students' mastery of the steps of the engineering design process or teacher perceptions, we consider the EDP assessment and teacher interviews as secondary data sources intended to frame our analysis of student design interviews, engineering notebooks, and written recommendations.

*EDP Assessment*

To examine whether there were differences in student performance on the EDP assessment related to the DCIs, we classified each of the multiple-choice items according to their alignment with each engineering DCI. We conducted a many-facet Rasch analysis (Engelhard, 2013) using a model that included five facets: student achievement, item difficulty, time point (pre or post), student achievement within school site, and student achievement related to items aligned with ETS1.A, ETS1.B, and ETS1.C. The model provided estimates of each facet that represent average student achievement on the multiple-choice items classified within each DCI.

Overall, analysis of EDP assessment results indicated significant increase in student achievement from pre- to post-test ( $p < 0.01$ ), significant differences in achievement across individual students ( $p < 0.01$ ), significant differences in the difficulty of the individual items ( $p < 0.01$ ),

and significant differences in student achievement between the two school sites, with Hickory Road performing significantly better on the EDP assessment than Sycamore Lane ( $p < 0.01$ ). We also examined the results when engineering assessment items were grouped by DCI and found there were no significant differences in student achievement across the three engineering DCIs at either time point within either school site, nor were there significant interactions between DCIs and time point within either school site. Table 3 summarizes student performance on the EDP assessment by school. Table 4 summarizes student performance by engineering DCI.

*Curriculum Implementation Findings*

Results from the curriculum implementation, as they relate to each of the three DCIs, are reported below.

*ETS1.A: Defining and delimiting an engineering problem*

In describing ETS1.A, the Framework provides the following definitions of criteria and constraints. Criteria "address such things as how the product or system will function (what job it will perform and how), its durability, and its cost" and the Framework specifies that "criteria should be quantifiable whenever possible and stated so that one can tell if a given design meets them" (p. 204). Constraints "frame the salient conditions under which the

Table 4  
Student performance on engineering design process assessment by engineering DCI.

|               | Proportion correct within DCIs |      |        |      |        |      |
|---------------|--------------------------------|------|--------|------|--------|------|
|               | ETS1.A                         |      | ETS1.B |      | ETS1.C |      |
|               | M                              | SD   | M      | SD   | M      | SD   |
| All students  |                                |      |        |      |        |      |
| Pre           | 0.63                           | 0.27 | 0.62   | 0.31 | 0.59   | 0.34 |
| Post          | 0.70                           | 0.27 | 0.72   | 0.28 | 0.68   | 0.32 |
| Hickory Road  |                                |      |        |      |        |      |
| Pre           | 0.83                           | 0.16 | 0.85   | 0.18 | 0.82   | 0.23 |
| Post          | 0.95                           | 0.08 | 0.95   | 0.10 | 0.87   | 0.21 |
| Sycamore Lane |                                |      |        |      |        |      |
| Pre           | 0.51                           | 0.25 | 0.47   | 0.28 | 0.45   | 0.31 |
| Post          | 0.57                           | 0.27 | 0.58   | 0.28 | 0.57   | 0.32 |

Table 3  
Student performance on engineering design process assessment by school.

|               | Average proportion correct |      | Average estimated achievement (logits) |      | Time effect within school (pre-post) | Difference between schools          |                                    |
|---------------|----------------------------|------|--|------|--------------------------------------|-------------------------------------|------------------------------------|
|               | M                          | SD   | M                                      | SD   |                                      | Pre                                 | Post                               |
| Hickory Road  |                            |      |  |      | 0.72 logits                          | 0.96 logits                         | 1.01 logits                        |
| Pre           | 0.83                       | 0.13 | 2.34                                   | 1.18 | $\chi^2(1) = 4.8,$<br>$p = 0.09$     | $\chi^2(1) = 114.4,$<br>$p < 0.001$ | $\chi^2(1) = 75.0,$<br>$p < 0.001$ |
| Post          | 0.92                       | 0.08 | 3.38                                   | 1.09 |                                      |                                     |                                    |
| Sycamore Lane |                            |      |  |      | 0.22 logits                          |                                     |                                    |
| Pre           | 0.49                       | 0.22 | 0.09                                   | 0.61 | $\chi^2(1) = 11.0,$<br>$p < 0.001$   |                                     |                                    |
| Post          | 0.57                       | 0.22 | 0.44                                   | 1.30 |                                      |                                     |                                    |

Table 5  
Evidence of ETS1.A: Defining and delimiting an engineering problem.

|   | Total             | Sydney's students | Alex's students   |
|---|-------------------|-------------------|-------------------|
| Design interviews and notebooks   | $n = 52$ groups   | $n = 28$ groups   | $n = 24$ groups   |
| Group references criteria and constraints in at least one design interview                    | 49 (94%)          | 28 (100%)         | 21 (88%)          |
| Group references cost as a factor in at least one design interview                            | 27 (52%)          | 21 (75%)          | 6 (25%)           |
| Written design recommendations  | $n = 96$ students | $n = 48$ students | $n = 48$ students |
| Students define criteria and constraints of the engineering problem in recommendation letters | 53 (55%)          | 32 (67%)          | 21 (44%)          |

problem must be solved” and “may be physical, economic, legal, political, social, ethical, aesthetic, or related to time and place” and “may include limits on cost, size, weight, or performance” (p. 205).

With these definitions in mind, we sought to identify instances of students attending to the criteria and constraints of the brake challenge. The curriculum provided students with the criteria and constraints for the challenge, namely limitations on the cost of their brake design, the materials available (LEGO brake, brake surface materials), and the requirement that their brakes stop the LEGO truck before it reached a certain threshold distance. Our focus was therefore not on students' initial identification of criteria and constraints, which took place before they began designing their brakes, but rather on how students attended to criteria and constraints as they iteratively designed and tested their brake designs.

As summarized in Table 5, the vast majority of students (94%) in both schools referenced the criteria and constraints of the brake challenge when interviewed about their design solutions. These references generally took the form of students mentioning the cost constraints of using various brakes or materials and/or the need to devise a design that would stop the truck short of the threshold distance. For example, one group referenced both cost-effectiveness and stopping distance when discussing their decision to experiment with a new, less expensive material for their second design after their first design had been successful: “We decided to try something new. We wanted to be cost-effective and also the rake brake worked pretty well with the balloon last time, we just wanted to see if it would increase the friction and have less stopping distance.” In describing the rationale for their third design, the same group again highlighted both cost and stopping distance, stating their design rationale as “Cost effective. We wanted to make the cheapest brake that we thought would stop the truck in the least distance.” Indeed, when data from design interviews, engineering notebooks, and written design recommendations were taken together and reviewed at the group level, we noted very few instances where students failed to attend to the cost constraints of the challenge. There were only two occurrences of student groups building designs exceeding the cost limit and no student groups submitted written recommendations for a design that exceeded the cost limit.

Across data sources and school sites, we found that students understood and reliably attended to the criteria and constraints of the engineering design challenge. Notably, students' ability to work with criteria and constraints during the challenge appeared to be more advanced than performance on the EDP post-assessment would predict, particularly in Alex's classroom where students provided correct answers to only 57% of items aligned to ETS1.A.

#### *ETS1.B: Developing possible solutions*

The Framework describes activities students may engage in as they develop possible solutions including brainstorming, communicating initial ideas through informal sketches and diagrams, and creating and testing models. According to the Framework, “the ability to build and use physical, graphical, and mathematical models is an essential part of translating a design idea into a finished product, such as a machine, building, or any other working system” (p. 206) and “data from models and experiments can be analyzed to make decisions about modifying a design” (p. 207). Our analysis of student data centered on determining whether and how students developed and tested multiple possible brake solutions.

Evidence of student engagement in developing possible solutions (ETS1.B) is summarized in Table 6. Student groups ( $n = 52$ ) documented a total of 141 designs representing 30 unique brake/material combinations in engineering notebooks.

There was a clear difference between the two schools in the number of engineering solutions developed by student groups. All of Sydney's students prototyped and tested at least three designs, with three groups going on to complete a fourth design. In contrast, the majority of groups in Alex's classroom (62%) built and tested only two designs. The vast majority of brake solutions were relatively straightforward, basically involving attaching one of the nine types of material available (balloon, plastic wrap, brillo, sponge, felt, plastic bag, rubber band, foil, string) to one of the three LEGO brake types (small brake, large brake, rake brake), although there were a few instances of student groups devising creative brake solutions involving the innovative use of materials. For example, rather than using the circular felt pads as we had envisioned (attaching them to the brake using the adhesive side of the pad), one group reversed the felt pad and attached it to the brake with a string

Table 6  
Evidence of ETS1.B: Developing possible solutions.

|  | Total                  | Sydney's students      | Alex's students        |
|--|------------------------|------------------------|------------------------|
| Design interviews and notebooks  | <i>n</i> = 52 groups   | <i>n</i> = 28 groups   | <i>n</i> = 24 groups   |
| Student groups prototype and test at least three brake designs                                   | 37 (71%)               | 28 (100%)              | 9 (38%)                |
| Student groups have at least one successful design<br>(e.g., brake stops truck before threshold) | 42 (81%)               | 28 (100%)              | 14 (58%)               |
| Student groups reference their test results in design interviews                                 | 39 (75%)               | 25 (89%)               | 14 (58%)               |
| Written design recommendations   | <i>n</i> = 96 students | <i>n</i> = 48 students | <i>n</i> = 48 students |
| Student communicates a design decision in their recommendation letter                            | 94 (98%)               | 48 (100%)              | 46 (98%)               |
| Student explicitly supports design decision with experimental evidence                           | 91 (95%)               | 48 (100%)              | 43 (90%)               |
| Students describe a systematic approach to developing a design solution                          | 26 (27%)               | 16 (33%)               | 10 (21%)               |

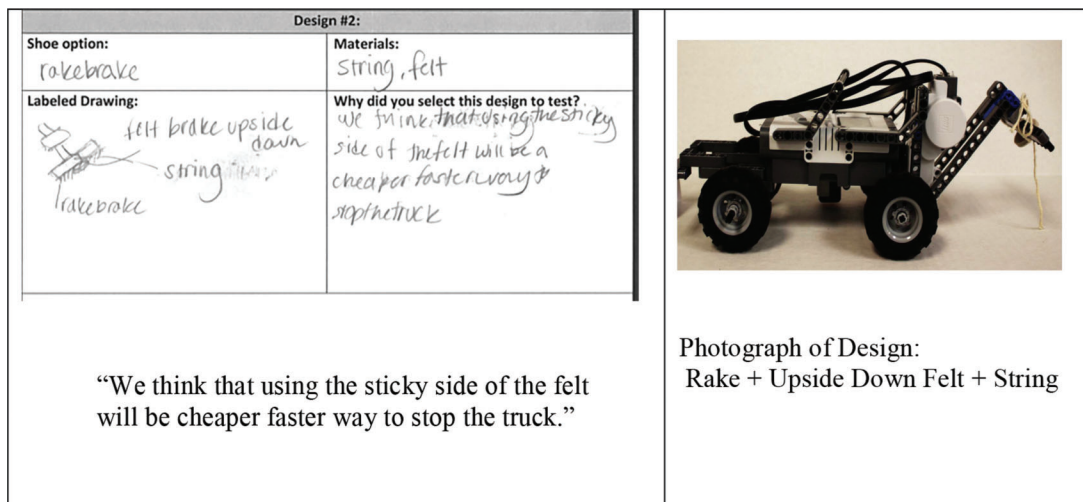


Figure 3. Student engineering notebook and design: innovative use of materials.

so the adhesive side faced downward. An excerpt from one of these students' engineering notebook and a photograph of this design are presented in Figure 3. The student explains this unconventional use of materials stating, "we think that using the sticky side of the felt will be a cheaper, faster way to stop the truck."

Reviewing engineering notebooks indicated varying levels of success when it came to creating brake solutions that met the design requirements (cost and stopping the truck before the threshold). As noted above, of the 30 design combinations, only two exceeded the price limit for the challenge. Nineteen (68%) of the design combinations that met the price criterion were successful in stopping the truck before the threshold at least once. Of the 141 individual designs documented in engineering notebooks, 70 stopped before the threshold, and 71 failed.

In addition to attending to criteria and constraints, as discussed above, interviews reveal various factors students considered as they developed possible solutions. A total of 23 groups (44%) noted that at least one design (most often their first design) was informed by class data that had been collected as part of a previous class investigation on the performance of various materials and brakes. For example,

one student specifically cites data from the class investigation as rationale for their choice to use plastic wrap and the small brake for their first design. "When we looked at the data, we saw that the small shoe had a medium average of 86 [cm] distance and the plastic wrap had like 64 [cm] and the other options that had better distance were too expensive."

The majority (75%) of student groups referred to the results of testing their designs as a factor influencing their brake and material choices for subsequent designs, and 95% of students explicitly supported their design decisions with experimental evidence in their written recommendations. In interviews, students tended to comment generally on how their brake designs performed, noting, for example, that "when we tested the rake brake and tin foil, it didn't do the best." In other instances, students noted that testing demonstrated that their design was successful in stopping the truck before it reached the threshold. Less frequently in interviews, students cited actual data collected during testing. For example, one group described their decision to use plastic wrap as a sort of parachute to "catch some air and slow it down a bit more," noting that their group's design was "literally three centimeters away from the threshold."

Students discussed data gathered from tests more frequently in written recommendations, with 63% using data from testing to draw comparisons between the performance of their recommended design and that of other competing designs in their class.

Design interviews and engineering notebooks also highlighted various strategies student groups employed as they developed their brake solutions. In describing their design rationale, 18 groups (35%) provided descriptions coded as “tinkering.” In these instances, students attributed a design decision primarily to a desire to try something new and different or to experiment with different materials or brakes simply because they were curious about what would happen. Most often, tinkering was isolated to either the brake or the material. For example, several student groups settled upon their choice of brake after testing their first design and decided to see what would happen if they tried a different material in designs two and three.

Another related strategy that became evident in the design interviews was the tendency to take a “control of variables” approach, much like one would in a science laboratory experiment. In these instances, which occurred exclusively in Sydney’s classroom, students described systematically keeping either the brake or the material constant across designs in order to discern the relative effects of modifying either the brake or the material. This approach is evident in the following student’s description of how his group decided to try a different material with the small brake: “In our first experiment, we were successful in keeping the truck under the threshold, and we knew that either the brake or the material was successful, so we decided to change the material and keep the brake.” Evidence of students systematically developing design solutions was relatively rare in written recommendations, occurring in 33% of the sample from Sydney’s classroom and 21% of letters from Alex’s classroom. Frequently, this evidence took the form of students providing data to compare how designs utilizing various materials performed. For example, one student recommended the small brake shoe wrapped with the balloon, stating “this can be shown in the data we collected.” The student goes on to compare the performance and cost of designs combining the balloon with either the small brake shoe or the rake brake.

#### *ETS1.C: Optimizing the design solution*

The Framework describes the process of optimizing design solutions as one that “often requires making trade-offs among competing criteria” adding, “when multiple possible design options are under consideration, with each optimized for different criteria, engineers may use a trade-off matrix to compare the overall advantages and disadvantages of proposed solutions” (p. 209). The Framework further prescribes that by the end of 8th grade, students should understand that the “iterative process of testing the most promising solutions and modifying what is proposed

on the basis of the test results leads to greater refinement and ultimately to an optimal solution” (pp. 209–210). Guided by this description of optimization, our analysis of student data sought to determine whether and how students (1) engaged in an iterative design process in order to refine their brake solutions, (2) utilized the optimization index feature of the curriculum as a method for evaluating brake solutions, and (3) demonstrated an understanding of the concept of trade-offs when describing their brake solutions.

As we analyzed design interview data alongside engineering notebooks, we characterized iteration as instances where students not only designed and tested multiple brakes, but also described their design rationale in ways that indicated clear intent to refine their designs. Designs were classified as iterative both when student groups maintained the same brake and/or material but made modifications or additions to improve the design, and when groups clearly described changing the brake or material to address shortcomings in the previous brake/material combination. The first “modification” strategy often occurred when groups were relatively successful with their first brake/material combination and devoted their second and third designs to attempts to improve performance or minimize costs. For example, one group iterated on their nearly successful first design using the rake and balloon by adding a plastic bag as a parachute for their second design and inserting a felt pad under the balloon in design three. Figure 4 presents design drawings and student rationale illustrating this iterative progression. Iterations involving changes in the brake or material often occurred after a first design was unsuccessful. For example, after an unsuccessful first test of a design with the rake/plastic wrap combination, one group decided to try something completely different and designed a brake using the small brake/rubber band combination.

Although this second design was also unsuccessful, the group saw the advantages of the rubber band and iterated on this design, returning to the rake brake with the goal of maximizing the effectiveness of the rubber bands. This third design was successful. One student described the group’s strategy, “we felt like the more rubber bands we could put on it, the more friction there would be on the ground.”

As summarized in Table 7, we saw differences in iteration across classrooms with nearly all of the student groups in Sydney’s classroom but fewer than half of the groups in Alex’s classroom iterating on their designs. We noted a relationship between the number of brake prototypes students designed and the likelihood of iteration. Of the groups in Alex’s classroom that only completed two designs, 33% demonstrated evidence of iteration compared to 62% of groups in both classrooms that completed three or more designs.

The curriculum introduced an “optimization index,” defined as the design’s stopping distance multiplied by its




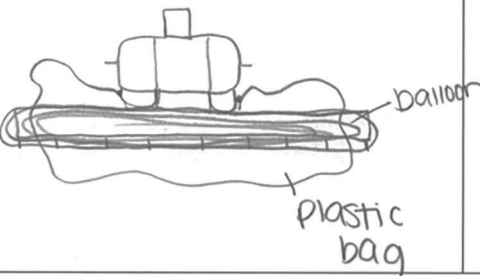
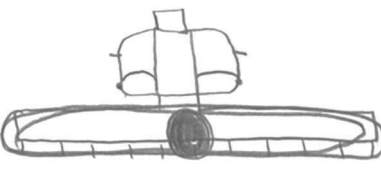
| Design #1:  |  |
|---|--|
| Shoe option:<br>rake shoe   | Materials:<br>balloon  |
| Labeled Drawing:<br>   | Why did you select this design to test?<br>We thought the rake shoe had the most surface area, so we put a balloon over the end of it. Then cut off the extra and spread it over the break. It was the cheapest option and it will add the friction. |
| Design #2:  |  |
| Shoe option:<br>rake shoe   | Materials:<br>plastic bag, balloon   |
| Labeled Drawing:<br>  | Why did you select this design to test?<br>We thought if we connected the balloon in a way, it would act as a parachute and slow the car.  |
| Design #3:  |  |
| Shoe option:<br>rake shoe   | Materials:<br>balloon, felt  |
| Labeled Drawing:<br> | Why did you select this design to test?<br>The felt is easy to add to the break and it will help increase the friction and surface area  |

Figure 4. Student engineering notebook example of iterative design.

cost, as a tool for evaluating brake designs. Although the engineering notebook guided students in calculating the optimization index as a method for evaluating their designs, in our sample of 144 student interviews, the optimization index was only mentioned once. In contrast, as presented in Table 7, the optimization index was cited as evidence in written design recommendations by over half of the total student sample including the majority of students in Sydney’s classroom and a large minority of students in Alex’s classroom.

The curriculum explicitly introduces the concept of trade-offs in engineering, describing how engineering often involves having to make tough decisions when weighing the relative importance of costs against the performance of a design. In spite of this, in the design interviews, students rarely used the actual term “trade-off” when describing their design decisions. Instead, instances that were coded as indicating application of the concept of trade-offs typically involved students describing the trade-offs they made in order to minimize costs or improve brake performance.



Table 7  
Evidence of ETS1.C: Optimizing the design solution.

|  | Total                  | Sydney's students      | Alex's students        |
|--|------------------------|------------------------|------------------------|
| Design interviews and notebooks                                  | <i>n</i> = 52 groups   | <i>n</i> = 28 groups   | <i>n</i> = 24 groups   |
| Group design descriptions indicative of iterative design process | 38 (73%)               | 27 (96%)               | 11 (46%)               |
| Group references a design's optimization index                   | 1 (2%)                 | 1 (4%)                 | 0 (0%)                 |
| Group references trade-offs                                      | 10 (19%)               | 9 (32%)                | 1 (4%)                 |
| Written design recommendations                                   | <i>n</i> = 96 students | <i>n</i> = 48 students | <i>n</i> = 48 students |
| Student supports decision using optimization index               | 52 (54%)               | 32 (67%)               | 20 (42%)               |
| Design recommendation indicates optimization                     | 28 (29%)               | 20 (42%)               | 8 (17%)                |

For example, one group described their choice to use the rake over the large brake stating:

If we had a larger surface area and then you add something with, like, a lot of friction, that would be the best brake, but it might also cost a lot because most of the things made out of rubber were in the higher cost area because they were the most effective, so that's why we chose the rake brake because you still have that large area.

Similarly, another group succinctly describes the trade-off between cost and performance as rationale for their decision to switch from the small brake to the rake brake: "we wanted to minimize cost without sacrificing effectivity of the brake."

#### *Teacher Perspectives on the Engineering DCIs*

Finally, we provide results of teacher interviews to contextualize student engagement in the NGSS engineering DCIs. Consistent with student interviews and written recommendations, teachers unanimously affirmed that their students capably worked with criteria and constraints as they completed the brake challenge. Two teachers noted that both they and their students were occasionally unclear about the difference between criteria and constraints as abstract concepts; however, even these teachers described how their students had little difficulty attending to the specific criteria and constraints of the brake challenge.

Teachers also described how the curriculum facilitated opportunities for students to design multiple solutions to the brake challenge (ETS1.B). Often, teachers noted the iterative design process as a highpoint in student engagement. For example, one teacher stated that "they loved reiterating that brake" but also noted that time constraints limited iteration, stating "some of my classes wanted to keep going but we didn't have time." Sydney described how his students "could have probably kept that going for a few more days...I think they could have easily gotten to five or six iterations," adding his observation that sharing data within and across class periods seemed to fuel student motivation to iteratively improve upon brake designs.

Alex expressed somewhat lower expectations for student engagement in an iterative design process. In discussing how students were permitted to "go at their own pace" as the engineering notebook guided them through the challenge, Alex stated "everybody got at least two iterations done...it just allowed them that freedom...and I thought they did pretty good with it." This satisfaction with students' design process was tempered by the observation that "I think there are some groups that were sitting there basically at random trying different things for no apparent reason." Interestingly, in discussing activities that were cut short due to time constraints, Alex did not regret limited time for iteration but rather expressed the need for students to take more notes and study the engineering content in the curriculum:

They read it in that book, but you know damn well they don't remember it ten minutes later. So, unless it's something that they have that they can go back to and study for and you're going to quiz them and hold them accountable for that...I kind of wish in hindsight that I had done that, but you know just to get everything else done, it didn't happen.

In describing their implementation of the brake challenge, teachers cited optimization as the most challenging of the disciplinary core ideas. As also evidenced in assessments, interviews, and written recommendations, Sydney describes how his students capably calculated and used the optimization index to make decision decisions; however, he also observed that students primarily focused on minimizing cost rather than thoughtfully considering trade-offs: "There were a few groups that really kind of honed in on optimization, but mostly it was just like 'Ok. Now, do it cheaper.'" Other teachers noted that they believed their students did not understand or disregarded the optimization index and failed to grasp the concept of optimization, generally. For example, in describing whether her students understood optimization, one teacher claimed "I think if you asked a kid today what they could tell you about optimization they'd go, 'What?'" Finally, Alex and one other teacher clearly described how, due to time constraints and misalignment with science standards, they do not consider engineering in general, and activities

focused on optimization in particular, priorities in their classrooms. For example, as one teacher discussed how engineering concepts do not appear on the state-level standardized science test students take at the end of the school year, she suggested that optimization should be considered an optional enrichment activity:

No offense, but none of that was on the test and it's never going to be on the test. It's an enrichment activity. It's not something we had time to spend on...I mean we did it because we are trying to stay with fidelity, but I totally would have dropped it for the sake of time if I could have because I was in panic mode at that point.

Although teacher accounts necessarily reflect individual teaching styles and attitudes toward engineering and NGSS, they also provide insight into the realities of integrating engineering within science classrooms. Often teachers' concerns centered on whether, given mandates to cover science standards and prepare students for standardized tests, they could afford to devote time to an iterative engineering design process. Indeed, teachers' willingness to prioritize student engagement in iterative design and optimization (ETS1.C) varied depending on how much pressure they felt to focus instructional time on science content aligned to state-level standardized tests. As illustrated by the teacher in "panic mode" cited above, teachers who reported expediting or truncating the engineering design process most often cited the need to allocate time to science standards. In contrast, Sydney reported that, given his students' level of achievement, he felt relatively little pressure to spend less time on engineering in order to prioritize science content standards. After sharing that his students excelled on the standardized test the previous year, with a number of students earning perfect scores, Sydney draws a connection between his relative autonomy and student performance on standardized tests:

I think it's one of those things, where it's like as long as I can deliver the standardized test score, they really don't care what I do. They seem to support innovation. That being said, if that standardized test score doesn't appear, then everything gets scrutinized.

*Research Question 2: Application of Science Concepts*

A thorough reporting of science learning outcomes is beyond the scope of this paper; however, to contextualize students' application of science concepts within the engineering design challenge, we reference assessments and performance assessment data indicating significant increases in student understanding of targeted physical science concepts following participation in the curriculum (Gale, Koval, Wind, Ryan, & Usselman, 2016a; Gale, Wind, Dagosta, Ryan, & Usselman, 2016b). For example, student performance on a pre-post assessment conducted contemporaneously with this study is presented in Table 8. This assessment includes validated AAAS force and motion items along with additional items developed and validated by the research team using Rasch modeling. The following section describes the extent and ways in which students drew upon their understanding of science concepts as they engaged in the SLIDER brake challenge.

Taken together, design interviews, written recommendations, and engineering notebooks provide clear evidence that students applied their understanding of physical science DCIs within the context of the brake challenge. Table 9 presents the frequency with which students referenced relevant science concepts by data source. Most often, in both interviews and written design recommendations, the application of physics core ideas centered on friction and the need to design a brake featuring a combination of brake and materials that would increase friction in order to stop the truck before the threshold. For example, one group in Alex's class described their decision to design a brake using both brillo and felt because they thought these materials "have bristles to scrub the ground and cause more friction." Similarly, in written recommendations, 79% of Sydney's students and 50% of Alex's students explicitly referenced friction.

As described previously, the SLIDER curriculum targets understanding of a number of physical science concepts beyond friction. Students should develop more broadly an understanding of how the balance of forces on an object affects the motion of an object (NGSS MS-PS2-2). In the brake challenge, students should realize that a change in the frictional forces acting on a moving object produces a change in the balance of forces acting on the object, *thus generating a new net force*. Subsequently, when the net

Table 8  
Student performance on core idea assessments.

|              | Unit 1 content                    |      | Unit 2 content                    |      |
|--------------|-----------------------------------|------|-----------------------------------|------|
|              | Proportion correct (n = 20 items) |      | Proportion correct (n = 16 items) |      |
|              | M                                 | SD   | M                                 | SD   |
| All students |                                   |      |                                   |      |
| Pre          | 0.47                              | 0.15 | 0.39                              | 0.16 |
| Post         | 0.66                              | 0.11 | 0.58                              | 0.12 |

Table 9  
Evidence of application of physical science DCI knowledge.

|   | Total                  | Sydney's students      | Alex's students        |
|---|------------------------|------------------------|------------------------|
| Design interviews and engineering notebooks                                     | <i>n</i> = 52 groups   | <i>n</i> = 28 groups   | <i>n</i> = 24 groups   |
| Group design rationale includes reference to relevant physics DCI knowledge     | 39 (75%)               | 26 (93%)               | 13 (54%)               |
| Written design recommendations  | <i>n</i> = 96 students | <i>n</i> = 48 students | <i>n</i> = 48 students |
| Student explicitly supports design decision with relevant physics DCI knowledge | 66 (69%)               | 39 (81%)               | 27 (56%)               |

force changes, the motion of the object (its speed and/or direction) will change, i.e., acceleration occurs. The curriculum targets this chain of reasoning, and student work and other assessments show development of this understanding (Gale et al., 2016a). Students' written recommendations did include reasoning with many of these concepts, albeit at relatively low rates: balance of forces (8%), velocity/speed (6%), energy (13%), force (8%), and acceleration (2%). For example, a written recommendation from Sydney's class concluded that, "our tests have shown that this brake creates the most friction which leads to a shorter stopping distance. The brake thus creates more net force opposite of the truck's direction. This leads to a decrease in the truck's velocity." This more comprehensive reasoning, however, was less frequent than reasoning more simply with the concept of friction alone. While it is reassuring that the curriculum, as intended, develops understanding of friction, it is also unsurprising that students' reasoning for their brake design centers primarily on friction, given that friction is the most evident and primary factor in achieving the challenge. Notably, in both design interviews and letters, instances where students referenced irrelevant science concepts or applied science concepts incorrectly were virtually nonexistent.

In addition to noting students' use of physical science DCIs, we observed the spontaneous application of certain science practices within the context of the brake challenge. Specifically, we noted that several student groups treated the brake and material options as variables that they systematically controlled in order to identify which contributed to their brake's performance. This practice, which is indicative of NGSS Practice 3: Planning and Carrying out Investigations (NRC, 2012), was present throughout the many earlier science investigations within the SLIDER curriculum but not prescribed as part of the brake challenge.

## Discussion

Taken together, the assessments and artifacts students complete as part of the SLIDER curriculum lend insight into both the possibilities and the limitations of engineering in the science classroom. In this section, we discuss implications of our results pertaining to each of the engineering DCIs along with general lessons learned from our project's experience integrating engineering DCIs within science classrooms.

Regarding ETS1.A, defining and delimiting an engineering problem, we found that the SLIDER curriculum fostered students' ability to work with criteria and constraints. The frequency with which students applied their understanding of criteria and constraints during the brake challenge contrasted with results for EDP assessment items aligned with ETS1.A. This discrepancy may stem from the difficulty of distinguishing between, and operationalizing, the concepts of "criteria" and "constraints." As the Framework defines criteria and constraints separately, our EDP assessment included separate items aligned with the definitions of criteria and constraints in the Framework. However, in the context of analyzing students' design descriptions, distinguishing between criteria and constraints became nearly impossible. This was particularly true with regard to students' discussions of the cost of their designs, as cost is identified in the Framework definition of criteria as a potential "need of an expected end-user of technology" (p. 204) and as a potential constraint under which a design problem must be solved.

In many ways, the development of possible design solutions (ETS1.B) was the centerpiece of the brake challenge. Observing the ways in which students engaged in this challenge highlights a number of important considerations for curriculum development and the introduction of engineering into core science classes. Our data suggest certain minimum expectations for successful DCI-aligned engineering design experiences included in a science curriculum. Recall that 100% of student groups within Sydney's classes produced a successful design by the third round of iterations. In contrast, in Alex's class, where the majority of groups only created two prototypes, 42% of students never designed and tested a solution that met both criteria for success. These results suggest a need for curricula to allow sufficient time for students to engage in multiple design iterations and, more generally, to scale design challenges such that students have opportunities for both success and failure as they prototype and test their designs. If students only experience failure, they are not likely to want to increase their engagement with engineering.

Optimizing the design solutions (ETS1.C) was more difficult to achieve than ETS1.A and ETS1.B within the science classes in this study. Although the curriculum explicitly referenced optimization and required that students iterate on their designs, achieving the endpoint envisioned by NGSS for this disciplinary core idea proved challenging for both students and teachers. Though concepts related to ETS1.C, such as the idea of trade-offs, are

explicitly scaffolded within the curriculum, these concepts occurred relatively infrequently in students' descriptions of their design solutions. More frequently, students referenced the optimization index in their recommendation letters; however, the degree to which these references reflect a fully developed understanding of optimization remains unclear. Indeed, given the constraints of working within school systems where achieving the engineering DCIs is not prioritized, the curriculum itself was limited in the degree to which it could emphasize optimization. For example, although the engineering notebook asks students to justify their design decisions, the brake challenge does not require students to analyze data to identify evidence of similarities and differences in the features of various design solutions. Although one of the project's teachers, Sydney, generally embraced the integration of engineering and actually hoped for *more* time to devote to optimization, we found that even after significant professional development over the course of several years, several of the teachers participating in the project continued to view optimization as a superfluous aspect of engineering. For these teachers, optimization was perceived as too advanced for their students, a distraction from other engineering tasks, or simply too time-consuming, given their priority of covering grade-level science content.

Our experience developing the SLIDER curriculum and the results reported herein highlight potential tensions between science and engineering as they manifest in classrooms attempting to integrate these two disciplines. On the one hand, we have accumulated clear evidence that engineering design can effectively serve as a context for students' application of their developing science knowledge. Our results also suggest possibilities for students to develop a working understanding of engineering DCIs during science instruction. On the other hand, we have come to appreciate the somewhat divergent goals of science and engineering, as articulated within the NGSS. When students engage in scientific experimentation and inquiry, we hope their effort and reason will enable them to acquire and apply specific knowledge about the natural world that governs the phenomena of the problem space. This is particularly evident in physical science, where there are many cause and effect relationships (e.g., if the balance of force changes on an object, the motion of an object changes proportionally). The problem of braking more quickly, in the case of the challenge here, demands a simple input—more friction. There is, indeed, an answer to the problem at hand. This contrasts with the goal of engineering—to engage in a design process to arrive at a solution to a problem, a solution that may be unlike any other solution, but just as effective. That is, there is more than one way to generate the friction needed, and thus there could be multiple solutions. The idea that students, even in a well-designed curriculum and challenge, could parse this nuanced difference seems unrealistic.

Our results from the field also suggest implications for assessing student mastery of the engineering DCIs. What we were able to discern about students' understanding of the engineering DCIs was dependent on the mode and timing of our various assessments. Interviews provided formative insights into the degree to which students systematically iterated on their designs that were not necessarily evident in summative written recommendations or the multiple choice EDP assessment. Similarly, the degree to which students were able to use the optimization index to support their design decisions was evident through an analysis of students' engineering notebooks and written design recommendations but did not occur in design interviews. These variations across data sources suggest the importance of a holistic approach to assessing student mastery of engineering DCIs.

Consistent with previous research on the implementation of innovations (Century, Cassata, Rudnick, & Freeman, 2012), when considered alongside student data, teacher interviews illustrate ways in which teacher attitudes, beliefs, and prior experience may influence the degree and manner in which engineering is integrated in science classrooms. Not surprisingly, with extensive previous experience with PBL and robotics, Sydney expressed a predisposition to engage students as fully as possible in the engineering DCIs. In contrast, Alex, a self-described "traditional" teacher embraced engineering in a more limited way, attempting to give students experience with an iterative design process but ultimately cutting the design challenge short. In describing her perception of student mastery of the engineering design process, Alex noted that she felt student understanding of the design process required more time spent on traditional approaches to instruction such as "studying" and completing quizzes. It is particularly noteworthy that Alex's inclination toward traditional teaching methods remained following several years of involvement with the project and participation in ongoing professional development. While differences between these focal teachers are noteworthy, because this study focused on understanding student engagement with the engineering DCIs, we cannot necessarily draw conclusions about how teacher beliefs and experience may interact to influence curriculum enactment and, ultimately, student experience. Thus, careful study of how teacher characteristics such as motivation, self-efficacy beliefs, and attitudes influence the introduction of engineering DCIs within science classrooms remains an important avenue for future research.

By exploring how student and teacher experiences with the same curriculum unfold at two very different school sites, the study adds to the field's understanding of the array of factors at play when the engineering DCIs land in real science classrooms. Although teachers were generally invested in the project and participated in trainings designed to build their understanding of the engineering

design process, meaningful differences emerged when they encountered realities of facilitating the design process in their science classrooms. Just as students participating in the design challenge negotiate trade-offs between performance and cost, teachers were faced with difficult decisions about how much time and attention they and their students could “afford” to devote to the engineering challenge. Our data suggest that students required a minimum of three design iterations to address the engineering DCIs; however, some teachers found this level of engagement difficult to justify, given competing priorities such as covering state science standards. This tension suggests a need for future research exploring the concordance of NGSS and the expectations placed on teachers and students by science education policy at the state and district levels.

Scholars of design-based implementation research raise concerns about the degree to which innovations that succeed in the context of DBIR can be effectively implemented, scaled, and sustained in the absence of the intensive support often provided by design-based research teams (Anderson et al., 2018; Fishman & Krajcik, 2003). Based on our experience working with teachers to create space for meaningful enactment of the engineering DCIs in their science classrooms, we certainly share these concerns. Future research should explore the staying power of curriculum innovations that integrate engineering in science classrooms with particular attention to factors that may either hinder or promote sustainability beyond the horizon of design-based research projects.

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