Prevalent Mathematical Pathways to Engineering in South Carolina

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Dr. Anand K. Gramopadhye's research focuses on solving human-machine systems design problems and modeling human performance in technologically complex systems such as health care, aviation and manufacturing. He has more than 200 publications in these areas, and his research has been funded by NIH, NASA, NSF, FAA, DOE, and private companies. Currently, he and his students at the Advanced Technology Systems Laboratory are pursuing cutting-edge research on the role of visualization and virtual reality in aviation maintenance, hybrid inspection and job-aiding, technology to support STEM education and, more practically, to address information technology and process design issues related to delivering quality health care.

As the the Dean of Engineering, Computing and Applied Sciences he has been involved in the initiation of programmatic initiatives that have resulted in significant growth in Engineering and Computing.

For his success, he has been recognized by the NAE through the Frontiers in Engineering Program, and he has received the College's Collaboration Award and the McQueen Quattlebaum Award, which recognizes faculty for their outstanding research. In addition, Dr. Gramopadhye serves as Editor-in-Chief of the International Journal of Industrial Ergonomics and on the editorial board for several other journals.

Work in Progress: Identifying Mathematical Pathways to Engineering in South Carolina

Abstract

National data indicate that initial mathematics course placement in college is a strong predictor of persistence to degree in engineering, with students placed in calculus persisting at nearly twice the rate of those placed below calculus. Within the state of South Carolina, approximately 95% of engineering-intending students who initially place below calculus are from in-state. In order to make systemic change, we are first analyzing system-wide data to identify prevalent educational pathways within the state, and the mathematical milestones along those pathways taken by students in engineering and engineering-related fields. This paper reports preliminary analysis of that data to understand trends in major selection and mathematics preparation within the state.

Introduction

National data indicate that initial mathematics course placement in college is a strong predictor of persistence to degree in engineering[1, 2, 3, 4], with students placed in calculus persisting at nearly twice the rate of those placed below calculus [3]. Underrepresented minority, low-income, and first-generation students are less likely to take precalculus or calculus in high school [4, 5, 6], and they subsequently enter two-year or four-year programs with fewer mathematics and science credits [7, 8]. Consequently, students in this group are more likely to be unprepared for college calculus [9, 10], are disproportionately represented in the cohorts that enter college not yet calculus-ready, and often do not persist in engineering beyond the precalculus stage [11, 12, 13, 14]. Taken together, over 60% of underrepresented minorities in the United States who start in engineering programs do not finish [15]. The exploratory statistical results presented in this paper are part of a larger sequential mixed-methods study intended to broaden participation in engineering by improving the mathematical pathways into and through engineering.

As of this writing, seventeen states and the District of Columbia now require four Carnegie units of math for high school graduation[16]. Nine of those policies went into effect for graduating classes between 2013 and 2018; the impact on mathematics preparation for college and on collegiate STEM retention in those states has not yet been fully realized. In contrast, South Carolina was one of only six states with a four-year math requirement for high school graduation as early as 2007 [17]. This provides an opportunity to examine mathematical pathways to engineering in an educational system that has had over a decade to stabilize with respect to mathematics teacher preparation, staffing, student expectations, and in-state college admissions.

As a first step toward broadening participation by improving mathematical pathways to engineering, we analyzed existing data for all four state-supported four-year colleges with ABET accreditation, as well as all sixteen two-year campuses in the state Technical College System, to identify patterns in initial mathematics placement for in-state students entering engineering or engineering-related fields. This paper specifically focuses on data from the four-year colleges to address the research question:

> *What patterns exist within the state for major selection and mathematics placement among students entering state-supported four-year programs in engineering and engineering-related fields?*

We bound our definition of *engineering fields* narrowly to include only programs that are accredited by the Engineering Accreditation Commission or the Engineering Technology Accreditation Commission under the umbrella of the Accreditation Board of Engineering and Technology (ABET). Our boundaries for *engineering-related programs* more broadly include the natural sciences (chemistry, physics, geology, biology, mathematics), other ABET-accredited programs such as computer science, and business. The inclusion of business is grounded in research indicating that professionals in business and engineering have similar work values but different skills and interests [18, 19, 20]. Identifying factors that place students on a pathway to business rather than to engineering might therefore contribute critical knowledge to broadening participation in engineering.

Education Landscape in South Carolina

Secondary Schools

Since 2005, the South Carolina State Board of Education has required that students in the tenth grade select one of the sixteen career clusters shown in Table 1.

Table 1 Career cluster options for high school students in South Carolina.

Agriculture, Food, & Natural Resources	Hospitality & Tourism
Architecture & Construction	Human Services
Arts, A/V Technology, & Communications	Information Technology
Business Management & Administration	Law, Public Safety, Correction & Security
Education & Training	Manufacturing
Finance	Marketing
Government & Public Administration	Science, Tech., Eng., & Math. (STEM)
Health Science	Transportation, Distribution & Logistics

The selection of career cluster is non-binding, but allows for systematic development of individualized graduation plans (IGPs) based on career interests. The IGPs primarily affect recommendations for course electives; all sixteen career clusters have identical recommendations for the four-year sequence of mathematics courses, as shown in Table 2.

Table 2 Mathematics course recommendations for high school graduation in South Carolina.

Grade 9	Grade 10	Grade 11	Grade 12
Algebra 1 or Math for the Technologies 1	Geometry or Math for the Technologies 2	Algebra 2 or Math for the Technologies 3	Precalculus or Math for the Technologies 4

We note that the Math for the Technologies sequence is being phased out statewide, and few schools still offer it, although it still appears in the IGPs. Also, although all 16 IGPs *recommend* the Algebra 1 - Geometry - Algebra 2 - Precalculus sequence, only Algebra 1 is specifically *required* for graduation, even for students in the STEM career cluster. Finally, there is no requirement that students take mathematics in their final year of high school. The prevalence of Algebra 1 in middle school results in many accelerated students completing the mathematics requirements for graduation by the end of their junior year of high school.

Any high school graduate in the state who follows the IGP recommendations will have completed precalculus or the equivalent, and should nominally be prepared for calculus upon entering college. In practice, this is not the case. A significant percentage of students entering the post-secondary system are placed below calculus, even among STEM-intending students and those who completed the STEM career cluster. The distribution of these students around the state is not uniform. Some counties produce high numbers of calculus-ready and STEM-intending students, while others under-produce. In this paper we report those results at a county level for students entering engineering-related fields at four-year post-secondary institutions in South Carolina.

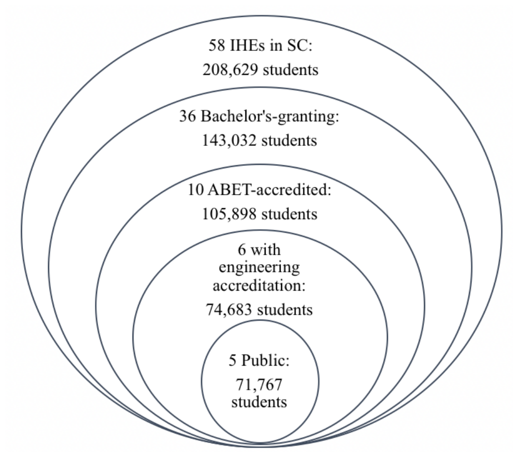


Figure 1 Total undergraduate enrollment at institutions of higher education (IHEs) in South Carolina (2017).

Post-secondary Institutions

In 2017, the 58 institutions of higher education in South Carolina enrolled a total of 208,629 undergraduate students. Of those, 143,032 (68.6%) were enrolled at one of the 36 bachelors-granting institutions [21]. Ten of those 36 institutions have ABET-accredited programs, but only six have engineering-specific accreditation. The other four have ABET-accredited computer science programs, which fall under our definition of engineering-related fields [22]. Of the six campuses with accredited engineering programs, five are state-supported and one is private. See Figure 1 for student enrollments at each level of institutional inclusion.

Methods

Data Sources

The results described in this paper are part of a larger study involving a coalition of twenty campuses in South Carolina: Clemson University (CU); South Carolina State University (SCSU); The Citadel, the Military College of South Carolina (Citadel); University of South Carolina - Columbia (USC); and the sixteen campuses in the South Carolina Technical College System (SCTCS). See Figure 2 for the geographic distribution of the coalition campuses. The shaded counties in Figure 2 were the subject of the 2005 documentary "Corridor of Shame: The Neglect of South Carolina's Rural Schools" [23].

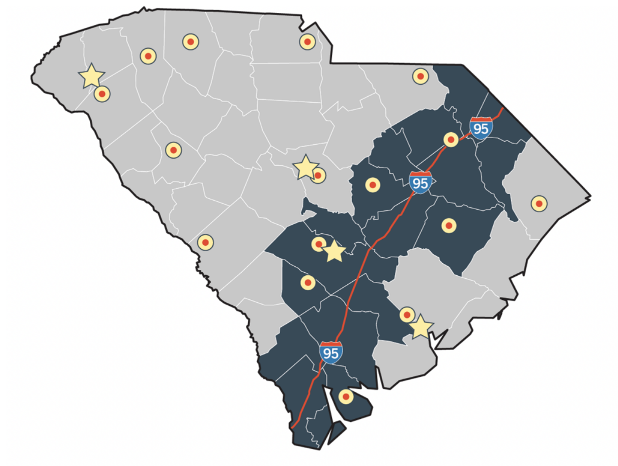


Figure 2 Locations of the twenty campuses from which data were drawn. Two-year campuses are indicated by a circle. Four-year campuses are indicated by a star.

Data were collected regarding first-year students at the twenty coalition campuses. For this paper, we examine the data from the four-year colleges. Two of the engineering-accredited four-year campuses in the state, University of South Carolina - Upstate (USCU) and Bob Jones University (BJU), are not part of the coalition and we do not have data from them.

However, the four included campuses account for 88% of all students enrolled at four-year colleges with engineering programs and 99.2% of students enrolled in four-year engineering programs in South Carolina [24] (Figure 3). While we recognize that there may be unique social forces in play among the students excluded from the study, we nonetheless argue that their inclusion would not significantly alter the observed trends among students originating in South Carolina.

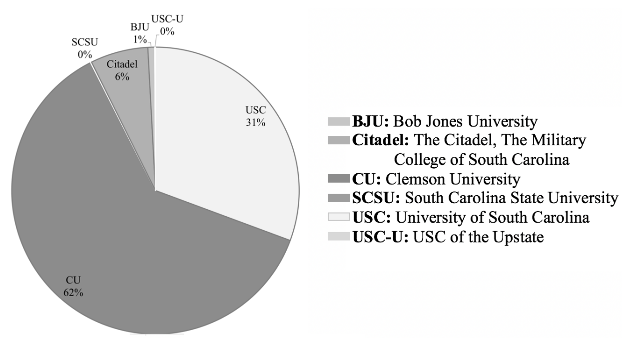


Figure 3 Distribution of 2017 enrollment in engineering programs among the six engineering-accredited bachelors-granting institutions in South Carolina.

For each coalition campus, we prepared a detailed data request specifying the programs, students, and variables of interest. We also provided a data template with columns in standard order. All twenty campuses responded, providing a total of 21,656 data points. The 8,625 data points from the four-year campuses are the subject of the analysis in this paper.

Bounding the Programs of Interest

In keeping with the scope of our study, we requested data only for students enrolled in engineering-related fields, as described in the introduction. To prevent different interpretations of "engineering-related" at different campuses, we identified specific programs at each campus, as determined by the two-digit Classification of Instructional Programs (CIP) codes assigned by the Integrated Post-Secondary Education Data System (IPEDS) [25]. The specific codes of interest are listed in Table 3.

Table 3 Two-digit CIP codes comprising 'engineering-related fields' for the purpose of this study.

10	Communications Technologies/ Technicians and Support Services	40	Physical Science
11	Computer and Information Sciences and Support Services	41	Science Technologies/Technicians
14	Engineering	47	Mechanic and Repair Technologies/ Technicians
15	Engineering Technologies and Engineering-Related Fields	48	Precision Production
27	Mathematics and Statistics	52	Business, Management, Marketing, and Related Support Services

In order to capture all students in these fields, we requested data not just for students with one of these CIP codes as their primary field of study, but also those who had any of the codes as a second program of study, dual major, minor, or certificate program.

Bounding the Student Population of Interest

The advising guidelines and requirements for high school graduation in South Carolina are stable and uniform across the state. There is no such uniformity for mathematics placement, course offerings, or curriculum across the IHEs in the state. In order to minimize the effects of policy changes at any single campus or combination of campuses, we sought data only for students who first enrolled at a given campus between January and October of 2017. That included both new transfers and new freshmen, but excluded students who had been re-admitted after a period of disenrollment. Although we were interested only in students who originated from South Carolina, we did not make that exclusion when we requested the data.

Bounding the Variables of Interest

In order to ensure compatibility of data between all 20 participating campuses, each of which uses its own data collection and storage protocols, we requested data using the same variables and values as those reported by law to the South Carolina Commission on Higher Education Management Information System (CHEMIS). The requested CHEMIS data fields that are relevant to this analysis are shown in Table 4.

Table 4 CHEMIS data fields used in analysis of placement and pathways trends in South Carolina.

Variable Name	Description and Values
PROG_CODE	Six-digit CIP code for student's primary course of study or major. VALUES: Six-digit CIP codes; 999999 =NULL.
PROG_CODE_2	Six-digit CIP code for student's additional course of study, major, minor, or certificate. VALUES: Six-digit CIP codes; 999999 =NULL.
PROG_CODE_2	Six-digit CIP code for student's additional course of study, major, minor, or certificate. VALUES: Six-digit CIP codes; 999999 =NULL.
ENTRY_YEAR	The first year student enrolled at the campus. VALUES: Valid year.
TRAN_INST	The six-digit institution code for the post-secondary institution upon which acceptance was based and from which the student transferred credits. VALUES: South Carolina FICE codes; 666666=out-of-state post-secondary institution; 777777=foreign postsecondary institution; 888888=unknown postsecondary institution.
HIGH_SCHOOL	CEEB code for the high school attended by the student. VALUES: CEEB Codes for in-state high school; 444444=home school; 555555=South Carolina General Educational Development (GED); 666666=out of state diploma or GED; 777777=foreign diploma or GED; 888888=unknown

In addition, we requested first math course taken and most recent math course taken, using the course number and title as shown in the campus course catalog. The campus-specific course numbers were then converted to the collective course codes and names shown in Table 5 using existing articulation agreements as registered in the South Carolina Transfer and Articulation Center. We also requested all AP scores, although only AP Calculus AB and AP Calculus BC scores were used in this analysis.

Table 5 Collective course names and groupings used to align campus-specific mathematics course numbers and titles.

Category	Collective Course Code and Name
No course	99 – No course
Below Calculus	01 – Developmental Math 02 – Basic Algebra 11 – College Algebra 12 – Trigonometry 13 – Precalculus
Calculus	21 – Calculus I 22 – Calculus II 23 – Calculus III 50 – Business Calculus 80 – Other (higher than Calculus III)
Other	60 – Statistics 70 – Other (not in calculus or calculus prep sequence)

Data Cleaning

For analysis, data from across all universities needed to be in a standard format and student identification codes needed to be changed to protect the privacy of each student. Data reports were taken one by one and a column for FICE institution code was added. The headings of all columns were checked and corrected as needed to preserve order alignment as it appeared in the data request template sent to each campus. Each student identification entry was recoded as a nine-digit `PSEUDO_ID`, with the first four digits indicating the institution's FICE code and the remaining five digits being sequential, starting at 00001. A record of the institution's student identification code paired with `PSEUDO_ID` was saved to a separate file and then the student identification was stripped from the main datafile. Birth dates were truncated as birth year only for further protection of anonymity and gender was coded numerically. Math course numbers and names were converted to collective codes and numbers as indicated above. After each individual data file was cleaned, it was added to a combined data file.

Within the combined data file, each College Entrance Examination Board (CEEB) code was paired with the corresponding high school name. CEEB codes outside of South Carolina were converted to 666666 (US, out-of-state), 777777 (foreign), or 888888 (unknown). Columns were added for county, 5-digit Federal Information Processing Standard (FIPS) county code, and city of the high schools within South Carolina.

Analysis

From the 21,656 records in the combined data file, we included only the 8,625 entries from the four-year campuses. We then excluded the 4,616 students with non-South Carolina, home-school, or 'unknown' CEEB codes, leaving 4,009 entries for first-year students in engineering-related fields who graduated from a South Carolina high school and were attending a four-year coalition campus.

The collective math course codes were grouped as shown in Table 5. Students in the "No Course" category were included with the "Calculus" category if they had a score of 3 or higher on either the AP Calculus AB or AP Calculus BC exam, as either of those yield college credit for Calculus I at all four campuses. Otherwise, the students in the "No Course" category were included in the "Below Calculus" category. The 72 students whose first math course fell in the "Other" category (statistics or other course not in the calculus or calculus prep sequence) were removed from the analysis, leaving 3937 records classified as either "Below Calculus" or "Calculus or Higher" for initial math course. The CIP codes were grouped as "Engineering" if they were in group 14, "Business" if they were in group 52, or "Other" for all other CIP codes.

We then carried out an exploratory analysis. We note that the sample sizes from one county to the next vary dramatically. The use of statistical tests was limited to χ^2 for independence, and the results presented are descriptive in nature. All analyses were carried out using R [26]. The code and raw data may be obtained from the corresponding author for verification of results upon request.

Results

Placement in or above Calculus I

Fourteen of the 46 counties in South Carolina (30.4%) accounted for 75% of the 11th graders enrolled in public schools in 2015-2016, a subset of whom entered college in Fall 2017. However, just eight of those 46 counties (17%) accounted for 75% of the population of interest whose initial college mathematics course was Calculus I or higher (Figure 4). This is not entirely surprising. Seven of these eight counties are among the eight most populous, with a larger tax base, higher average parental education levels, and more industry.

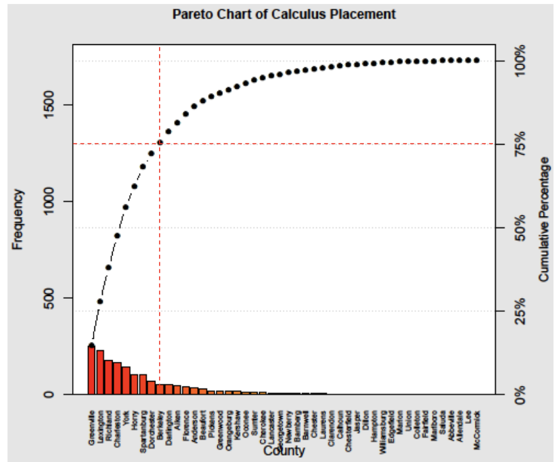


Figure 4 Pareto chart of placement in Calculus I or higher by South Carolina county in 2017.

More generally, most of the 46 counties in South Carolina were close to the same rank for number of 11th-grade students and number of students entering four-year engineering-related program placed into calculus or higher (Table 7). The counties with a rank order difference of five places or more (Sumter, Lancaster, Darlington, Chesterfield, Dillon, Marion, Colleton, Marlboro, Barnwell, Abbeville, Bamberg, Jasper, Calhoun) are of particular interest. We note that the significant rank order difference for Darlington County (22nd in number of 11th-graders, 10th in number of students placed into calculus or higher) can be attributed in large part to the fact that it is home to the South Carolina Governor's School for Science and Math, a selective, residential public high school for 11th and 12th graders with particular interest in mathematics and science.

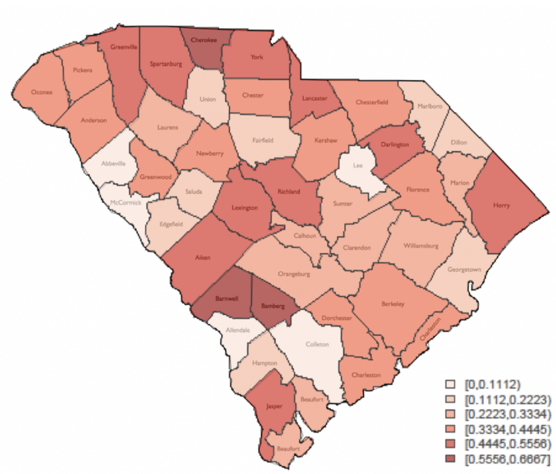


Figure 5 Rates of placement in calculus or higher among South Carolina students entering engineering-related fields at a four-year campus in 2017.

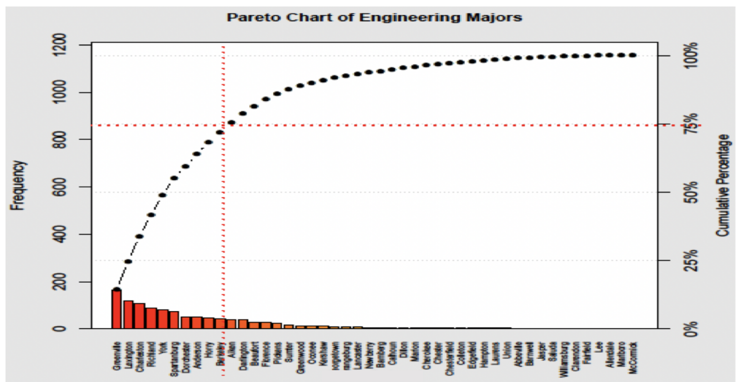
When we consider the *rates* of placement in calculus among students entering engineering-related fields at four-year institutions (Figure 5), we get a more nuanced view, although we note that the sample sizes vary widely by county. With this view, we emphasize Barnwell and Bamberg counties, and add Cherokee county to our list for additional exploration, since between

55% and 67% of the four-year students from those counties place into calculus or higher. At the other end, we emphasize Abbeville and Colleton counties and add Allendale, Lee, and McCormick counties, where less than 11.2% of the students entering four-year engineering-related fields placed into calculus.

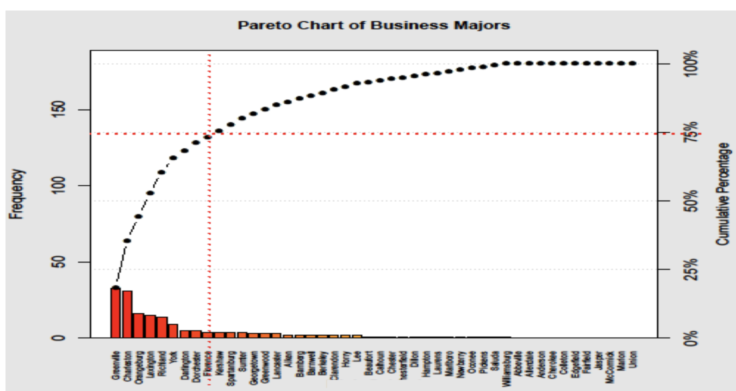
Program selection

When we consider how many students from our population of interest enter specifically into an engineering program, we find that ten of the 46 counties again produce 75% of the engineering majors (Figure 6a). There is a strong, but not complete, overlap with the counties producing calculus-ready students, and again much of the effect is due simply to population.

As previously mentioned, business majors are of specific interest in this study since the work values associated with business professionals are nearly identical to those associated with engineering professionals. Moreover, recruiting students into engineering from business would increase overall STEM enrollment, rather than simply shifting enrollment within STEM fields. In South Carolina, nine counties again produce 75% of all business majors among the population of interest (Figure 6b). In this case, however, only five of those counties (Charleston, Greenville, Lexington, Richland, and York) are among the most populous. The other four (Darlington, Dorchester, Florence, and Orangeburg) are all along the I-95 "Corridor of Shame".



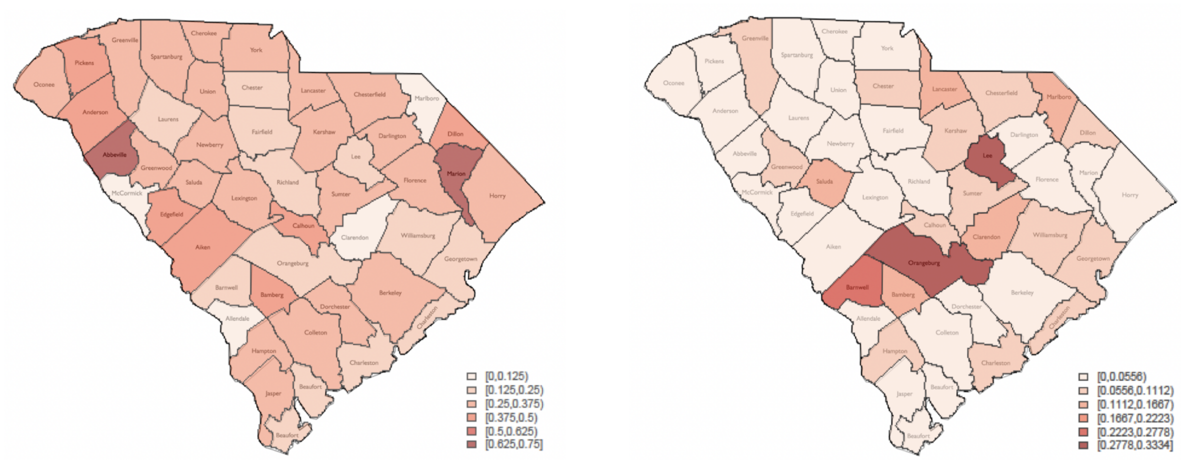
(a) Engineering



(b) Business

Figure 6 Pareto charts of major selection among students entering four-year engineering-related fields, by county.

If we again look instead at the *rates* of major selection within the population of interest (Figure 7), we notice very different patterns than when we considered rates of calculus-readiness. The three counties with highest calculus-readiness rates (Barnwell, Bamberg, and Cherokee) have between 12.5% and 50% of the students entering engineering-related fields going specifically into engineering. In contrast, the two counties with 62.5% to 75% of their engineering-related students going into engineering (Abbeville and Marion) have calculus-ready rates of under 11% (Abbeville) and 22-33% (Marion). In looking at rates of production of business majors among the population of interest (Figure 7b), we also see higher rates in the counties along the I-95 corridor.



(a) Engineering **(b)** Business

Figure 7 Rates of major selection among South Carolina students entering four-year engineering-related fields in 2017. Note that the ranges for rates associated with each color differ between the two maps.

Calculus-readiness and declaration of major

We performed simple χ^2 tests for association of calculus-readiness and choice of major for both business and engineering (Table 6).

Table 6 χ^2 tests for independence of calculus-readiness and choice major (business, engineering).

	Below Calculus	At/Above Calculus
Non-Business	2,072	1,685
Business	134	46

$\chi^2 = 25.78$
$p = 5.23 \times 10^{-7}$

	Below Calculus	At/Above Calculus
Non-Engineering	1,739	1,043
Engineering	467	688

$\chi^2 = 160.56$
$p \approx 0$

For students in engineering-related fields, we find extremely strong evidence to indicate an association between whether or not a student declares engineering as their major and whether or not they are initially enrolled at or above calculus. We also find strong evidence to indicate an association between whether or not a student declares business as their major and whether or not they are initially enrolled at or above calculus.

However, the direction of the association is reversed: placement at or above calculus is associated with declaring a major in engineering, while placement below calculus is associated with declaring a major in business. This provides some indication that, among students with similar work values, initial math placement might be a deciding factor between engineering and business as choice of major. This provides a critical direction for exploration in follow-up studies with these populations.

Discussion

This analysis focuses solely on the pathways and patterns among students entering four-year programs from high schools in South Carolina. We have not reported on data for students entering two-year technical colleges, nor have we carried out any model-building. Those are left for next steps in the study. However, these patterns in the pathways data do yield anomalies worth exploring, as well as directions for potential interventions. Not only have we identified specific locations that stand out as unusual, but we have specific aspects to focus on in each.

Some of the questions we will explore as a follow-up to the exploratory analysis include: What is happening in the counties that produce relatively high rates of engineering majors or calculus-ready students? How can we translate those practices to other counties? What barriers are in place in the counties producing relatively low rates of engineering majors or calculus-ready students? What resources are needed in order to mitigate them? What forces are in play along the I-95 corridor that result in a high rate of business majors? What interventions might we put in place to bring more of those students, who are predominantly from marginalized populations, into STEM disciplines and, more specifically, into engineering?

These preliminary results from our work in progress have set the stage for next steps: a series of focus groups held in the anomalous locations to determine the forces in play that led to unusually strong or unusually weak placement and pathway results.

Table 7 11th grade enrollment (public schools only) and rank for students placing into calculus among South Carolina counties, ordered by 11th grade enrollment in 2015-2016.

County	**11th grade enrollment 2015-2016**	**Rank for calculus placement**
1. Greenville	5,065	1
2. Lexington	3,716	2
3. Richland	3,395	3
4. Spartanburg	3,205	7
5. York	3,040	5
6. Horry	2,939	6
7. Charleston	2,869	4
8. Berkeley	2,322	9
9. Anderson	1,936	13
10. Dorchester	1,827	8

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County	**11th grade enrollment 2015-2016**	**Rank for calculus placement**
11. Aiken	1,611	11
12. Beaufort	1,403	14
13. Florence	1,397	12
14. Sumter	1,178	20
15. Pickens	1,139	15
16. Lancaster	838	22
17. Orangeburg	835	17
18. Greenwood	809	16
19. Kershaw	713	18
20. Oconee	706	19
21. Georgetown	680	23
22. Darlington	667	10
23. Cherokee	573	21
24. Laurens	558	28
25. Chesterfield	450	31
26. Dillon	384	33
27. Newberry	366	24
28. Chester	346	27
29. Marion	331	37
30. Clarendon	329	29
31. Colleton	325	39
32. Williamsburg	297	35
33. Marlboro	268	41
34. Union	242	38
35. Barnwell	235	26
36. Hampton	211	34
37. Fairfield	185	40
38. Abbeville	177	43
39. Edgefield	170	36
40. Bamberg	153	25
41. Lee	150	45
42. Jasper	144	32
43. Saluda	115	42
44. Calhoun	102	30
45. Allendale	90	44
46. McCormick	45	46

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