Work-in-Progress (WIP): Roadblocks and Fast Cars - Using Roadways and Drivers as Metaphors to Map the Undergraduate Engineering Student Journey

Olivia Ryan, Virginia Polytechnic Institute and State University

Olivia Ryan is a Ph.D. student in Engineering Education at Virginia Tech. She holds a B.S. in engineering with a specialization in electrical engineering from Roger Williams University and an M.S. in engineering mechanics from Virginia Tech. Her research interests include understanding curriculum barriers that exist within engineering related to mathematics.

Malini Josiam, Virginia Tech Department of Engineering Education

Malini Josiam has a Ph.D. in Engineering Education from Virginia Tech (2026), a M.S. in Civil Engineering from Virginia Tech (2023) and a B.S. in Mechanical Engineering from UT Austin (2021). Her research interests center around undergraduate engineering culture, women of color, student support, and social technical engineering.

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Abstract

This work-in-progress (WIP) paper seeks to put two dissertations in conversation to discuss the interaction between engineering curriculum and engineering culture through a single metaphor. There are numerous factors that impact a student's experience in and journey through undergraduate engineering: institutional policies, curriculum difficulty, social culture, etc. To consider these factors together, we use roadways and drivers as conceptual metaphors. Roadways represent the institutional structures in place that shape a student's journey through engineering. Drivers represent engineering students interacting with each other and the roadway during their journey. Taken together, these metaphors allow us to map out prominent features of the undergraduate engineering student journey - structures and cultures. We use roadways and drivers to weave together two engineering education dissertations focused on undergraduate engineering. Putting these dissertations in conversation with each other through metaphors enables us to discuss both environmental and social factors that shape the undergraduate student journey, ultimately in pursuit of broadening participation in engineering.

Introduction

> *"And even if you do end up switching [majors], it's okay because* ***on the way to that stop sign, crosswalk, crossroad, you have learned so much*** *that now you can bring [that] to whichever other direction you want to turn. ... If you hit a dead end, then just make a right, make a left, see where life takes you."* - Snow (participant from Author Josiam's dissertation)

Two engineering students can be at a crossroads in their degree and experience it in very different ways. One sees a clear road ahead, while the other is forced to take a detour. The different roads ahead for different students are shaped by both the structures that define engineering education and individual perceptions. While Snow's quote did not directly inspire our metaphor usage in this paper, she helps us identify that students have agency in navigating engineering, just like drivers on the road.

As undergraduate engineering students pursue their degrees, they encounter and navigate many environmental structures, such as degree requirements, course offerings, placement thresholds, and transfer policies [1], [2], [3], [4], as well as environmental cultures, such as discipline-specific culture [5], class norms [6], and beliefs about who should do engineering [7]. Together, these structures and cultures create roadblocks and regulate fast cars that shape students' experiences in and perceptions of engineering (e.g., [8]). No two students have the same undergraduate engineering experience, just as no two road trips are identical.

Using roadways and drivers as metaphors, this paper seeks to synthesize a subset of findings from two dissertations, one on engineering curriculum and one on engineering culture, to explore how students' experiences in engineering are shaped by curriculum structure and perception of culture. Inspired by prior work that puts dissertations in conversation with one another [9], we weave together two conceptual metaphors [10] of roadways and drivers to delineate the impact of structure and culture on engineering students and depict the relationship between the two. Considering both environments and individuals at the same time [11] enables us to better inform efforts to broaden participation in engineering.

Roadway as a Metaphor for the Engineering Curriculum

The road to completing an engineering degree is shaped by a long list of required courses that must be completed in a specific order [1], [12]. Each institution and discipline has its own required courses, prerequisites, corequisites, and recommended sequencing - no two roads to an engineering degree are the same. In our roadway metaphor, the engineering curriculum can be thought of as the road an individual is taking to reach their destination, completing their degree. The road to an engineering degree may present traffic, roadblocks, detours, or different highways that drivers need to navigate. Each of these road components, or engineering environmental structures, represents an aspect of the engineering curriculum that may help or hinder students' degree progress.

The road to an engineering degree may present traffic that slows down a student's progress. For example, math placement is a key component of the curriculum and affects degree progress [13], [14], so if a student does not place into the desired first-year math course, their progress may slow due to the curriculum requirements. This is similar to encountering traffic; the roadway is backed up, but it is still possible to reach your final destination, although it takes a little longer. Similarly, the road to an engineering degree could present roadblocks that the driver needs to bypass by taking a detour or reconsidering their route. In engineering, failing a class is relatively common [15], but it can present an obstacle to completing a degree on time. The road may offer them a detour, like taking summer classes to catch up [16], or bypass the roadblock. Beyond obstacles, different routes may appear faster. For example, different majors may make it easier for students to graduate due to degree requirements, so students may find it advantageous to change their major [17] to graduate in a timely manner. Similarly, a different road may be a better fit for helping students reach their destination, so they may transfer institutions if the school is a better fit [18], [19]. These examples show different ways the engineering curriculum may affect students' progress toward their degrees.

Dissertation on Curriculum Complexity

The road, or the macro-structures of the engineering environment, specifically the curriculum, will shape each student's experience throughout their degree. Different road conditions may be represented by curriculum requirements, math prerequisites and corequisites, and elective flexibility. These road conditions are important to consider, as no two students will experience or approach curriculum requirements in the same way. Additionally, each institution and program has different curriculum requirements that shape these road conditions.

A subset of the first dissertation studies engineering curriculum by examining curriculum complexity and math cruciality across three engineering majors and 48 institutions. The motivation to study curriculum is due to the requirement that engineering students need to start their first semester in Calculus 1 to stay on track in their major [20], [21], [22]. However, many students are not ready to begin their degree in Calculus 1, and if they start below Calculus 1, they will likely need to do additional work to catch up or fall behind [13], [23]. Therefore, the purpose of the study is to quantify and compare engineering curricula across multiple majors and institutions, highlight the role of mathematics in the curriculum, and examine how institutional and program characteristics may contribute to curriculum complexity patterns.

Curriculum complexity is a quantitative descriptor of a curriculum that reflects its hierarchical structure by accounting for prerequisites, corequisites, and course sequencing. Each course in the curriculum is assigned a cruciality value, and all these values are summed to determine the structural complexity. (More details about curricular analytics can be found here [24]). A higher structural complexity score indicates a more complex curriculum, while a lower score indicates a less complex curriculum. Research has shown that adjusting the curriculum surrounding highly structured sequences can improve graduation rates [1]. Math cruciality is a metric that author Ryan developed to represent the amount of the structural complexity score that is attributable to the required math courses. Since each course has its own cruciality value, the math course's cruciality can be summed to determine the proportion of the complexity score due to math.

Author Ryan identified three majors (i.e., civil, electrical, and mechanical engineering) and 48 institutions, collected curriculum plans, and calculated complexity scores for each degree plan. More details about collecting the curriculum plans and modeling a student's degree plan can be found in her dissertation [25]. Across the institutions, mechanical engineering (M = 377.5) had significantly higher curriculum complexity scores than civil engineering (M = 299.3), indicating some disciplinary differences in complexity. Interestingly, regardless of the curriculum complexity score, each discipline had a mean math cruciality of approximately 30 percent. This percentage is notable because, although 30 percent may not seem large, math is typically only five or six of the 40 to 45 required courses in a curriculum, underscoring its importance.

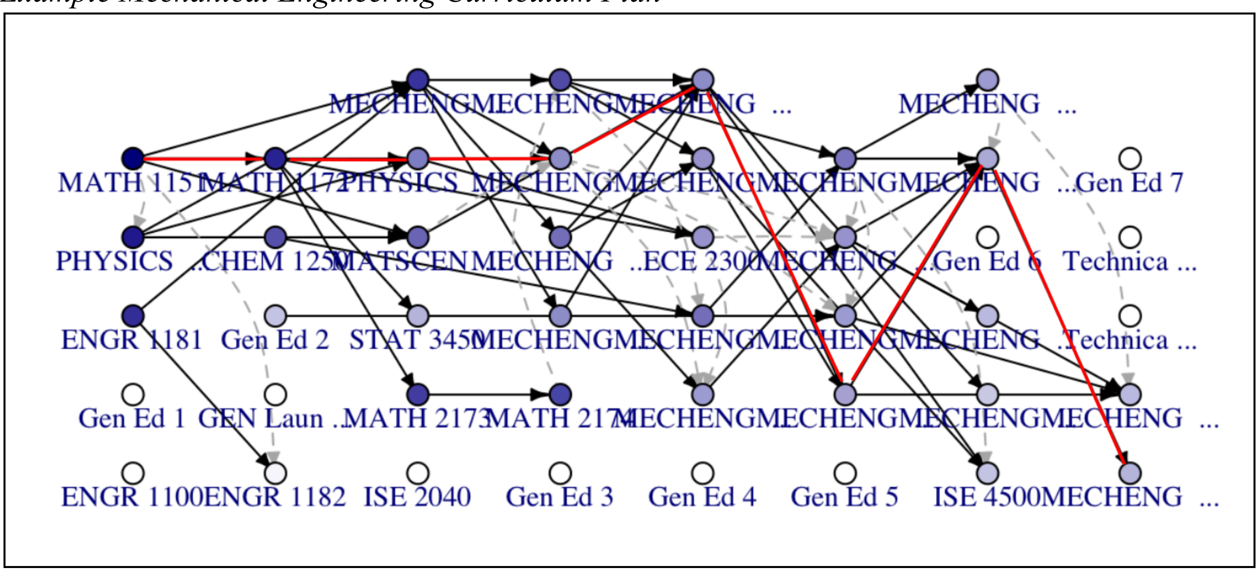
Author Ryan also considered how institutional and program characteristics may contribute to complexity scores. She found that institutions with higher complexity in one discipline tend to have higher complexity in other disciplines. Additionally, after conducting a cluster analysis, institutions were clustered into 2 categories. The first cluster includes "smaller" institutions (~23,000 undergraduates) with more open enrollment and lower-ranked engineering programs, and they generally had higher curriculum complexity scores. The second cluster includes "larger" institutions (~37,000 undergraduates) with more selective enrollment and higher-ranked engineering programs, and they generally had lower curriculum complexity scores. This shows that institutional and program factors may shape curriculum sequencing and requirements, which affect curriculum complexity.

Beyond the quantitative findings, the process of collecting and examining curriculum plans illuminated differences across disciplines. These observations provide a broad overview of disciplinary patterns, but they are not representative of every discipline at every institution. First, civil engineering curriculum plans had very similar structures across institutions, and it was typically very easy to find the necessary information about required courses, prerequisites, and corequisites. For civil, there are typically breadth classes across different specialties (i.e., construction, structural, transportation, environmental, geotechnical, and water) required in the third year, and students need to take three to four breadth classes. The prerequisites for the breadth classes are primarily classes from the first two years of the degree plan. After the breadth classes, students typically need to take some depth and/or design classes, with the breadth classes serving as prerequisites for the depth classes.

Similarly, electrical engineering tends to offer a lot of freedom in upper-level electives like civil engineering, but across institutions, it was consistently challenging to figure out which classes are actually feasible to take. Many electrical engineering upper-level electives have prerequisites that are not required classes or are not scheduled until a later semester, so students need navigational capital to figure out which electives are feasible to take based on the classes they have already taken and those they are scheduled to take. Mechanical engineering typically had fewer electives than civil and electrical engineering, and they were primarily offered in a student's final three semesters.

These observations show that within the same institution, there are significant disciplinary differences in terms of flexibility, and different majors may require students to have a certain level of navigational capital to understand their degree plans. Additionally, because some majors are more flexible, students at the same school in the same major can have very different experiences in their final semesters of their degree. An example degree plan for Mechanical engineering, with the prerequisites and corequisites shown, can be seen in Figure 1. This figure shows how complicated the engineering curriculum can be to navigate because of the hierarchical structure and the many requirements. The figure is supposed to represent how complicated it is to understand curriculum plans; thus, it is hard to interpret. We highlighted the longest curriculum chain in red to showcase the hierarchical nature of the engineering curriculum.

Figure 1
Example Mechanical Engineering Curriculum Plan



Note: Solid black lines represent prerequisites and dotted gray lines represent corequisites. The red line represents an 8-semester curriculum plan that begins with Calculus 1.

Connecting back to the metaphor, the study's findings indicate that there are both disciplinary differences throughout the curriculum and institutional influences on it, meaning that each road or road trip is unique. No two students will travel the same road to their degree, even if they are pursuing the same major (on the same highway) or attending the same institution (in the same lane on the same highway). One may encounter different obstacles, such as traffic at certain times of day (curriculum requirements) or limitations on how fast their car can go (disciplinary differences). Curriculum complexity can be thought of as the traffic students must navigate to reach their final destination, or complete their degree. Traffic can be caused by a variety of factors, such as rush hour, construction, or an accident-related traffic jam. Just as students' academic trajectories are affected by a variety of factors, such as their math placement or whether they fail a course.

As educators, researchers, and administrators, we should not assume that everyone in engineering experiences the same road conditions on the same route. This study showed that there are an infinite number of combinations of routes and road conditions that students will face while pursuing their degree, and even if students appear to be on the same route, roadblocks will affect them differently. If administrators assume that all routes and road conditions are the same, this could significantly hinder students' progress toward their degrees. Understanding that roadways and road conditions may look different is an important realization for those with authority over the curriculum, and it should be considered when efforts are made to update policy surrounding curriculum requirements, requisites, and placement.

Drivers as a Metaphor for Social Culture

A driver’s view and the driving experience are shaped by road conditions, other drivers, and personal mindset. Similarly, a student’s perception and experience of undergraduate engineering culture is shaped by institutional structures, peers, and personal circumstances.

Roadway conditions are structures that shape road culture and driver behavior. For example, when a driver encounters a school zone, they consciously slow down within the zone to abide by the lower speed limit. Similarly, when a student encounters a competition in a semester-long project-based course, they may work harder to ensure their team’s robot wins the competition [26]. In another example, some cars are able to climb hills more easily than others. In engineering, some students’ effort translates to successful outcomes more easily than others, indicating that engineering does not always operate as a meritocracy [27].

Other drivers on the road also shape road culture and driver behavior. Drivers on the road are not operating fully independent of one another. Similarly, in engineering, students are impacted by other students in terms of the values they espouse and the norms they inhabit. For example, a driver switching lanes abruptly without using their turn signal could cause another driver to brake quickly to avoid a collision, frustrating the latter driver. In parallel, in engineering, students experience the cultural norms of hardness [28] and individualism [29]. For example, a student refusing to help another student solve a difficult engineering problem would contribute to frustration for the latter student, similar to the driver who needed to slam their brakes.

A driver’s experience on the road is also shaped by their own personal circumstances. A driver who is running late may speed and perceive that other drivers are driving too slowly. Similarly, an engineering student who is passionate about environmental sustainability may perceive that their mechanical engineering coursework does not discuss the environmental impact of engineering designs, a result of technical social dualism in engineering [30].

Dissertation on Perceptions of Engineering Culture

Author Josiam conducted traffic stops of drivers in small cars on different routes by interviewing 24 undergraduate women of color in engineering across nine engineering disciplines and six large R1 Primarily White Institutions (PWIs) in the United States. The number of participants per discipline was as follows: Biomedical Engineering (BME) - 6, Chemical Engineering (ChemE) - 3, Civil and Environmental Engineering (CivE EVE) - 4, Computer Science and Electrical and Computer Engineering (CS ECE) - 4, Industrial and Systems Engineering (ISE) - 2, and Mechanical and Robotics Engineering (ME) - 5. Author Josiam stopped drivers in small cars (e.g., women of color) specifically because they had a unique vantage point in a road designed for big cars (e.g., white men) These drivers were asked some questions about their driving experience and perception of their road and routes.

In this qualitative phenomenographic dissertation [31], each student participated in two think-aloud activities during their interview. In the first activity, students looked at a list of 81 value words and selected five to seven words they perceived that engineering valued most, inspired by previous work using value reflection with engineering students [32]. Table 1 summarizes the quantitative findings of the most selected values from the first activity by discipline.

Table 1
Count of Top Eight Values Identified by Students by Discipline

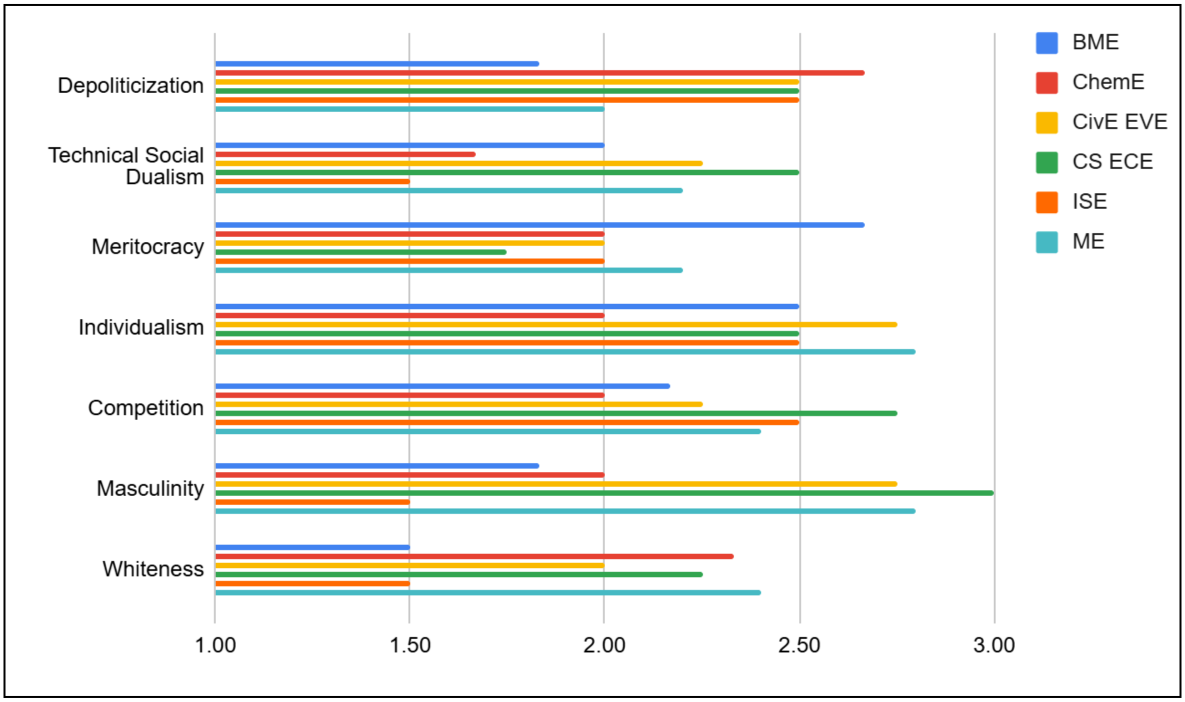
	BME	CHE	CivE EVE	CS ECE	ISE	ME	Total
Balance	1	2	2		1	2	8
Cooperation	2	1	1	2		2	8
Flexibility		2	2	1		4	9
Reliability	2	1	2	1	2	1	9
Determination	2	2	3	2		1	10
Self-sufficiency	2	1		3	1	3	10
Support	3	1	1	2	1	3	11
Achievement	3	2	3	4	1	4	17

Overall, there were no notable disciplinary patterns for the values selected. In fact, the opposite is notable: each value selected more than once was selected by students in different majors.

In the second activity, students reflected on engineering norms (depoliticization, technical social dualism, meritocracy, individualism, competition, masculinity, and whiteness) that Author

Josiam selected based on prior research identifying dominant cultural norms in undergraduate engineering [29], [30], [33], [34]. Students ranked these norms as: represents engineering always/mostly, represents engineering sometimes, represents engineering never. Author Josiam quantified this data by converting each student selection into a number: represents engineering always/mostly - 3, represents engineering sometimes - 2, represents engineering never - 1. Then, Author Josiam computed the average rating of each element by student discipline. This data is presented in Figure 2.

Figure 2
Rating of Cultural Norms by Discipline



Analysis of students' reactions to the cultural norms, in Figure 2, reveals that students in CivE EVE, ME, and CS ECE share similar perceptions that engineering culture can be depoliticized, competitive, and masculine, and their department's social culture can be exclusive. Meanwhile, students in BME, ChemE, and ISE share similar perceptions that engineering is more meritocratic, less masculine, and more socially oriented, and their department's social culture is inclusive. This shows that there are potential disciplinary differences for perceptions of engineering cultural norms, aligning with prior work [35]. This finding is notable considering there were no observable differences in perception of engineering values across disciplines. The similarity in values selected and difference in norm rankings by discipline indicate undergraduate engineering has distinct perceptible values across disciplines (i.e., achievement and support); however, these values contribute to different subcultures within disciplines.

Students' perceptions of culture were shaped by institutional structure, social culture, and personal circumstances. Herein, we share examples from participants across three institutions from Author Josiam's dissertation data. Justine (CS) shared how engineering is a discipline that can take longer than four years, compared to other majors, because of rigid structures, like co-op requirements:

> "[In the] business college … they tried to get me to be a fifth-year … [But] they [were helpful] like, 'Oh, here's what you need. Let's break this down smaller.' Versus in the beginning, engineering is like, 'Oh, this is really hard. You just need the extra year,' off the bat....Don't get me wrong. Both colleges will both try to make you a fifth-year. …. engineering does it a little earlier … especially since it's normalized to be a fifth-year, especially with the co-ops and the internships."

Additionally, students indicated how the structure of student demographics shaped the culture of their environment. Emma (EVE) shared:

> "I think I got lucky in that my degree program is, I think, roughly half male and female. And a lot of my classes are split that way, too. So I feel like there's a greater sense of collaboration. I feel less intimidated in those courses."

As showcased by Justine and Emma, students' experiences in engineering and perceptions of culture were shaped by institutional structures.

Students' perceptions were also shaped by cultural norms of engineering. For example, Jude (BME) discussed how she recognized how BME could make a positive social impact, pushing back against the culture of technical social dualism [30] in engineering:

> "I think especially for BME, I think it's taught me a lot that engineering can really make a positive impact on other people's lives. … I think BME has … a lot of recognition around engineering ethics and a drive to actually make a positive impact with engineering."

Jude also noticed the culture of interdisciplinary collaboration she engaged with in her discipline:

> "For BME … a lot of what we do as real-world engineering is [interdisciplinary]. I work on different clubs in BME and stuff where there's an electrical engineer, there's a graduate student, there's undergraduates, there's mechanical engineers, nuclear engineers."

Students' interaction with the impact of their discipline and with other engineers shaped their perceptions of undergraduate engineering culture.

Students' experiences in engineering were also shaped by personal circumstances. For example, Camila [Robotics Engineering] shared how her entry into engineering was rocky because she joined with no personal connections nor credits:

> "Because I'm out of state. … I just came in not knowing anybody at all. … Freshman year, I didn't do so good because I was too scared to talk to people, and I was shy, and I wasn't able to fit in culturally, and … with education, too, because my parents didn't go to school at all. … I didn't come in with any credits at all either…. So I felt kind of behind already."

As demonstrated by what Camila shared about her entry into engineering, students' experiences with and perceptions of undergraduate engineering culture were shaped by their personal circumstances.

Connecting back to the metaphor, when asked to describe what they perceived as valued driving etiquette on the road, drivers across routes perceived the same, mostly positive, norms: balance, cooperation, flexibility, reliability, determination, self-sufficiency, support, and achievement. When asked if they noticed specific driver behavior, such as switching lanes with no turn signal (i.e., individualism) and speeding (i.e., competition), drivers on some routes (i.e., certain disciplines) noticed it more than drivers on other routes. Furthermore, three factors contributed to the perceptions of the drivers: roadway conditions (i.e., institutional structures), other drivers (i.e., social culture), and personal conditions (i.e., constrained agency). All three are relevant to shaping an overall picture of the driving journey. There is no objective view of the road. Rather, it is shaped by the drivers. Taken together, the drivers depict that the driving journey (i.e., undergraduate engineering culture) is perceived and experienced in a range of ways.

Bringing the Metaphors Together and Implications

You start a road trip by making a plan. You map out the route, plan your rest stops, and pack some snacks. But things may not go according to plan. Changing road conditions, other drivers' behavior, and personal circumstances can all affect the quality of your journey. Similarly, students make a plan when they start their undergraduate engineering degree, but often things do not go according to plan. Engineering structures, like a rigid curriculum, lengthen the journey [13], [36], and engineering cultures, like competition, make the journey more exhausting [37]. Furthermore, there are disciplinary differences, like different routes, that make the journey to an engineering degree different for two individuals at the same institution. This aligns with recent research in the field: some majors retain students better than others, while others repel students more than others [11]. These disciplinary differences can potentially be explained by the structures and culture of engineering, showing that there are layers to engineering retention and persistence, especially across disciplines. In addition to structure and culture differentially shaping student experience, students' individual backgrounds, like their prior exposure to math and engineering, can also influence their journey.

Engineering educators and administrators are metaphorically responsible for maintaining and improving roadway conditions, including rules, signage, road quality, and driver's education. In a state with poor infrastructure, drivers may encounter more roadblocks than in one with well-maintained roads and fast cars. Similarly, an institution and its cultural contexts can really help or hinder a student's path [38]. Therefore, engineering educators and administrators also have the power to metaphorically shape driver etiquette through roadway management and driver training [39]. Furthermore, students and practitioners may find this technology metaphor appealing for explaining and understanding the supports and barriers they may encounter in pursuing an engineering degree. This metaphor may provide a way for students to express the obstacles they encounter throughout their degree.

We cannot just think about the road or the driver, because both play a role in the driving experience. In engineering education research, we should not separate considerations of individuals from those of the structural environment. Rather, we should be bringing them into conversation with each other. Bringing both into conversation with each other can help efforts to broaden participation in engineering by offering a more holistic view of the varied paths students take in pursuing an engineering degree [11]. A route that one student takes and their experience on that route is going to be different from those of other students, so we should not be treating all routes in engineering the same. Work to broaden participation in the field should focus on differences across disciplines and consider the different routes students take, in terms of student experiences and rates of persistence and graduation (i.e., [11]). This will provide rich insight that can inform future curriculum changes and student support initiatives.

Our goal in writing this piece is to inform efforts to broaden participation in engineering. These efforts should consider both environmental structures alongside cultural considerations. Through many conversations about our studies, we recognized the intersection and interaction of our work, but it was challenging to communicate it. Using a road metaphor helped us find a shared language to talk about our studies and share it with others. Further, a metaphor helped us both zoom out and zoom in on different components of our studies, see our data through a different lens, and discuss them in different ways.

Limitations of the Metaphors and Our Approach

This paper has many limitations. First, this is not a research study; it is a conceptual piece that brings subsets of findings from two dissertations into conversation with one another. There is minimal overlap in the background literature, theory, and methods, as neither study was conducted with the other one in mind, limiting the power of our findings presented here. For example, the study on curriculum did not specifically consider culture at any of the institutions in the study, and the study on culture did not explicitly ask students about curriculum structure. Additionally, there is no complete overlap of disciplines or institutions between the two studies. Although a lack of overlap or intentionality between the two studies is a limitation, it also provides an example of an alternative research approach. Dissertations are seldom brought into conversation with one another, so this provides a novel way to use dissertation data and contribute to scholarship in the field. Second, the metaphor we used is not grounded in theory and thus oversimplifies the theoretical rigor necessary for engineering education research.

Future Work

This paper presents an opportunity for potential future research directions, since neither author explicitly designed their study with this framing in mind. Author Ryan was explicitly looking at the quantitative differences in curriculum complexity across institutions and majors; however, throughout the data collection process, she observed differences across disciplines in terms of how easy it was to figure out requirements for electives or how user-friendly some institution websites were. This paper provided an opportunity to highlight some of the observations she noticed. Future work can focus on how students actually interact with curriculum plans and how they use navigational capital or institutional resources to ensure they meet all their degree requirements. Author Josiam was focused on understanding women of color's perceptions of engineering culture. Disciplinary differences were outside the scope of her dissertation, but she saw potential in splicing the data by discipline to see what differences emerged. Future work can analyze disciplinary differences in her findings further. More insights about the two studies and findings can be found in our dissertations [25], [31].

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