Developing a Highway Crash Safety Barrier

Using Science and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas to Solve Problems

BY TODD HUTNER, VICTOR SAMPSON, HANNAH BROOKS, CHRISTINA BAZE, JILL GREGORY, KAREN SOMMERHAUSER, AND MARK BROADWAY

In response to a lack of high quality instructional materials encompassing three-dimensional instruction, STEM integration, and issues of access and inclusion, we developed an instructional framework—Argument-Driven Engineering (ADE)—and associated STEM design challenges (SDCs) based on this framework. ADE was developed as a way to support science teachers in teaching DCIs through engineering practices, allowing students to figure out both engineering and science questions about how things work and why they happen. Our group involves a partnership of education researchers, district administrators, and middle school science teachers formed to develop SDCs.

Argument-Driven Engineering

The intent of the Argument-Driven Engineering (ADE) instructional model is to provide teachers with a way to focus on STEM and frame engineering as a way to make positive societal changes (NAE, 2008). We define STEM as the use of core ideas and practices from multiple disciplines (science, technology and computer science, engineering, and math) to understand the world, improve existing ways of doing things, or to figure out solutions to problems. Our main goal is to give students more opportunities to use disciplinary core ideas (DCIs), crosscutting concepts (CCs), and science and engineering practices (SEPs) to design a solution to a problem that is important and meaningful to them. In designing the ADE instructional model, our group also placed a premium on valuing student ideas and perspectives as they design solutions to meaningful and relevant problems. In turn, this will help students see themselves as knowers and doers of engineering. In addition, integrating engineering into the middle school science curriculum makes engineering more inclusive, allowing all students, not just a select few, to have these experiences.

To provide all students with authentic engineering experiences, the ADE instructional model exposes science students to the iterative nature of design and systems thinking, encouraging purposeful solutions based on constraints and criteria (NCE and NRC 2009). In addition, the ADE instructional model highlights the interdisciplinary nature of engineering, and provides opportunities for students to develop "engineering habits of mind," which means engaging students in creativity, optimism, collaboration, communication, and ethi-

CONTENT AREA

Physical science

GRADE LEVEL

6–8

BIG IDEA/UNIT

Newton's laws

ESSENTIAL PRE-EXISTING KNOWLEDGE

Newton's three laws

TIME REQUIRED

Seven to ten 45-minute class periods

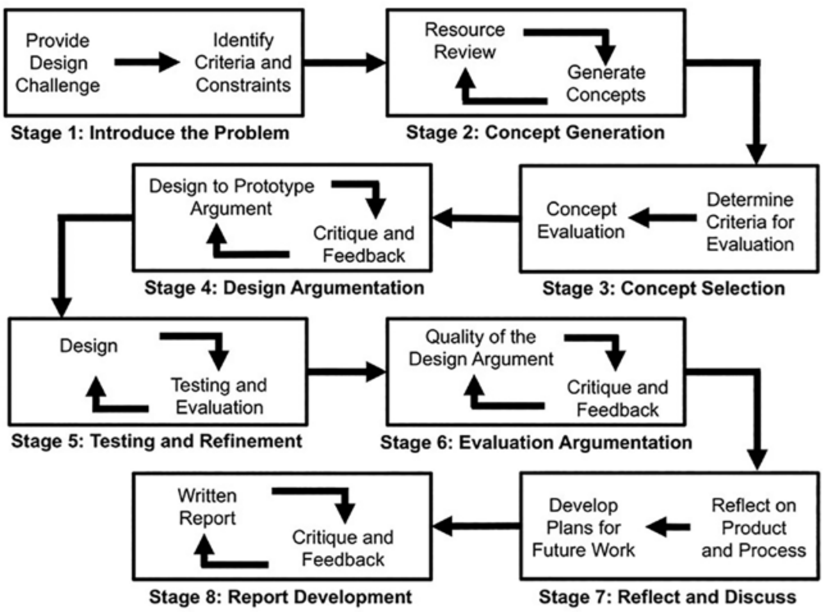
COST

$400

SAFETY

See safety notes in article

FIGURE 1: The eight stages of the ADE framework. Student products are indicated in gray boxes.



cal analysis (NCE and NRC 2009). Building on these themes, the ADE instructional framework embeds argumentation within an eight-stage process shown graphically in Figure 1.

Stage 1: Introduce the problem

During each ADE STEM Design Challenge (SDC), students work on an authentic problem (a societal challenge) which provides motivation and context for their learning. As an introduction to Newton's laws of motion, students learn about highway crashes and the origins of seatbelts, a familiar topic. In this SDC, students design a crash safety barrier, such as those seen on many highways. We chose to focus on crash safety barriers for two reasons. First, crash safety barriers are external to the car, which allows students to design a universal safety measure. In this way, the SDC identifies a way to help make the world a better place for people regardless of their ability to purchase an expensive car with the latest safety features. Second, the barrier provides a way to more clearly focus on Newton's laws.

Newton's laws are central to understanding collisions, including automobile accidents. Newton's first law explains that a force must act on the car because it comes to a stop; Newton's second law calculates the magnitude of the force; and Newton's third law explains why a force is exerted back on the car when it crashes into a stationary object. To further engage students in the challenge, the class views a short clip from *Mythbusters* investigating the amount of damage resulting from automobile collisions and noted important science content and related questions (see Resources).

To provide equitable access to scientific vocabulary and content, students will read through a short passage containing bolded key terms and scientific principles related to the DCI (see Figure 2). This process allows each student to review and reflect on the foundational scientific content and the problem they are trying to solve before starting group collaboration. Students are asked to write down what they learned from the reading and to identify the problem they need to solve at the end of the reading, providing teachers with a formative checkpoint.

The design task (Figure 3) is outlined and followed with a fundamental scientific question. In this ADE STEM design challenge, the fundamental science

FIGURE 2: A brief introduction to key scientific content related to Newton's third law

Scientists and engineers define a **collision** as two objects exerting an equal but opposite **force** on each other. A **force** is a push or a pull. Every force is described by both its **magnitude** (how much force) and **direction**. The most common unit for measuring force is the **Newton.** (If you hold a small apple in your hand, the force of the apple against your hand is about equal to 1 Newton.)

In everyday language, we tend to use "collision" to mean two objects "crashing into" each other, often with considerable force. For engineers and other scientists, collisions can occur when two small things interact as well. For example, when you walk, each step you take is a "collision." Your foot and the ground collide.

When studying automobile collisions and designing safety systems to keep people safe, engineers apply **Newton's 3rd Law** to understand the forces acting on the objects. Formally, Newton's 3rd Law states:

Whenever one object exerts a force on a second object, the second exerts an equal force in the opposite direction on the first (Giancoli, 2005, p. 78).

One type of automobile collision that engineers and safety experts study is a head-on collision between a car and a wall or barrier. According to Newton's 3rd Law, when a car crashes head-on into a wall, it will exert a force on the wall. This force is what causes the wall to break. At the same time, the wall will exert an equal force back on the car. In other words, the wall exerts an equal and opposite force on the car.

FIGURE 3: The design task and the underlying scientific content

The Task

In this **design challenge** you will use what you know about collisions, Newton's 3rd Law, and models to create a crash safety barrier that will enable more people to avoid serious injury during a car accident. The crash safety barrier must be able reduce the force acting on a moving object as a result of a head-on collision by at least 80% compared to the force without the barrier. However, the client would like the crash safety barrier to be able to reduce the force acting on the moving object by even more if possible. The prototype for your crash safety barrier must have a mass between 100 and 250 grams. In addition, the crash safety barrier must be able to be attached to the ground so it will not move during a collision and it cannot have a footprint that is greater than 120 cm^2. The client would also like the barrier to be reusable so the entire barrier does not have to be replaced after each accident. The company wants to be able to produce the barrier for under $15.00 so it must cost as little as possible to make.

The **fundamental scientific question** related to this design is: ***How do you know the magnitude and direction of the force acting on the moving object during the collision?***

question asks: How do you know the magnitude and direction of the force acting on the moving object during the collision? The goal of each SDC is to weave the SEPs and DCIs together in a seamless learning experience, and the fundamental science question helps students think about the relationship between their design and the underlying DCI.

Student groups use a graphic organizer embedded in the SDC handout to summarize the design goal and potential impact on the world or society. The groups also identify design criteria and constraints mentioned in the handout, a practice that encourages students to internalize the process of identifying design parameters. In addition, students are asked to describe the science underlying the design. This process is aided by providing students with the results of materials tests, conducted by the authors, which highlight the DCI (see Online Supplemental Materials).

Stage 2: Concept generation

Once students have identified the design parameters, they move to the second stage of the model—generating ideas for potential solutions. Students brainstorm individual designs using the parameters outlined in the problem statement, providing ideas each student can contribute to the group design. Students calculate the cost of materials (Figure 4) as they develop each new design, allowing for easy integration of mathematical principles.

Stage 3: Concept selection

After each student has had time to develop their own designs, groups use a criterion matrix to evaluate contributed designs—an important step transitioning students from tinkering toward careful design analysis through authentic engineering practices. Using the criteria and constraints identified earlier, evaluation criteria are determined as a class, ensuring that each group uses the same standard of evaluation. For example, students ensure that each design is under $15 (constraint) and evaluate their designs based on the ability to reduce the force acting on the car (criteria). A criterion matrix (see Online Supplemental Materials) is used to help students objectively evaluate the designs by considering trade-offs inherent to each design and to establish group consensus on the design to prototype.

Groups use the design selected by the group to sketch the prototype in their SDC handouts (Figure 5) and are required to consider the available materials necessary for the product.

FIGURE 4: Options for materials are provided, requiring students to consider cost

Materials Review

You may use any of the following materials during this challenge. Take a minute to examine all the different materials. You will also be given the results of some tests conducted on these materials. You may want to use some of the information from these tests to help you determine the advantages and disadvantages of using each material. Be sure to take notes about their characteristics and how you might be able to use them.

Materials	Unit	Cost
Consumables		
Plastic bottle (8oz)	1 bottle	$0.75
Plastic bottle (20oz)	1 bottle	$1.00
Plastic jug (64oz)	1 jug	$2.00
Styrofoam cups	1 cup	$1.00
Sand	100g	$1.00
Popsicle sticks	1 stick	$0.25
Rice	100g	$1.50
Foam	100cm^2	$2.25
Duct tape	25cm	$0.50
Equipment		
Cart with force-probe attachment		N/A
Testing ramp		N/A
Scissors		N/A
Box cutter		N/A

Notes...

Stage 4: Design argumentation

To gather feedback from peers on their prototype design, students participate in a design argumentation session. Students' design arguments consist of a claim and reasons. The claim includes a sketch of their prototype, a description of how it works, and the underlying science principles informing their design (Newton's third law for this SDC). The *reasons* allow students to explain why the proposed design is the best option in light of the evaluation criteria.

The class then engages in a modified gallery walk with half of each group moving around the room to provide peer feedback on other groups' prototypes. The other half of each group stays behind to explain their argument to visiting peers (see Online Supplemental Materials). The SDC handout provides a place for students to document suggestions for improvement and ideas they may want to integrate into their design (see Online Supplemental Materials). Student groups discuss their experiences during the gallery walk and make any modifications. This step allows students to reflect and consider alternatives and revisions to optimize the design.

Stage 5: Building, testing, and refining

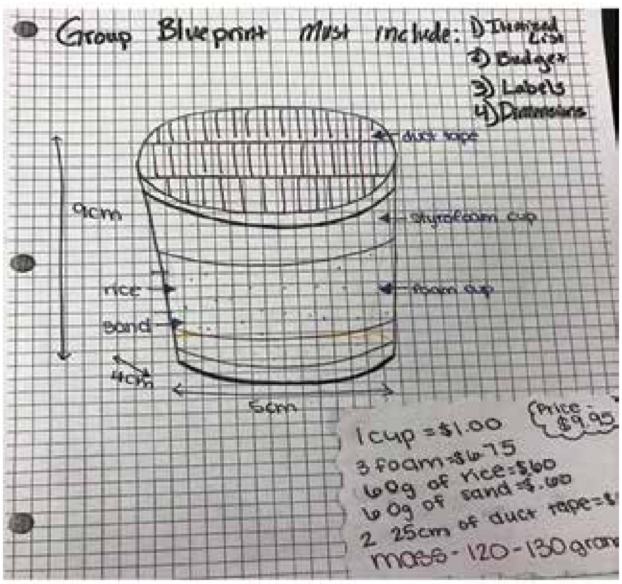
As engineering uses an iterative testing approach to problem solving, students learning through engineering design should model a similar process (Cunningham and Carlsen 2014). The ADE framework promotes multiple design-test-revise cycles. As groups build their prototypes, they keep track of materials, including the amount and cost of each item, and modifications made to the original design. The development stage includes several additional *NGSS* science and engineering practices that allow students to gather rich data to evaluate their prototypes (see *NGSS* connections box, p. 43).

Students develop a procedure to test their prototype using the tools available to them and consider the type of data they want to collect. Groups must obtain teacher approval before starting to build and test, which allows teachers to review the testing procedure. Students should use caution when using hot glue, and we recommend providing a low-temperature hot glue gun. Because students may want to cut the plastic bottles, we recommend using thin plastic water bottles that can be easily cut with scissors.

In this SDC, student groups placed their prototypes on a track between a force probe and a colliding "car" to determine the forces acting on the car during collision (Figure 6). The force probe is fastened to the track (and not the car) to highlight the connection to Newton's third law and the student performance expectation from the *NGSS*. Data from these tests are collected in the SDC handout, so that students are able to easily access the information later for a second argumentation session and a written report.

During testing, student groups are allowed to make modifications to the prototype that would improve the overall design and update the materials and cost information as they proceed. Because of time restrictions, most teachers have students complete two or three iterations, but teachers can choose to allow more. Once groups have completed the necessary tests, they compile the data from all test sessions and discuss how well the prototype met the design criteria.

FIGURE 5: An example prototype and material needs from a participating group



Stage 6: Evaluation argumentation

Students then participate in a second argumentation session to share why their design is a good way to solve the problem (see Online Supplemental Materials). To share their design, the students create an evaluation argument that consists of a claim, evidence in support of their claim (analyzed data and interpretations of the analysis), and justification of the evidence (Figure 7). The justification requires students to explain why their evidence matters and why they collected the data they did, and how it relates back to the scientific foundation of the DCI. Students engage in another modified gallery walk and are encouraged to question one another and provide feedback on all components of the argument, with teachers helping to scaffold student interactions.

Stage 7: Reflect and discuss

At this point, the teacher leads a whole-class discussion with two components. First, the teacher should discuss the DCIs and the CCs at the heart of the SDC to help students think about how they used DCIs and CCs to develop a solution to a problem. If students express everyday ideas that are not consistent with the DCIs or CCs during this discussion, we suggest addressing them during this time. Everyday ideas that students often use to explain the forces acting on objects during a collision include (1) a force is a property of an object (rather than an interaction between two objects) and (2) when two objects collide, the force acting on the one object occurs before the force acting on other one (rather than at the same time). A productive way to help students think about the usefulness of these everyday ideas in this context is to encourage them to use these ideas to explain what is happening during a collision, compare that to how Newton's third law could also be used to explain the same collision, and then ask them which set of ideas is more useful in this context. The teacher should then encourage students to reflect on how they designed a solution to the problem. As part of this discussion, the teachers should ask students to think about both the strengths and weaknesses of the process and then brainstorm specific ways to improve for their next SDC.

Stage 8: Report development

After reviewing the peer feedback collected during the gallery walk, students work individually to draft a written design report that details the completion of the entire design task and describes new understanding gained from the SDC. Student reports consist of four sections including the nature of the problem, what they did to design a solution to the problem, their final product, and quality of the design argument. To show their understanding of Newton's third law and their mastery of the performance expectation, students should include an answer to the fundamental science question as part of the report.

Reports undergo a blind peer review using a guide so that students are able to give and receive actionable feedback and have an opportunity to discuss differences between stronger and weaker reports. The

FIGURE 6: Students test their prototype using the force probe

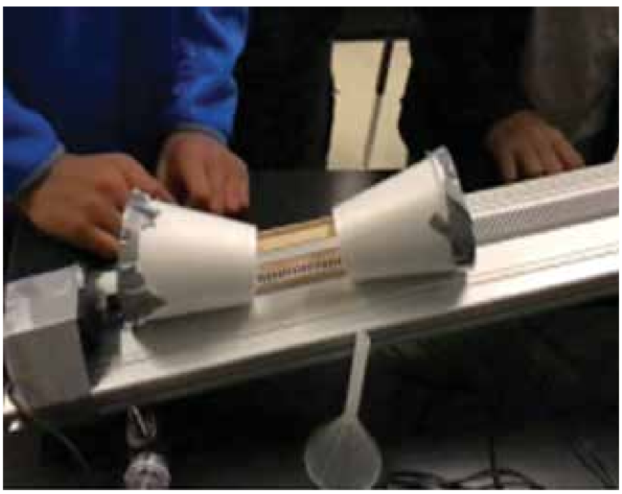
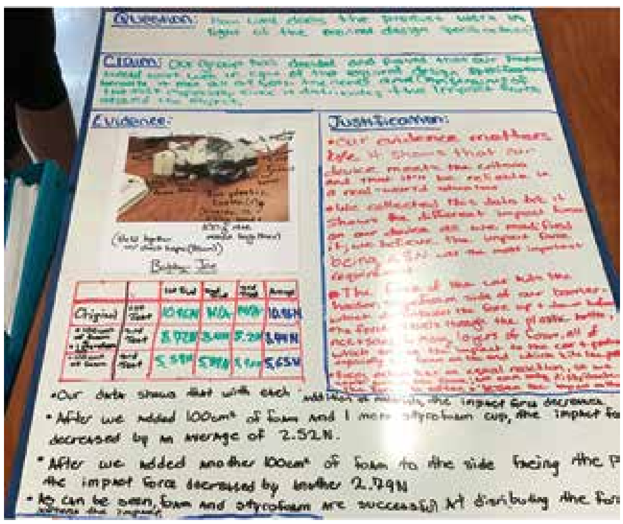


FIGURE 7: Students evaluate what evidence to use during the argumentation session



writing component of this framework is critical, as it promotes individual learning and helps students solidify their understanding of the DCIs and argument construction (Sampson et al. 2013). Through peer review and revision, students are able to clearly communicate what they have learned about engineering practices and the scientific principles associated with Newton's third law of motion. The peer-review guide also has sections for the teacher to provide a grade on each criterion. The students' grade for the report is their summated score on the rubric.

Hints from teachers

The teachers who implemented this unit also provided the following hints to make this SDC successful:

- Use questioning during the testing and refining (Stage 5) to make sure students are using their understanding of Newton's third law and the materials to reduce the amount of force.
- Spend time in small groups or as a whole class having students describe how Newton's third law applies to the barrier. Make sure they understand before they design and build.
- While the lab focuses on Newton's third law, allow students to draw on their understanding of the first and second laws as well. This will help solidify students' understanding of all three laws and how they relate to each other.
- Allow students to make mistakes, as productive struggle will result in better understanding of the concepts and practices.

Conclusion

The inclusion of engineering practices in the *NGSS* requires teachers to think creatively about how to engage students in authentic problems requiring solutions that can be addressed in the confines of the classroom, a practice supported by the ADE instructional model. The flexibility inherent in the ADE model provides teachers with a more accessible way to engage students in the engineering field, while still honoring the role of scientific practices in the classroom. Using argumentation as a way to make student thinking visible helps teachers determine where students may need further scaffolding to learn DCIs or develop proficiency with practices. ●

ACKNOWLEDGMENT

The development of the ADE framework and this specific STEM design challenge was supported by the National Science Foundation's Research in the Formation of Engineers program (Award Number 1607916). We want to acknowledge Melissa Brophy-Plasencio, Kenneth Gustafson, Stephanie Rivale, and Melissa Schermerhorn in the development of the ADE framework and this particular STEM design challenge. We would also like to thank Lawrence Chu, Rachel Gonzalez, Stacy Dinkins, Chevaun McCray, and Richard Crawford for their contributions to this article.

RESOURCES

Mythbusters, "Crash Force"—*www.dailymotion.com/video/x2n9j62*

ONLINE SUPPLEMENTAL MATERIALS

Materials tests, design matrix, design argument template, sample student responses, evaluation argumentation sample, guiding questions—*www.nsta.org/scope1908*

REFERENCES

Cunningham, C.M., and W.S. Carlsen. 2014. Precollege engineering education. In *Handbook of research in science education*, eds. N. Lederman and S.K. Abell, 747–758. New York: Routledge.

National Academy of Engineering. 2008. *Changing the conversation: Messages for improving public understanding of engineering*. https://doi.org/10.17226/12187

National Council of Engineering and National Research Council (NCE and NRC). 2009. *Engineering in K–12 education: Understanding the status and improving the prospects*. Washington, DC: National Academies Press. *www.nap.edu/catalog/12635/engineering-in-k-12-education-understanding-the-status-and-improving.*

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press.

Sampson, V., P. Enderle, J. Grooms, and S. Witte. 2013. Writing to learn by learning to write during the school science laboratory: Helping middle and high school students develop argumentative writing skills as they learn core ideas. *Science Education* 97 (5): 643–70. *https://doi.org/10.1002/sce.21069.*

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013)

- The chart below makes one set of connections between the instruction outlined in this article and the *NGSS*. Other valid connections are likely; however, space restrictions prevent us from listing all possibilities.
- The materials, lessons, and activities outlined in the article are just one step toward reaching the performance expectation listed below.

Standards

MS-PS2: Motion and Stability: Forces and Interactions
www.nextgenscience.org/pe/ms-ps2-1-motion-and-stability-forces-and-interactions

MS-ETS1-4 Engineering Design
www.nextgenscience.org/topic-arrangement/msengineering-design

Performance Expectations

MS-PS2-1: Apply Newton's third law to design a solution to a problem involving the motion of two colliding objects.

MS-ETS1-4: Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

DIMENSIONS	CLASSROOM CONNECTIONS
Science and Engineering Practice	
Constructing Explanations and Designing Solutions	Students use the engineering design process to develop an innovative way to protect passengers during a head-on collision. Student groups design, build, and test a prototype to determine the optimal product. This process involves multiple iterations and opportunities for reflection and revision.
Disciplinary Core Ideas	
PS2.A: Forces and Motion • For any pair of interacting objects, the force exerted by the first object on the second object is equal in strength to the force that the second object exerts on the first, but in the opposite direction (Newton's third law).	Students use a force probe to determine the amount of force acting on their prototype.
ETS1.B: Developing Possible Solutions • A solution needs to be tested, and then modified on the basis of the test results, in order to improve it.	Students test and refine their prototype for protecting passengers during a head-on collision.
Crosscutting Concept	
Systems and System Models	Students build a prototype to model a solution for protecting passengers during a head-on collision based on what the actual solution might look like in the field. They consider the type of data needed and the scientific testing required to acquire the ideal data.

Todd Hutner (*thutner@gmail.com*) is an assistant professor of secondary science education at the University of Alabama. **Victor Sampson** is an associate professor of STEM Education at the University of Texas at Austin. **Hannah Brooks** and **Christina Baze** are graduate students in the STEM Education program at the University of Texas at Austin. **Jill Gregory** and **Karen Sommerhauser** are science teachers at Cedar Valley Middle School in Round Rock, Texas. **Mark Broadway** is a science teacher at Hopewell Middle School in Round Rock, Texas.