

Infusing STEM Courses with Problem-Based Learning about Transportation Disruptive Technologies

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1.0 INTRODUCTION

Transportation is on the cusp of a transformative change in how we move about due to the introduction of disruptive technologies such as automated vehicles (AV). These vehicles are fully automated and designed to drive themselves without human input. Leveraging the advances in GPS and sensor technologies, these vehicles can sense the roadway and detect obstructions, as well as steer themselves and accelerate/decelerate accordingly. Many of these advanced features, such as active cruise control, automatic braking, lane departure guidance, have been available in luxury cars and high-end models in recent years. Building on this, the next generation of vehicles will move from partial automation to complete automation (i.e., self-driving vehicles). Driverless vehicles will transform transportation and the world as we know it. Specifically, they will (1) significantly reduce the number of vehicle-related crashes, and thereby improve safety and travel time reliability; (2) increase roadway capacity, and thereby reduce the need to widen or build new roadways; (3) improve transportation access for the young, older adults, and people with disabilities; (4) reduce costs associated with delivering freight, and (5) reduce the need to engage in driving, and thereby reduce stress associated with driving and allow for more productive use of commuting time. To that end, the development of AV and other transportation disruptive technologies has and will continue to require an interdisciplinary approach, leveraging input from engineers and scientists from multiple fields and varied backgrounds.

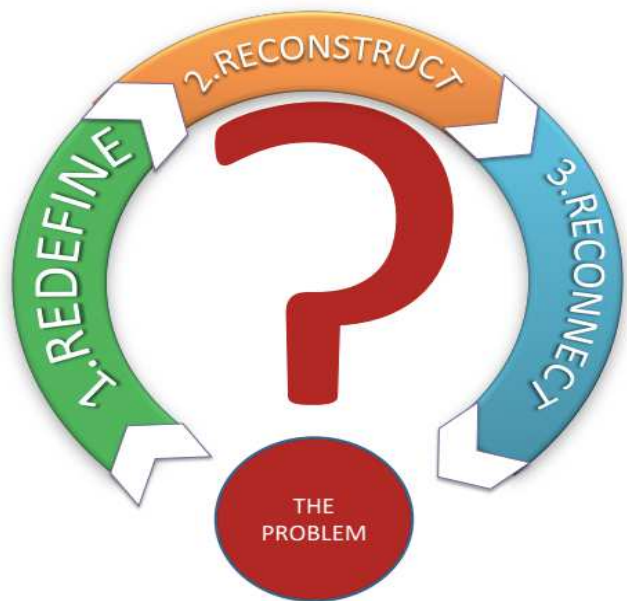
However, there are significant challenges with introducing new and cutting-edge content (e.g., transportation disruptive technologies) into the curriculum for a broad population of students across multiple science, technology, engineering and mathematics (STEM) majors. This paper describes the first wave of results from a Targeted Infusion Project (TIP) that is being conducted to address this challenge at a private, liberal arts, historically black college. The main project goal is to transform the approach for educating students who are pursuing STEM majors at a local HBCU. The project is structured around an implementable set of pedagogical strategies in active learning with an emphasis on problem-based learning (PBL), for both in-classroom and outside-the-classroom settings (e.g., undergraduate research), in the context of transportation disruptive technologies.

The project has three major strands. First, PBL modules were developed and implemented, and the development is continuing, in a diverse range of STEM courses at the host institution, using the Environments for Fostering Effective Critical Thinking (EFFECT) framework developed at a neighboring institution. The collaborative partner institution is a state flagship classified as Carnegie R1 Doctoral Universities with Highest Research Activity. Second, three annual cohorts of undergraduate students at the host institution will have integrated, PBL-driven research experiences across both institutions. Third, a new physical space is being created at the host institution to serve as the hub of this transformative effort. The space is referred to as the Autonomous Vehicles (AV) Learning Lab for teaching and research, and it includes computational facilities for students and a hands-on room with smart cars and drones, among other AV support items. This paper focuses on the first strand of the project.

2.0 OVERVIEW OF PROBLEM-BASED LEARNING

Problem-based learning, or PBL, as an instructional strategy arose from a need in delivering content knowledge to students while equipping them with modern personal and social skills (Barrows, 2002). Initially, problem-based learning was designed to improve the problem-solving skills of medical students, but its use has been expanded to teaching activities of instructors in engineering, social sciences and education (Hoidn & Kärkkäinen, 2014). While the direct instructional method has remained a prominent teaching mode in higher education, problem-based learning has empowered the learning space through a student-centered approach in which students are expected to do independent inquiry, interdisciplinary investigation, and collaborative group work (Barrows, 2002; Schwartz et al., 2009).

It is proposed that PBL progresses through three phases of learning activities: (1) Redefine, (2) Reconstruct and (3) Reconnect, as illustrated in Figure 1. The proposition of three phases is built upon the connection between constructivist learning theory and problem-based learning. Constructivism places emphasis on the learning environment and the process of instructional activity, as they can be equipped with ill-structured problems to promote students to think critically and collectively to come up with new ideas (Savery & Duffy, 1995).



2.1 Redefine

One of the core ideas in PBL activities is to provide students with ownership of their learning. To do so, teaching the subject matter with PBL creates a process that allows the instructor to have active participation from the students through self-directed learning, group discussion and generating new knowledge (Savery, 2006). The process is expected to be guided by an instructor who facilitates the students and the learning space by using a problem as an instructional tool. A real-life problem is introduced to the students in a context in which they are provided with prior knowledge recognition, a group work setting and scaffolding of activities (Maudsley, 1999). After the problem and the expectations are explained, students participate in a collaborative effort to redefine it in a manner that represents their prior knowledge and current understanding of the problem, and what needs to be performed in terms of researching the unknown parts of the problem (Schmidt, 1993).

Figure 1. Three phases of problem-based learning.

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elaborating their ideas on understanding parts of the main problem. In this sense, the main problem is reconstructed by identifying and researching its smaller components (Schmidt, 1993; Wee, 2004). By reconstructing the problem, students are expected to compile various thoughts that represent cross-disciplinary research and stimulation of prior knowledge. PBL activities focus on students' self-directed learning, and it aims to improve the students' engagement, problem-solving and reasoning skills (Strobel & van Barneveld, 2009). By utilizing independent study and group projects, students are placed in an active learning environment in which they may take ownership in the process of problem-solving by defending and reasoning their findings (Wood, 2003).

2.3 Reconnect

In an active learning environment, problem-based learning advances student abilities to understand, explain and reconnect the findings to the original problem posed by the instructor. After defining the scope of the problem, reconstructing the main problem, and performing independent and collaborative studies, students then revisit the original problem with a renewed approach, new knowledge, and skills (Savery & Duffy, 1995; Barrows, 2002). The action of reconnecting to the problem with a constructive approach encourages students to take ownership of their short- and long-term learning goals. As part of life-long learning skills, students develop self-learning habits to understand the need for recognizing real-life problems, allocating time to do independent research and reflect upon findings (Hmelo-Silver, 2004; Hoidn & Kärkkäinen, 2014).

3.0 ENVIRONMENTS FOR FOSTERING EFFECTIVE CRITICAL THINKING

The Environments for Fostering Effective Critical Thinking, or EFFECTs, are modular, inquiry-based course materials that develop critical thinking skills and collaborative teamwork skills. The EFFECTs framework revolves around active learning strategies that guide students towards an appropriate solution for an open-ended problem. It relies on the principles of problem-based learning that have been established for student-centered learning in engineering education (Smith et al., 2005; De Graaf & Kolmos, 2003; Perrenet et al., 2000). In an EFFECT module, the PBL environment begins with a driving question, which serves as the student prompt to solve a specific problem set within a realistic context. Driving questions can be likened to Fermi problems, which have been used in engineering education (Thomas et al., 2013; Shakerin, 2006; Lunt & Helps, 2001) to help students learn how to estimate an answer to a problem with little to no assigned information.

The first phase of *redefining* the problem is captured in writing with a decision worksheet. Each student completes an individual worksheet first, which permits him/her with sufficient time for independent thinking about the problem. After, students collaborate in small groups to discuss with each other and consult with the instructor in an effort to achieve consensual responses to the worksheet prompts. Throughout these activities, students document their processes of using prior knowledge to establish what is known and what is unknown; making reasonable qualitative assumptions and appropriate quantitative approximations for the unknowns; and estimating an answer using dimensional analysis, when needed.

The module continues with a sequence of active learning exercises, which are designed to support learning of the core concepts that underlie the problem. Acquiring this new knowledge facilitates students' *reconstructing* of the problem. There are a multitude of active learning techniques available; examples of ones that have been embedded in EFFECT modules can be found in Starcher and Pierce (2016) and Pierce et al. (2013). Active learning does not require hands-on components, although their inclusion is often valuable and can help link psychomotor learning and cognitive learning domains. The most significant element of active learning is that it must engage students in minds-on exercises. In the end, student learning must lead to *reconnecting* with the original problem, such that a viable solution to the driving question can be presented in a final design calculation, report, and/or presentation.

4.0 EFFECTS IMPLEMENTATION AT HBCU

The School of Arts and Sciences at Benedict College offers STEM majors within two departments: Biology, Chemistry, and Environmental Health Science (BCEHS) and Computer Science, Physics, and Engineering (CPENG). These departments offer cross-discipline courses that support multiple majors. The first phase of EFFECTs implementation targeted three of these courses, as shown in Table 1.

Introduction to Engineering (ENGR 110) is a fundamental course that introduces freshman engineering students to basic engineering concepts and skills. Computer engineering (CE), electrical engineering (EE), environmental engineering (EnvE), and transportation engineering (TRP) students are required to take this course. Occasionally, other STEM students who need 1 credit hour to complete their degree program will take this course. It is intended to use EFFECTs as a focused, simple, and practical introduction to transportation engineering and related technologies in this course.

Air Pollution Control (ESC 331) is required for both environmental health science (EHS) and EnvE students, and it is an elective for TRP students. EFFECTs in this course focus on the environmental impacts of emissions in the transportation sector. Software Engineering (CSC 435) is required for Computer Science (CS) and CE students. It is also an elective for other engineering students. This course can offer EFFECTs that focus on the design and development of new and disruptive technologies in the transportation sector, with an emphasis on automated vehicles (AV).

Table 1. Course Information for Phase 1 EFFECTs Implementation

Course	Term	No. of Students	Requirement	Majors
ENGR 110	Fall 2017	36	Required	CE, EE, EnvE, TRP
ESC 331	Spring 2018	10	Required/Elective	EHS, EnvE, TRP
CSC 435	Fall 2017	12	Required/Elective	CS, CE

There is purposeful overlap in the majors represented in the selected courses, as seen in Table 1. In other words, the identified set of three courses has high potential impact on a diverse number of majors. Over time, a subset of the student population in a given major will be exposed to a string of transportation-related EFFECTs as part of their degree program. For example, EnvE and TRP students could encounter EFFECTs as a freshman in ENGR 110 and later as a junior in ESC 331. If some of these students elect to enroll in CSC 435, then they will be exposed to a

third EFFECT as seniors. As the number of courses with EFFECTs is expanded, the curricular impact on student learning about transportation disruptive technologies in a given major will increase further.

4.1 Transportation Disruptive Technologies in Introduction to Engineering

4.1.1 Course Description for Introduction to Engineering [ENGR 110]

ENGR 110 is a 1-credit hour course that meets once per week. It introduces students to different engineering majors, functions of engineers, fundamental units and conversion problems, estimation, mathematical models and modeling, statistics, and spreadsheet computations. In addition, it engages students in the practice of specific professional skills, such as engineering ethics, teamwork, and communication skills.

4.1.2 EFFECT Learning Objectives and Outcomes

Introduction to Engineering was selected to help students understand how transportation disruptive technologies can improve travel time and mitigate environmental impacts of automobiles. Autonomous vehicles can eliminate parking circulations, for example, through the use of its connectivity and/or access to parking in remote locations. In turn, these vehicles can save time, reduce gas consumption, and minimize emissions. The context of the problem was rooted in the challenges with parking cars on the campus of Benedict College, in an effort to ensure the problem was relatable to students.

The EFFECT was designed for students to develop their abilities to (1) formulate mathematical modeling of a real transportation problem; (2) identify the factors that contribute to parking delays for the entire campus; (3) derive descriptive statistics and understand the effects of assumptions on distribution of arrivals, demand, and capacity for each user group; and (4) communicate the reasoning and technical information of high level system modeling through connection among assumptions, units, graphical views of the model, and numerical results.

4.1.3 In-Class Activities

The EFFECT was implemented in six class sessions of 50 minutes each during the Fall 2017 semester. This course was scheduled in a computer lab, which was not the ideal setting for the active learning exercises that were developed. Most of the activities did not require computer access, and the physical environment somewhat hindered effective teamwork (which can be observed in Figure 2).

In the first session, students completed a decision worksheet to estimate the total empty spot search time in hours per person per weekday. The driving question was followed with supporting prompts, which are designed to elicit knowledge of the critical variables, such as the number of available parking spots on campus, current student population, and the percentage of students with cars, among others.

Prompt 1: List the information and/or factors that need to be considered in order to solve this problem. Identify the factors that will have the most impact on your solution, and explain why.

Prompt 2: Make reasonable assumptions and/or approximations for the factors identified in the previous question.

Prompt 3: Draw a decision tree or a flow chart that shows the steps needed to solve the problem.



Figure 2. Students in Introduction to Engineering discussing the problem.

In the remaining sessions, students participated in class activities that were designed to support the required course content, including visual diagrams, observations and assumptions, lists of variables, and equations and solutions. This content was embedded in Fermi problems that helped students to practice their problem solving skills and gain confidence in their solution to the parking problem. Students completed these four Fermi activities: (1) “How long of a wire is needed to manufacture 10^6 regular paper clips?” (2) “How many cubic yards of asphalt is needed to construct a mile of an interstate freeway?” (3) “What is the mass in kilograms of gravel stored in a rectangular bin with the given dimensions?” and (4) “During rush hour, cars back up when the traffic signal turns red. How many cars will make it through the light?”

4.2 Transportation Disruptive Technologies in Environmental Science and Engineering

4.2.1 Course Description for Air Pollution Control [ESC 331]

ESC 331 is a junior level course that teaches students about natural and anthropogenic sources, environmental impacts, and elimination and/or control of air pollution. More specifically, students learn how to compare and contrast natural and man-made events or processes that

produce air emissions; engage in the identification and classification of different types of emissions; and analyze a problem to identify and define emitting parameters appropriate to perform a materials balance.

4.2.2 EFFECT Learning Objectives and Outcomes

This course was selected purposefully to help students understand how transportation disruptive technologies can facilitate the eradication and/or minimization of air pollution. Unlike human driver behaviors that contribute to the emission of criteria pollutants, autonomous vehicles could cut down on such emissions due to standardized and controlled vehicular maneuverings. Hence, its infusion will enable students to understand the importance and urgency in finding and implementing novel technologies to enhance the movement of goods and humans, while keeping the environment much cleaner and safer.

The EFFECT was designed for students to develop their abilities to (1) identify the major sources of both natural and anthropogenic emitters of the criteria air pollutants, (2) compute the amount of emissions produced by cars and trucks, and (3) understand the effects of mobile vs. stationary emitters and the type of fuel consumed. It is expected that students will gain a strong sense of discovery and connection between concepts and their applications.

4.2.3 In-Class Activities

The EFFECT was delivered in two consecutive class sessions during the Spring 2018 semester. A decision worksheet with a real-world problem was distributed in the first of the two class sessions. Before handing out worksheets, the problem statement was projected on a smart board for a five-minute, open-ended discussion of the driving question. This brainstorming approach was intended to encourage students to make initial assumptions and stipulations, while allowing them to make revisions after the concepts and content of interest were learned and understood. Once the class discussion was completed, students were allotted 20 minutes to work through the problem worksheet in small groups of three students. Next, the class was provided another 20 minutes for individual completion of the same worksheet.

During the next class session, core concepts were introduced and discussed using interactive lecturing. After learning the concepts, students were provided the same amount of time (as in the prior class period) to solve the problem. At the end of class, an open forum discussion was held for students to share feedback on the exercise. This approach enabled the instructor to gauge the before-and-after knowledge and understanding of the concepts for each student. It should be noted that the class was comprised of three EnvE students and seven EHS students, and so the prior knowledge and perspectives of students were varied.

4.3 Transportation Disruptive Technologies in Computer Science and Engineering

4.3.1 Course Description for Software Engineering [CSC 435]

CSC 435 is a senior level course that provides practical experience in software system design. The course develops and integrates skills in applied computer science, project management,

communication, problem solving, and design methodology. Three of the core course outcomes are that students should be able to (1) analyze a problem, identify, and define computing requirements appropriate to its solution; (2) design, implement, and evaluate a computer-based system or program to meet desired needs; and (3) develop software system(s) within teams.

4.3.2 EFFECT Learning Objectives and Outcomes

In the context of improving lane departure guidance systems, students will learn about requirements for the sensing system on driverless vehicles (e.g., drones) and the embedded vehicle control system (e.g., drone controller). Through hands-on experimentation, students will develop an understanding of the necessary specifications for the sensors and vehicle control system to ensure that driverless vehicles can safely navigate complex topologies and physical environments. Specifically, students were required to inquire and study the characteristics of a drone controller. Although user and system requirements are standard concepts in a software engineering course, the applications to drones and drone controllers were integrated as new learning objectives.

The EFFECT was designed for students to develop their abilities to (1) identify and understand the user and system requirements; (2) understand software processes and system modeling by designing an application for a drone controller that meets operating system, sensors, and user requirements; and (3) validate software systems and understand software evolution.

4.3.3 In-Class Activities

The EFFECT was implemented in two computer lab sessions in consecutive weeks during the Fall 2017 semester. Each session occurred during class on Friday. Highlights of the activities are listed below.

In Lab 1, students completed a decision worksheet regarding the weight of a drone controller. Each student completed an independent worksheet, as shown in Figure 3. The driving question was, “What are the consideration(s) that will determine the optimal weight of the drone controller and what will be the optimal weight?” There were two supporting prompts on the worksheet designed to help students come up with an initial answer to the driving question. The prompts are:

Prompt 1: Draw a block diagram that illustrates the different components of the drone controller. Specify the dimensions that are feasible.

Prompt 2: Determine the optimal weight of each component identified in prompt 1.

In Lab 2, students were tasked with completing a Requirements Document for a drone controller. It is a professional document that details user and system requirements. User requirements are written from the point of view of end users, and are expressed in narrative form. System requirements are detailed specifications describing the functions of the system. These are usually more technical in nature. Students were allowed to conduct online research while developing their Requirements Document. This active exercise facilitated student understanding of the significance of such documentation. At the same time, students had to consider the effects of

technical requirements on controller weight in contrast with user demands for a functional and lightweight product.



Figure 3. Students in Software Engineering working on the decision worksheet.

5.0 EVALUATION

The two main evaluation questions involved the kinds of impacts these learning experiences had on the instructors and students. Specifically, we wanted to know (1) if the EFFECT framework for problem-based learning was perceived as providing instructors with tools for more effectively teaching difficult concepts, and (2) if student course outcomes were improved. On the student side, we wanted to explore whether participation in an EFFECT module impacted students' understanding of engineering as a discipline, and on their self-perceptions as developing engineers. To address these questions, the project's external evaluator observed some of the class sessions in which the EFFECTs were implemented, and interviewed the instructors and students. The facilitator of the summer training program was also interviewed. We have also begun to compile data on course outcomes (e.g., grades and persistence measures), but do not yet have sufficient data to provide useful analysis.

The three instructors of the implementation courses had not been familiar with the literature on problem-based learning prior to the project. Although engineering pedagogy often includes labs and other experiences in which students work on problems and applications after learning about essential concepts, the EFFECT approach has some features that are not a typical part of such learning experiences. In particular, this approach requires students to engage with problems in which learning an unfamiliar concept is necessary in order to address the problem. This approach reverses the traditional method, in which concepts are first introduced and explained in detail and only then are students expected to apply them. In the EFFECT approach, students are given a problem that requires them to learn a new concept and then they are encouraged to identify the need for the new concept and guided to formulate and apply it themselves. Thus, teamwork, discussion, and trial-and-error are essential components of EFFECTs. At first, instructors often

find it frustrating to watch their students struggle with such problems, and it is challenging to design EFFECTs that provide a productive balance of students' drawing on prior knowledge and creating new knowledge for themselves. Previous EFFECT projects have demonstrated that two or three iterations may be required before this balance is consistently achieved. The other crucial feature of the EFFECTs process is that students must reflect on what and how they have learned at the conclusion of the module.

5.1 Training Program

A summer training program was developed to help the instructors create EFFECTs that were appropriate and meaningful for their courses and students. During several days spread over the summer, the instructors were introduced to some of the literature on problem-based learning, received an intensive introduction to the problem-based EFFECTs approach, and designed EFFECTs that they would implement during the following academic year.

The training program revealed two significant issues. First, there is a need to differentiate between problem-based learning and project-based learning, and further, to distinguish between deductive and inductive modes of learning. Inductive learning, which is central to the EFFECTs approach, requires that the problem or project be presented to students as the vehicle for learning new content knowledge, rather than as an application of what has been learned prior to receiving the problem or project. Second, student-centered learning requires students to be engaged in the classroom during class—instructors must be actively engaged with the students as a facilitator and classroom resource. So, the EFFECT cannot be an out-of-class project. This transition from an instructor-centered, lecture-based classroom to a more active, student-centered learning environment can be difficult, and it requires time for instructors to practice being comfortable and patient with that mode of knowledge acquisition. The instructors agreed that the initial implementation was challenging without opportunities to practice in a real or simulated classroom.

5.2 Instructor and Student Interviews

Based on student and instructor interviews, the use of problem-based learning with the EFFECTs approach revealed six positive observations or outcomes:

(1) It allowed students to make mistakes without penalty. EFFECTs are based on problems that do not have one correct answer, but which require the students to “think like engineers,” i.e. to identify and estimate the variables and parameters of a problem and to design solutions that account for these. Students were evaluated not solely based on the correctness of their solutions, but on their problem-solving processes and reasoning.

(2) It allowed students to have a point of reference of discovery and learning based on the situational and experiential learning approach created using EFFECTS.

(3) It allowed for a before and after comparative analysis of thoughts and knowledge acquisition based on students' individual and group work results.

(4) It provided instructors a better understanding and practice of what actual problem-based learning means versus the traditional end-of-semester course project approach.

(5) The instructors were enthusiastic about seeing students thoroughly engaged and working diligently on a problem. Many students reported enjoying the process of exploring and discovering that went with the EFFECTs problems.

(6) A review of student work shows that students generated individual ideas and unique solutions, which re-emphasized the value of the EFFECTs approach for both the instructors and students.

In addition to the positive outcomes, the instructors and students identified several challenges and difficulties.

(1) As a practical matter, EFFECTs are time-consuming, requiring at least one class session, but usually several sessions. It would probably not be practical to implement an all-EFFECTs curriculum, and it may not always be obvious which concepts are the best candidates for incorporating into an EFFECT. Thus, selecting a concept and then designing a learning experience that is effective and reasonably time-efficient is a challenge, especially for instructors just getting started in this approach.

(2) A related issue was the design of the learning experience itself. One aspect that turned out to be particularly challenging was achieving clarity about the specific learning goals of the EFFECT. Although hands-on, problem-based activities may have value in themselves, EFFECTs are intended to help students achieve specific learning outcomes. Allowing the learning goals to drive the EFFECT design can be quite difficult.

(3) In the first year, several pieces of equipment did not arrive in time for one of the EFFECTs, necessitating that the experience be adapted.

(4) The unfamiliar format of the learning process made some students question it. Some were confused because they were used to being given examples with correct answers and for which they were given all the information needed to develop a solution. EFFECTs typically include the expectation that the students must operate in a messy world of unknown parameters and estimated values.

(5) Some students found the teamwork aspect of the EFFECTs to be frustrating. They said they did not like being dependent on their teammates for the quality of the group's work and, ultimately, for their grade.

Despite these challenges, both instructors and students said that they enjoyed and valued their EFFECTs experiences. The instructors cited student engagement as a major benefit, and the students appreciated the opportunity to experience something of the real-world applications of the material they were learning. PBL generally, and EFFECTs specifically, are often unfamiliar modes of learning, but the students adapted quickly.

6.0 FUTURE DIRECTIONS

The implementation of EFFECTs in the School of Arts and Sciences at Benedict College has been well received so far. It is considered to be a promising pedagogical approach for motivating students in their respective studies. Furthermore, two new instructors have expressed interest in developing and implementing EFFECTs for transportation disruptive technologies in CE and EE courses. Table 3 shows the next phase of infusion will include courses in digital logic and digital signal processing. There are also plans to implement EFFECTs for introduction to transportation, environmental engineering, and computer architecture courses starting in the Fall 2019 semester.

Summer training workshops will be held to support Phase 2 infusion. Workshop materials will be revised based on lessons learned from the first three EFFECTs. It is anticipated that future EFFECTs will benefit from utilization of the Autonomous Vehicles (AV) Learning Lab space that has been created at Benedict College.

Table 2. Target Courses for Phase 2 Infusion of Transportation Disruptive Technologies

Target Semester	Course No.: Title	Proposed Module Content
Fall 2019	TRP 230: Introduction to Transportation Engineering	Decreasing air drag with enhanced platooning from autonomous vehicles
Fall 2019	EnvE 230: Introduction to Environmental Engineering	Inspecting environmental infrastructure with autonomous technologies
Fall 2019	CSC 337: Computer Organization and Architecture	Designing reliable and secure computing systems in context of autonomy
Fall 2019	EE 331: Digital Logic	Designing robots to make deliveries using shortest paths
Spring 2019	EE 332: Digital Signal Processing	Using multiple heterogeneous data sources to provide relevant updates to travelers

7.0 ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 1719501.

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