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**ABSTRACT**

Two-year community colleges enroll nearly half of all first-time undergraduates in the United States, but to ambiguous effect: low persistence rates and the potential for diverting students from 4-year institutions cast ambiguity over 2-year colleges' contributions to upward mobility. This paper develops a new instrumental variables approach to identifying causal effects along multiple treatment margins, and applies it to linked education and earnings registries to disentangle the net impacts of 2-year college access into two competing causal margins: significant value-added for 2-year entrants who otherwise would not have attended college, but negative impacts on students diverted from immediate 4-year entry.

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# 1 Introduction

Since 1980, the earnings gap between college and high school graduates has roughly doubled in the United States (Autor, 2014). Rising demand for skilled labor has outpaced modest growth in the supply of college-educated workers (Katz and Murphy, 1992; Goldin and Katz, 2008; Acemoglu and Autor, 2011), and this modest supply growth has been uneven: children from high-income families are more likely to enroll in and complete college than their low-income peers (Chetty et al., 2014), and this college gradient in family income has steepened since 1980 (Belley and Lochner, 2007; Bailey and Dynarski, 2011).

In response to these trends, a recent wave of policies aimed at broadening college access have focused on 2-year community colleges, which enroll nearly half of all college entrants and a disproportionate share of low-income students, as key arteries in increasing the flow of young Americans into higher education.<sup>1</sup> Several states and major cities have launched free 2-year college tuition programs since 2014, with many more considering similar legislation (National Conference of State Legislatures, 2016), all in the hope that expanding access to 2-year colleges will help extend the prospects of postsecondary attainment and upward mobility to a broader share of young Americans.

Even if expanding 2-year access succeeds in increasing enrollment in 2-year colleges, however, causal evidence on the efficacy of 2-year colleges in ultimately boosting educational attainment and earnings is limited (Belfield and Bailey, 2011, 2017; Denning, 2017), and greater 2-year access may even detrimentally divert college-bound students from directly entering higher-resourced 4-year institutions (Clark, 1960; Brint and Karabel, 1989; Rouse, 1995). Concerns stem from low observed rates of degree completion and upward transfer among 2-year entrants: while 81 percent begin with the intention to earn a bachelor’s degree, only 33 percent actually transfer up to a 4-year institution within six years, and just 14 percent complete a bachelor’s degree (Jenkins and Fink, 2016). In contrast, 60 percent of students who begin college directly at a 4-year institution complete a bachelor’s degree over the same timeframe, and substantial outcome gaps between 2-year and 4-year entrants remain after adjusting for observable differences in test scores and demographic backgrounds (Reynolds, 2012). To the extent that these gaps reflect causal impacts of beginning college at a 2-year versus 4-year institution, the potential for 4-to-2 diversion casts further ambiguity over the role of 2-year colleges in promoting upward mobility.

This paper develops new econometric tools and marshals linked administrative data to explore the consequences of expanding access to 2-year colleges on student outcomes. Does 2-year access boost educational attainment and earnings, on net? Are some students diverted from 4-year entry, with detrimental effects? How large are the gains, if any, among 2-year entrants who otherwise would not have attended any college? To answer these questions, I develop a new instrumental variables approach that nonparametrically identifies causal effects along multiple margins of treatment. Applied to the 2-year college setting, this approach unlocks a decomposition of the overall net effects of 2-year access into two distinct and potentially opposing treatment margins: causal

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<sup>1</sup>Following Cohen et al. (2014), I use the terms community colleges, 2-year colleges, and junior colleges interchangeably when referring to non-profit institutions that award associate’s degrees as their highest credential.

value-added for new 2-year entrants who otherwise would have not enrolled in any college, versus causal diversion impacts on 2-year entrants who otherwise would have started directly at a 4-year institution.<sup>2</sup>

Methodologically, this new approach overcomes a challenge in the instrumental variables (IV) literature: standard IV methods like two-stage least squares (2SLS) do not generally recover causal effects of one alternative versus another when individuals face multiple treatment alternatives and reap heterogeneous treatment effects (Heckman and Urzua, 2010), even when researchers have access to as many instruments as treatment margins (Kirkeboen et al., 2016). In contrast, I show how a nonparametric separate identification approach, which studies instrument-induced variation in outcome-by-treatment interactions, can isolate the mean potential outcomes of instrument compliers along each distinct treatment margin. Differencing these mean potential outcomes then delivers margin-specific treatment effects.<sup>3</sup> This approach generalizes the binary complier-describing logic of Imbens and Rubin (1997), Abadie (2002), and Carneiro and Lee (2009) to multiple treatments and instruments: the data do not directly reveal which individuals are compliers, nor the treatment margin along which they would comply, but the distributional characteristics of each complier group, including their potential outcomes, emerge when studying compositional changes in each treatment group driven by specific instruments.<sup>4</sup> This separate identification approach has a straightforward implementation as a series of 2SLS regressions, replacing the usual outcome variable with outcome-by-treatment interactions and using local instrumental variation around a given evaluation point. Stratifying the estimates across different instrument evaluation points helps probe external validity of the local IV estimates, in this case examining how marginal returns evolve as 2-year access further expands and draws deeper into the population of potential entrants.

I implement the method on longitudinal administrative data spanning the state of Texas. I link all Texas public high school students with enrollment and degree completion records at all public and private Texas colleges and universities, then further link these students with quarterly earnings records for all Texas employees from the state unemployment insurance administration. These data are unusual in the U.S. context in their combination of breadth and depth of coverage, spanning the population of the second largest state (comprising 10.5% of all public K-12 students in the U.S.) and providing detailed information on demographics, test scores, college enrollment dynamics, degree completion, and longitudinal earnings.

Linking the student-level microdata with the locations all high school and college campuses in Texas, I identify causal effects along the multiple margins of 2-year enrollment with instrumental

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<sup>2</sup>This paper focuses on identifying and estimating ex post treatment effects. See Cunha et al. (2005) and Arcidiacono et al. (2014) for examples of methods to recover ex ante effects of schooling choices, as perceived by students at the point of decision, through additional data on student expectations and/or structural modeling of choice behavior. See also Manski (1993) and Dominitz and Manski (1996) for discussions of student expectation formation.

<sup>3</sup>The proposed method can recover any features of the marginal distributions of complier potential outcomes, so estimating quantile treatment effects, for example, remains an avenue for future work.

<sup>4</sup>Kline and Walters (2016) consider the case of multiple treatments but only one binary instrument, showing nonparametric identification of certain complier characteristics. This paper shows how additional instruments can secure nonparametric identification along all relevant complier margins and thus yield margin-specific treatment effects.

variation in students' proximities to local 2-year and 4-year college campuses. Departing from most papers in the returns-to-schooling canon that employ distance instruments,<sup>5</sup> I control directly for detailed neighborhood-level measures of urbanization, as well as commuting zone fixed effects, to ensure that distance comparisons come only from students who grow up in similar neighborhoods and face similar local labor markets when deciding whether and where to begin college. I also do not rely on one-dimensional variation in a student's distance to any type of college; instead, identification comes from varying 2-year distance while holding 4-year distance fixed, and varying 4-year distance while holding 2-year distance fixed. Encouragingly, I show that these two dimensions of conditional instrumental variation are uncorrelated with excluded student ability measures that strongly predict college choices and long-run outcomes. Given this balancing result, the instruments yield causal estimates that are unaffected by the inclusion of ability measures as controls, providing evidence against the concern that the IV results are spuriously driven by families with different levels of human capital systematically sorting into neighborhoods with different residual proximities to 2-year and 4-year colleges.

The results of this IV approach offer four main conclusions. First, greater access to 2-year colleges boosts educational attainment and earnings on net. Second, these net effects shroud opposing impacts along the two distinct treatment margins: roughly one third of induced 2-year entrants are diverted from 4-year entry and ultimately complete less education as a result, empirically confirming concerns over the diversion channel but with smaller magnitudes than OLS regressions would suggest. The other two thirds of induced 2-year entrants would not have otherwise attended college, and they reap significant gains in educational attainment and earnings. Third, stratifying by demographics reveals that women drive these results with effects of larger magnitude along both margins compared to men, while 2-year access particularly boosts the upward earnings mobility of students from low-income families thanks to their lower likelihood of diversion from 4-year entry. Finally, stratifying the local IV estimates across the range of 2-year college proximity suggests that causal impacts on marginal students do not diminish as 2-year access further expands and draws deeper into the population of potential entrants.

Taken together, the methods and results of this paper contribute a quantitative causal framework for studying the long-run impacts of community college access policies, highlighting the trade-off between democratizing new students into higher education and diverting college-bound students from direct 4-year entry. Since the Tennessee Promise program launched in 2014, offering recent high school graduates free tuition at all 2-year community colleges in the state, Oregon, Minnesota, Kentucky, and Rhode Island have implemented similar programs, with many more considering similar legislation. Several major metropolitan governments have launched analogous local programs, including the Chicago STAR Scholarship (launched in 2014), San Francisco's Free City program (2017), and the Boston Bridge program (2017). The results of this paper suggest that broad expansions of 2-year college access are likely to boost the upward mobility of students "democratized"

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<sup>5</sup>E.g. Card (1995), Rouse (1995), Kling (2001), Cameron and Taber (2004), Carneiro and Lee (2009), Carneiro et al. (2011), Eisenhauer et al. (2015), and Nybom (2017), among others.

into higher education from non-attendance, but more targeted policies that avoid significant 4-year diversion may generate larger net benefits.

The empirical results build on an interdisciplinary literature studying the outcomes of 2-year college students, reviewed by Kane and Rouse (1999) and Belfield and Bailey (2011, 2017).<sup>6</sup> Most of this literature relies on selection-on-observables assumptions to interpret OLS and matching results as causal. A growing set of papers relax this assumption in panel specifications with individual fixed effects (e.g. Jacobson et al., 2005; Jepsen et al., 2014; Dynarski et al., 2018; Stevens et al., 2018), but this approach necessarily focuses on older workers who have accumulated pre-enrollment earnings histories. Several recent papers exploit natural experiments that directly or indirectly influence 2-year college enrollment (Denning, 2017; Zimmerman, 2014; Goodman et al., 2017; Carruthers et al., 2020; Grosz, 2020; Gurantz, 2020; Smith et al., 2020; Acton, 2021), but much of this variation is too recent to examine longer-run outcomes, and these papers do not offer methods to nonparametrically disentangle net impacts into separate causal effects along each treatment margin.

In estimating causal impacts of 2-year college entry along both the “democratization” and “diversion” margins through the use of multiple instruments, this paper advances the related work of Rouse (1995, 1998) and Miller (2007) by relaxing the implicit assumption of homogeneous treatment effects embedded in their multivariate two-stage least squares (2SLS) specifications. As shown by Kirkeboen et al. (2016), multivariate 2SLS estimands generally combine comparisons across multiple treatment margins and complier groups, making multivariate 2SLS estimates difficult to interpret in the general case where treatment effects vary across individuals.<sup>7</sup> Multiple pieces of evidence point to such heterogeneity across potential 2-year college entrants, motivating the development of a nonparametric identification approach that is robust to such heterogeneity.

Methodologically, the identification results contribute to the literature on identifying causal effects of multivalued treatments with instrumental variables. Heckman and Urzua (2010) discuss the identification challenges inherent in settings with multiple margins of treatment, highlighting how individuals induced into a specific treatment by instrumental variation can come from multiple economically distinct alternatives. A growing set of papers have developed conditions under which margin-specific treatment effects can be identified. This paper’s nonparametric separate identification approach allows the analyst to relax many of these conditions: it does not require parameterizing unobserved heterogeneity (Feller et al., 2016; Hull, 2020), or imposing homogeneity in treatment effects or selection behavior across observable covariate stratifications (Hull, 2018;

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<sup>6</sup>The 2-year versus 4-year comparison also contributes more broadly to the college quality literature; see Hoxby (2009) for a review, along with Andrews et al. (2016), Mountjoy and Hickman (2021), and Black et al. (2020) for recent contributions using the same administrative data source as this paper. The Peltzman (1973)-esque 4-to-2 diversion results in this paper are reminiscent of Cohodes and Goodman (2014), who study diversion across vertical quality tiers within the 4-year sector. The greater prevalence of vocational courses in the 2-year sector could alternatively cast the comparison as one between horizontally differentiated curricula, e.g. Altonji et al. (2012), Kirkeboen et al. (2016), and Bertrand et al. (2021).

<sup>7</sup>In Appendix B, I derive and decompose the multivariate 2SLS estimands corresponding to my setting, showing how they fuse multiple treatment margins and complier types into each coefficient. Kline and Walters (2016) and Hull (2018) derive related results in the 2SLS case where a single instrument is interacted with a stratifying covariate to generate another dimension of instrumental variation. See also Pinto (2016) for a related discussion in the context of the multiple treatment arms of the Moving to Opportunity experiment.

Kline and Walters, 2016), or observing individuals’ preference rankings over treatment alternatives (Kirkeboen et al., 2016).<sup>8</sup>

My employment of multiple continuous instruments most closely resembles Heckman et al. (2008) (with related expositions in Heckman and Vytlacil, 2007a,b) and Lee and Salanié (2018). Heckman et al. (2008) rely on a multidimensional identification-at-infinity argument: they show how the challenge of identifying the effect of one treatment against a specific alternative can collapse to a binary treatment problem in the limit if sufficiently extreme instrument values are available that force the probability of choosing any of the other treatments—other than the binary comparison of interest—to be arbitrarily small. My approach does not require any such large support conditions; instead, I show how local instrument shifts that induce overlapping complier flows can identify marginal treatment effects at each point in whatever support the instruments happen to enjoy. Lee and Salanié (2018) explore identification of similar target parameters in an index model framework that generalizes the illustrative discrete choice model I use to visualize the mechanics of my approach in Section 4.3. Their framework allows for complex complier behavior, with each treatment choice governed by threshold-crossing rules involving potentially multiple unobservables crossing multiple thresholds, but generally requires nonparametrically identifying the index functions that comprise these thresholds in a first step. My approach in Section 4.4 bypasses this demanding empirical challenge by deriving conditions on complier behavior that allow a set of easily-implemented local two stage least squares (2SLS) regressions with modified outcome variables to recover all of the ingredients necessary for identifying margin-specific treatment effects.

Finally, while the institutional focus of this paper lies with higher education in the United States, the methodology could apply to a broad range of settings. The 2-year and 4-year college distance instruments play the role of prices or cost shifters, suggesting parallels to other multivalued treatment choices that depend on initial costs, including migration, occupational choice, insurance enrollment, hospital admission, K-12 school choice, and firm location decisions, among others. This method also enhances program evaluation in settings with crowd-out or substitution bias (Heckman et al., 2000; Kline and Walters, 2016), since the task of evaluating a policy or program with readily-available substitutes—here the encouragement of 2-year enrollment in the presence of the 4-year alternative—is aided by the ability to decompose net policy impacts into distinct effects among individuals who would otherwise go untreated (no college) versus those who would have obtained the substitute (4-year entry).

The remainder of the paper proceeds as follows. Section 2 provides institutional background on the American community college. Section 3 describes the linked administrative data and presents descriptive results on initial enrollment choices and outcomes. Section 4 discusses the identification challenges posed by multiple treatment margins and develops the nonparametric separate identification approach. Section 5 discusses estimation and conducts diagnostics on the instruments. Section 6 presents the empirical results. Section 7 concludes.

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<sup>8</sup>See also Lee and Salanié (2020), Rodriguez and Saltiel (2020), Galindo (2020), Wang (2020), Kamat (2021), and Arteaga (2021) for recent contributions to this literature. Section 4.4 discusses Heckman and Pinto (2018).

## 2 Institutional Background

Two-year community colleges straddle a complicated space in American higher education. From the emergence of the first “junior colleges” at the dawn of the 20th century, through their explosive mid-century growth and modern stabilization at roughly one thousand campuses across all fifty states, debate over the proper role of this “contradictory college” (Dougherty, 1994) has continued apace, centering around three interrelated questions. The oldest, and largely resolved, question from the primordial period at the turn of the 20th century was whether 4-year universities should spin off their first two years of teaching to these emerging junior colleges, allowing 2-year college faculty to specialize in undergraduate instruction while freeing up university faculty and resources to focus on the “higher” academic pursuits of research and graduate training. This sharp bifurcation into separate junior and senior institutions—advocated by the University of Chicago’s William Rainey Harper, Stanford’s David Starr Jordan, and several other prominent university presidents at the time (Cohen et al., 2014)—never materialized on a large scale in the U.S., as the vast majority of colleges and universities that offer bachelor’s degrees have maintained their common model of four continuous undergraduate years.<sup>9</sup>

The resulting functional overlap between 2-year and 4-year colleges helped fuel debate over a second question: should 2-year colleges continue to prepare students for 4-year transfer through academic coursework, or should they differentiate themselves from 4-year institutions by focusing on terminal vocational training to prepare students for workforce entry? The academic transfer function remained the core mission of 2-year colleges from their inception through the mid-20th century, despite persistent efforts from the leadership of the American Association of Junior Colleges to carve out a clear niche for 2-year colleges by providing vocational training (Brint and Karabel, 1989; Cohen et al., 2014). A confluence of events in the 1960s and 1970s finally brought vocational education to the fore, including the federal Vocational Education Act of 1963, billions of dollars of subsequent vocational program funding championed by the Nixon administration, the early 1970s downturn in the wage premium to bachelor’s degrees, several reports from the influential Carnegie Commission on Higher Education advocating more vocational emphasis at 2-year colleges, and the shift in terminology from “junior” to “community” college, shedding the former connotation of subordination to 4-year institutions in favor of responsiveness to community needs, including occupational education suited to local industry demand (Freeman, 1976; Brint and Karabel, 1989; Cohen et al., 2014). These forces coincided with a rise in the share of 2-year college students pursuing vocational instead of academic programs, from less than a third in 1970 to more than half in 1977 (Blackstone, 1978), and settling at rough parity today (Cohen et al., 2014).

The rise of vocational education at 2-year colleges has only intensified debate over a final

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<sup>9</sup>William Rainey Harper did manage to separate the undergraduate experience at the nascent University of Chicago into a Junior College and a Senior College, and even pioneered the American associate’s degree as an award to students who completed the two-year Junior College curriculum (Brint and Karabel, 1989). But while separate 2-year colleges did emerge and grow dramatically over the 20th century, Harper’s own bifurcation of the University of Chicago never resulted in two standalone institutions—evoking grumbles from faculty members whom Harper had recruited to the new university with assurances that there would be no need to teach lower-division undergraduates (Boyer, 2015).



question, on which this paper focuses: do 2-year colleges boost the upward mobility of individuals who otherwise would not participate in higher education, or do they mainly divert college-bound students away from 4-year institutions, perhaps to their own detriment? The early champions of the community college movement focused almost exclusively on the “democratization” effect along the extensive margin, viewing 2-year college accessibility as a cornerstone in building a higher education system that offered equal opportunity to Americans from all backgrounds (Eells, 1931; Koos, 1944). In more recent decades, concerns over the diversion channel have grown more prominent in the academic literature, with Brint and Karabel (1989) arguing in an influential book that diversion is actually the dominant function of modern 2-year colleges, and others like Grubb (1989) and Dougherty (1994) noting that both of these margins are likely at play as simultaneous features of the “contradictory” community college.

With nearly 10 million community college students in the United States annually generating over 50 billion dollars in costs, over 70 percent of which are subsidized by local, state, and federal taxpayers (National Center for Education Statistics, 2015), building a clear understanding of democratization, diversion, and their impacts on student outcomes is vital in evaluating a wide range of higher education policies that influence student decisions on whether and where to enroll in college. The recent wave of policies promoting and subsidizing 2-year college enrollment, atop a century of controversy over the role of community colleges in American social mobility, motivates the empirical analysis of this paper.

### 3 Data and Descriptive Results

#### 3.1 Data Sources

My empirical analysis combines several restricted administrative datasets spanning the state of Texas. As the second largest U.S. state by population, land area, and GDP, Texas comprises 9 percent of the U.S. population and educates over 10 percent of U.S. public K-12 students. This large populace supports a comprehensive statewide system of higher education: roughly 75 public and private 4-year colleges and universities collectively enroll over 760,000 students, and roughly 57 2-year community college districts collectively enroll over 730,000 students (National Center for Education Statistics, 2015).

The analysis sample begins with student-level data from the Texas Education Agency (TEA) covering the population of Texas public high school students.<sup>10</sup> I link these students to administrative records from the Texas Higher Education Coordinating Board (THECB), capturing all

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<sup>10</sup>Private high school students, who are not observed in this data, account for less than 5 percent of all Texas high school graduates (National Center for Education Statistics, 2015). Nationally representative surveys show that private school students tend to come from more advantaged backgrounds: roughly 70% of them have parents with at least a bachelor’s degree, for example, compared to 40% of public school students (Wang et al., 2019). Augmenting my public sample with the 5% of Texas students who come from private high schools would therefore slightly increase the socioeconomic profile of the sample, and in turn likely lead to slightly larger estimates of the share of students on the diversion margin between 2-year and 4-year entry rather than the margin between 2-year and no college.

enrollments and degrees at all public and private Texas colleges and universities.<sup>11</sup> I further link these students to individual quarterly earnings records from the Texas Workforce Commission (TWC), measuring total earnings at each job each quarter for all Texas employees subject to the state unemployment insurance system.<sup>12</sup> I complement these administrative student-level records with several auxiliary school- and neighborhood-level data sources: high school characteristics from the National Center for Education Statistics (NCES) Common Core of Data, college characteristics from the Integrated Postsecondary Education Data System (IPEDS), and neighborhood characteristics from the 2000 Decennial Census measured at the tract level.<sup>13</sup>

One obvious limitation of any administrative data from a particular state is attrition due to outmigration. In my setting, college enrollments and earnings of Texas high school students who leave the state will not be observed. Fortunately, Texas has the lowest outmigration rate of any U.S. state, with 82 percent of all Texas-born individuals remaining in Texas as of 2012 (Aisch et al., 2014). On the college enrollment front, National Student Clearinghouse (NSC) records are available for a subset of my sample—students who graduate from high school in 2008 and 2009—allowing me to study college enrollment patterns inclusive of the small fraction of Texas high school students who do attend college out-of-state.<sup>14</sup> On the earnings front, missing earnings values could represent either nonemployment or outmigration; I show below that students with missing earnings in my analysis sample look nearly identical to those with non-missing earnings in terms of observable characteristics, suggesting that the scope for sample selection bias may be limited.<sup>15</sup>

### 3.2 Variable Definitions

*Cohorts.*—The main analysis sample consists of five cohorts of Texas public high school students enrolled in 10th grade between 1998 and 2002. I will hereafter refer to their projected high school graduation years of 2000 through 2004.<sup>16</sup> 2000 is the oldest cohort for whom private Texas college enrollments are observed,<sup>17</sup> and 2004 is the latest cohort for whom I observe earnings around age 30. I also make separate use of the 2008 and 2009 cohorts in the descriptive results, leveraging their National Student Clearinghouse coverage to show college enrollment patterns inclusive of students who attend out-of-state.

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<sup>11</sup>I do not observe for-profit college enrollments. In the fall of 2004, when the last of my main analysis cohorts begin to enter college, the for-profit share of enrollment at all degree-granting postsecondary institutions is only 5.1 percent (National Center for Education Statistics, 2015).

<sup>12</sup>Excluded from the state UI system are the self-employed, independent contractors, military personnel, some federal employees, and workers in the informal sector. Stevens (2007) estimates that roughly 90 percent of the civilian labor force is captured in state UI records.

<sup>13</sup>Census tracts delineate neighborhoods of roughly 1,200 to 8,000 people, averaging around 4,000.

<sup>14</sup>The NSC records cover 90 percent of nationwide college enrollment (Dynarski et al., 2013).

<sup>15</sup>Andrews et al. (2016) and Dobbie and Fryer (2020) arrive at similar conclusions using different extracts from the same Texas administrative data as this paper.

<sup>16</sup>Appendix Table A.1 shows that the 2-year and 4-year college proximity instruments have no detectable influence on the probability of graduating from high school.

<sup>17</sup>The private Texas college enrollment data begin in Fall 2002, so the 2002 high school graduates are officially the first with complete private college enrollment coverage. Persistence rates at private colleges are quite high, however, so catching the 2001 and 2000 cohorts in their second and third years, respectively, at private colleges allows me to significantly increase the sample size with little measurement error in treatments.

*Covariates.*—Student-level demographics are measured in the 10th grade TEA enrollment files and include categorical variables for gender, race/ethnicity,<sup>18</sup> and eligibility for free or reduced price lunch, a proxy for economic disadvantage. To obtain a single test score measure for each student, I combine raw 10th grade math and reading scores in a one-factor model separately by cohort, then normalize this factor to its within-cohort percentile.<sup>19</sup> High school-level controls are measured in the NCES Common Core of Data and include the share of students eligible for free/reduced price lunch, the NCES geographic locale code, which measures local urbanization in twelve detailed categories based on Census geospatial data,<sup>20</sup> and a county variable, which I group into the 62 Texas commuting zones using the year-2000 mapping provided by the U.S. Department of Agriculture’s Economic Research Service.<sup>21</sup> To control for any local influences of the oil and gas industry in Texas, I also measure the long-run share of oil and gas employment at the high school level using NAICS industry codes in the TWC workforce data. Finally, I construct an index of neighborhood quality by combining the tract-level Census measures of median household income and percent of households under the poverty line with the high school-level percent eligible for free/reduced price lunch into a one-factor model, then normalize this neighborhood factor to within-cohort percentiles.<sup>22</sup>

*Treatments.*—The three mutually exclusive and exhaustive treatments of interest are starting at a 2-year college, starting at a 4-year college, and not enrolling in any college. I define these by taking the first observed postsecondary enrollment, if any, starting the fall semester after projected high school graduation through the subsequent three academic years.<sup>23</sup>

*Instruments.*—I measure proximity (in miles) to the nearest 2-year and 4-year college campuses by computing ellipsoidal-earth surface distances between the coordinates of all Texas public high schools (from NCES CCD) and the coordinates of all Texas postsecondary institutions (from IPEDS), then taking minimum distances for each high school within the 2-year sector and 4-year sector separately.<sup>24</sup> For colleges with missing geospatial data in IPEDS, I manually collected their locations by first checking each college’s institutional profile for standalone branch campuses and location changes over my sample period, then converting those year-specific physical addresses to geocoordinates via Google Maps.

*Academic outcomes.*—I study the effects of 2-year college enrollment on two key academic

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<sup>18</sup>Due to small shares in some descriptive statistics, Native American students are pooled with Hispanic students.

<sup>19</sup>The factor model, estimated with Stata’s *factor* command, decomposes the test score measures  $X_m$ ,  $m \in \{1, 2\}$ , according to  $X_m = b_m F + e_m$ , where  $F$  is the common latent factor of interest,  $b_m$  is a loading coefficient, and  $e_m$  is homoskedastic measurement error uncorrelated with  $F$  and uncorrelated across measures.

<sup>20</sup>These 12 urbanization categories are large city, midsize city, small city, large suburb, midsize suburb, small suburb, fringe town, distant town, remote town, fringe rural, distant rural, and remote rural.

<sup>21</sup><https://www.ers.usda.gov/data-products/commuting-zones-and-labor-market-areas.aspx>.

<sup>22</sup>The estimation of the neighborhood factor model is similar to the test score model in footnote 19, with three neighborhood measures  $X_m$ ,  $m \in \{1, 2, 3\}$ , instead of two test scores.

<sup>23</sup>For the very small number of students who initially enroll in both sectors simultaneously, I assign them to the sector with greater credit hours. Following Andrews et al. (2014), I ignore summer terms when defining sector of enrollment.

<sup>24</sup>In determining minimum distances, I ignore small private college campuses as well as small community college extension centers that offer limited courses and student services.

outcomes: bachelor's degree completion and years of completed schooling. Bachelor's degree completion is an indicator for appearing in the THECB public or private 4-year degree completion files within ten years of projected high school graduation. To study time-to-degree, I also construct separate indicators for completing a BA by each integer year from 4 to 10. And to study the broad content of these bachelor's degrees, I decompose them into STEM vs. non-STEM majors. Years of completed schooling, as a more continuous measure of college completion, are calculated using the algorithm detailed in the footnote below.<sup>25</sup>

*Earnings.*—I measure real quarterly earnings by summing TWC earnings within each person-quarter, deflating by the quarterly U.S. consumer price index (base year 2010), winsorizing at the 99th percentile, and averaging the non-missing quarters within person over ages 28-30, which are the oldest common ages available across my analysis cohorts.<sup>26</sup> To study earnings dynamics, I also construct similar within-person averages over ages 22-24 and 25-27, as well as an annual panel of mean quarterly earnings at each observed age.

### 3.3 Sample Construction and Summary Statistics

To construct the main analysis sample of 2000-2004 cohorts and the NSC sample of 2008-2009 cohorts, I begin with the population of 10th grade students in each cohort with valid student identifiers, covariates, and high school locations. Table 1 presents summary statistics for these base samples. Column (1) shows that 3.7 percent of students in the 2008-2009 NSC cohorts attend college outside of Texas. To mitigate any bias from outmigration in the 2000-2004 main analysis cohorts for whom out-of-state enrollments are unobserved, column (3) drops the highest ability students with test scores above the 80th percentile. Appendix Figure A.1 shows that out-of-state enrollment in the 2008-2009 NSC cohorts is concentrated among students with test scores above this threshold, and that top-scoring students are also more likely to have missing earnings in the main 2000-2004 cohorts. Appendix Table A.1 shows that after dropping top-scoring students, the proximity instruments have no effect on the small remaining share of out-of-state enrollments in the 2008-2009 NSC cohorts.

To complete the main analysis sample, column (4) of Table 1 drops the remaining students with no observed quarterly earnings over ages 28-30. Comparing columns (3) and (4) shows that students with non-missing earnings look very similar to the full sample in terms of covariates, though those with non-missing earnings are a bit more likely to have (observed) college enrollments and degrees. In Appendix Figure A.2, I project earnings on all covariates and instruments within the earnings sample, predict earnings for those with missing earnings, and plot the two densities of predicted

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<sup>25</sup>Years of completed schooling range from 10 to 17. To complete 10: enroll in 11th grade. To complete 11: enroll in 12th grade. 12: complete high school. 13: enroll in college with 2nd year standing, or complete a certificate, or complete the academic core requirement at a community college. 14: enroll in college with 3rd year standing, or complete an associate's degree. 15: enroll in college with 4th year standing. 16: complete a bachelor's degree, or enter a postsecondary program with post-baccalaureate standing, or enroll in graduate school. 17: complete any graduate degree.

<sup>26</sup>These ages assume the student was 16 at the end of 10th grade, which is true for roughly 96 percent of students in the sample. Earnings for the 2004 cohort, the youngest in the sample, are only available over ages 28-29.

Table 1: Summary Statistics

	(1)	(2)	(3)	(4)
	NSC cohorts 2008-2009	Main cohorts 2000-2004	Main cohorts w/out top scoring quintile	Main cohorts w/out top scoring quintile or missing earnings
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
<i>Covariates</i>				
Female	.514	.513	.516	.517
White	.456	.529	.477	.464
Hispanic	.370	.319	.358	.369
Black	.142	.122	.141	.145
Asian	.032	.029	.024	.021
Free/reduced price lunch	.395	.311	.354	.359
Test score percentile	50.6	50.7	40.5	40.4
Neighborhood quality pctile	50.6	50.6	48.7	48.3
Oil/gas employment share	.017	.018	.018	.018
City	.364	.377	.389	.386
Suburb	.276	.256	.243	.242
Town	.119	.134	.134	.136
Rural	.242	.233	.234	.235
<i>Treatments</i>				
No college	.318	.388	.433	.391
Start at 2-year college	.371	.339	.366	.394
Start at 4-year college	.274	.273	.201	.215
Start at 4-year (out of state)	.037	-	-	-
<i>Instruments</i>				
Miles to 2-year college	8.5 (10.1)	9.7 (11.4)	9.7 (11.5)	9.7 (11.5)
Miles to 4-year college	19.5 (18.7)	20.5 (19.7)	20.5 (19.9)	20.4 (19.8)
<i>Academic Outcomes</i>				
Bachelor's degree	-	.255	.187	.207
Years of schooling	-	13.1 (2.1)	12.8 (2.0)	13.0 (2.0)
<i>Earnings Outcomes</i>				
Mean quarterly earnings	-	8,826 (5,841)	8,168 (5,413)	8,168 (5,413)
Has quarterly earnings	-	.764	.773	1.000
Observations	454,076	957,739	763,835	590,392

Notes: NSC cohorts are those with National Student Clearinghouse college enrollment data. The twelve NCES geographic locale categories are grouped into four values (city, suburb, town, rural) to save space. Academic outcomes are measured at age 28. Earnings outcomes are measured over ages 28-30.

earnings for comparison. The distributions are nearly identical, with a mean difference of just 58 dollars. These results cannot rule out differential attrition based on unobservables, but they offer some assurance that the scope for sample selection bias may be limited.

### 3.4 Sorting into Initial College Enrollments

Figure 1 describes how initial college enrollment choices vary across observable student characteristics in the 2008-2009 NSC cohorts.<sup>27</sup> Across demographic groups and neighborhood quality deciles, the 2-year college enrollment share is remarkably constant around the grand mean of 37 percent; what differ are the outside option shares of 4-year enrollment and no college, with men, disadvantaged students, underrepresented minorities, and students from poor neighborhoods more likely to forego college altogether than enroll in a 4-year institution. The bottom panel of Figure 1 shows that the 2-year enrollment share is hump-shaped across 10th grade test scores with a peak at the 40th percentile, though 2-year enrollment is still quite broadly distributed. 4-year college enrollment and no college enrollment, meanwhile, are strongly monotonic in test scores in opposing directions.

### 3.5 Enrollment and Earnings Dynamics

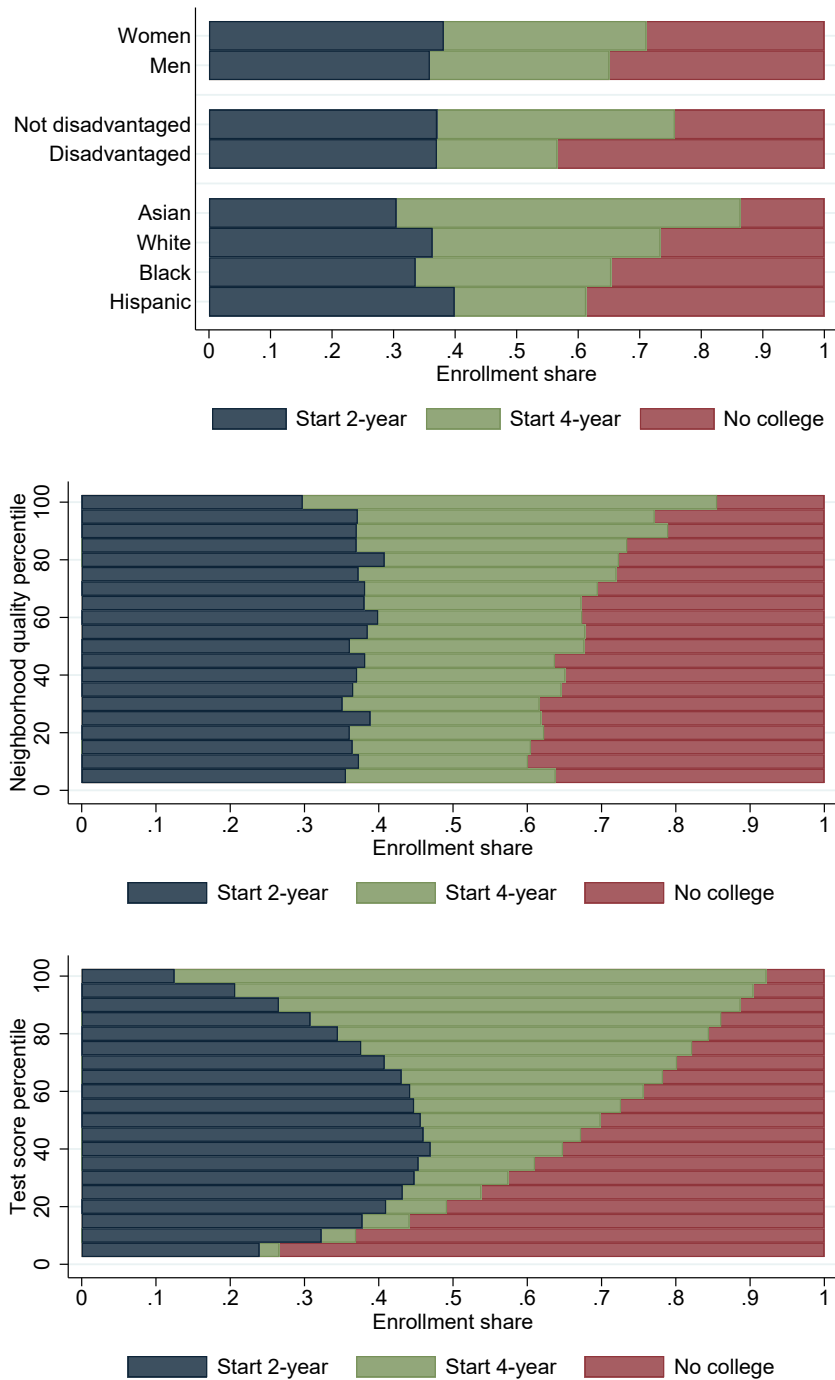
Figure 2 describes how the initial sector of enrollment relates to enrollment in subsequent years. The left panel conditions on initial 2-year entrants and shows that the vast majority of them stay in the 2-year sector, if any, for the first few years after entry. Enrollment in 4-year colleges among these 2-year entrants then rises and peaks around 20 percent at ages 22-23, with both 2-year and 4-year enrollment slowly trailing off thereafter. The right panel, conditioning on 4-year entrants, tells a similar story of “sticky treatment” in that the vast majority of 4-year entrants stay in the 4-year sector. Roughly 20 percent of initial 4-year entrants enroll in a 2-year college in their early 20s, either as a transfer or dual enrollment.

Figure 3 plots the earnings profiles associated with each initial enrollment choice, controlling solely for cohort fixed effects. As expected, 4-year entrants overtake 2-year entrants, and 2-year entrants overtake those who do not enroll in any college, but differences by gender emerge: women experience this overtaking a full two years prior to men, and the raw college premiums for women are larger. These gender differentials persist into the causal results, as shown in Section 6.

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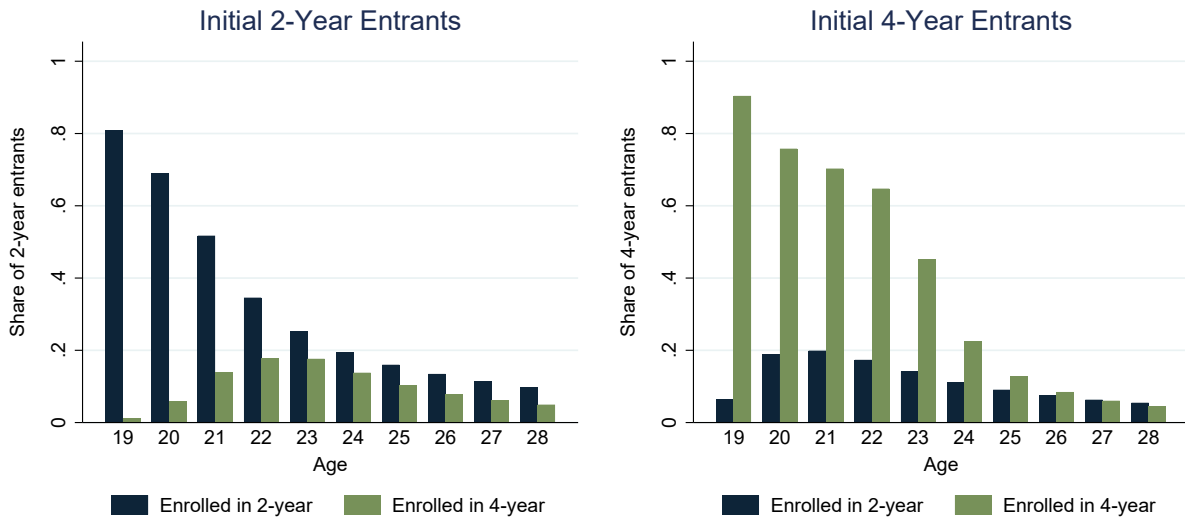
<sup>27</sup>Appendix Figure A.3 reproduces these results for the 2000-2004 main analysis cohorts. The plots are very similar up through the 80th percentile test score sample cutoff, beyond which the share of students in the 2000-2004 main analysis cohorts starting 4-year is somewhat understated, and no college overstated, due to unobserved out-of-state enrollments.

Figure 1: Sorting into College Enrollment Choices by Observable Characteristics



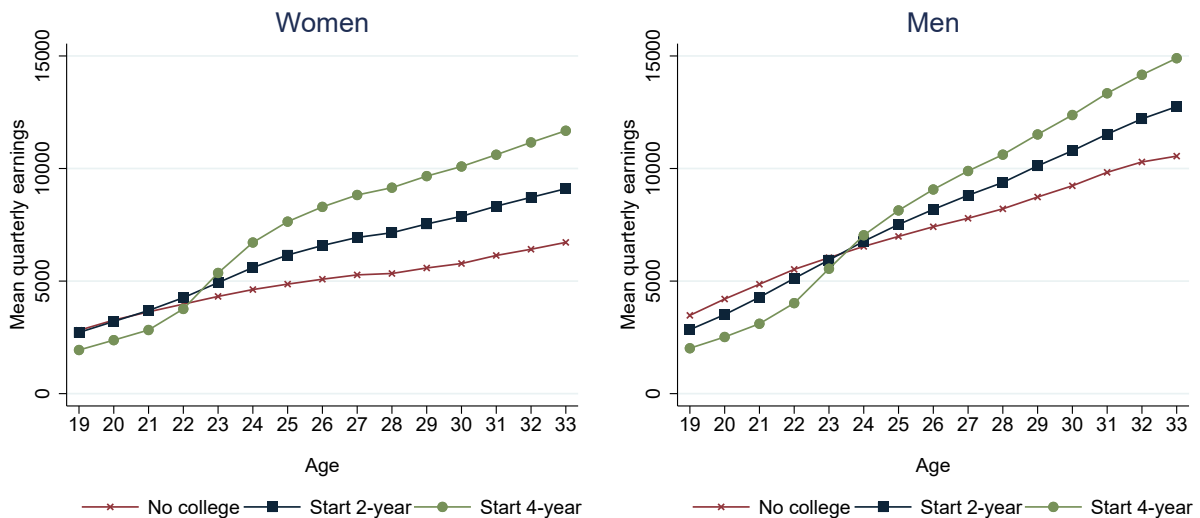
Notes: 2008-2009 cohorts with National Student Clearinghouse college enrollment coverage; see Appendix Figure A.3 for comparison to the main analysis cohorts for whom out-of-state enrollments are not observed. Disadvantaged is an indicator for free or reduced price lunch eligibility in 10th grade. Neighborhood quality and test score percentiles, defined in Section 3.2, are grouped into 5-unit bins.

Figure 2: Enrollment Dynamics by Sector of Initial Enrollment



Notes: Enrollment shares at age 19 are not equal to 1 due to the 3-year window in defining the sector of initial enrollment. Subsequent enrollments are not mutually exclusive at a given age; a small fraction of students enroll in both sectors simultaneously.

Figure 3: Earnings Profiles by Sector of Initial Enrollment



Notes: Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over each age. Each point is the coefficient on the corresponding age dummy in a regression of earnings on age indicators and cohort indicators. Earnings after age 29 are only available for progressively older cohorts in the analysis sample, as the earnings data end in 2015.



Table 2: Raw and Controlled OLS Regressions

	Years of schooling		Bachelor's degree		Quarterly earnings	
	Raw	Controlled	Raw	Controlled	Raw	Controlled
Start 2-year vs. no college	1.75 (.01)	1.48 (.01)	.189 (.002)	.149 (.001)	1,418 (20)	1,089 (17)
Start 2-year vs. start 4-year	-1.58 (.01)	-1.33 (.01)	-.392 (.002)	-.355 (.002)	-1,660 (30)	-1,402 (23)
$R^2$	.407	.457	.286	.323	.046	.169
$N$	590,392	590,392	590,392	590,392	590,392	590,392

Notes: Standard errors in parentheses are clustered at the high school campus by cohort level. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30. Controlled specification includes dummies for each categorical covariate and cubic polynomials in each continuous covariate listed in Table 1, plus cohort fixed effects and commuting zone fixed effects.

### 3.6 Regression Results

Turning to regression specifications that quantify outcome differences across initial enrollment choices, Table 2 presents coefficients from OLS regressions of the following form:

$$\text{Outcome} = \alpha - \beta_{2\leftarrow 0}\mathbb{1}\{\text{No college}\} - \beta_{2\leftarrow 4}\mathbb{1}\{\text{Start 4-year}\} + \text{Controls} + \epsilon \quad (1)$$

Writing the specification in this form, with 2-year entry as the excluded category, immediately delivers a comparison between 2-year entry vs. no college in  $\beta_{2\leftarrow 0}$ , and a comparison between 2-year entry vs. 4-year entry in  $\beta_{2\leftarrow 4}$ . The control set includes dummies for each categorical covariate and cubic polynomials in each continuous covariate listed in Table 1, plus cohort fixed effects and commuting zone fixed effects.

Taken at face value, the OLS results in Table 2 suggest democratizing students from no college into 2-year entry yields significant gains in educational achievement and earnings, while at the same time diverting students from 4-year to 2-year entry has large negative consequences. Compared to observably similar 4-year entrants, 2-year entrants complete 1.3 fewer years of schooling, are 36 percentage points less likely to complete a bachelor's degree, and earn 1,400 dollars less per quarter around age 30. But how much do these outcome disparities reflect causal consequences of different enrollment choices, versus selection bias from systematically different students making systematically different choices? And what share of students are actually democratized versus diverted when 2-year college access expands? These questions motivate the instrumental variables method developed in the next section.

## 4 Identification

### 4.1 The Methodological Challenge

Instrumental variables (IV) offer a potential solution to the problem of selection bias in college enrollment choices, since valid instrumental variation can induce otherwise similar students into different choices and thus enable causal comparisons of their subsequent outcomes. For the well-known case of binary treatment, Imbens and Angrist (1994) demonstrate that such comparisons identify a local average treatment effect (LATE) among compliers—individuals whose choices respond to instrumental variation—under the standard IV assumptions of independence, exclusion, and monotonicity.

Multiple margins of treatment present a challenge within this paradigm. When instruments shift individuals among more than two treatment states, the relevant counterfactual states for compliers induced into a specific treatment may be both multiple and unobserved, which hampers causal comparisons of the consequences of one treatment versus another.<sup>28</sup> To see this in the setting of 2-year community college enrollment, suppose a valid instrument  $Z_2$  induces students into 2-year college entry. The multiple margins of treatment in this case are the “democratization” margin and the “diversion” margin: some  $Z_2$  compliers are “democratized” into higher education from the counterfactual of not attending any college ( $2\leftarrow 0$ , “two from zero”), while other  $Z_2$  compliers are diverted from the counterfactual of starting directly at a 4-year institution ( $2\leftarrow 4$ , “two from four”). Abstracting from covariates, the standard two-stage least squares (2SLS) approach to IV would specify the following outcome and first stage equations:

$$\begin{aligned} Y &= \beta_0 + \beta_2 D_2 + \epsilon \\ D_2 &= \alpha_0 + \alpha_2 Z_2 + \eta, \end{aligned}$$

where  $Y$  is a student outcome (e.g. bachelor’s degree attainment or earnings),  $D_2$  is a binary indicator for starting college at a 2-year institution, and  $\beta_2$  is the coefficient of interest. Appendix A shows that the 2SLS estimand  $\beta_2$  represents a pooled local average treatment effect (LATE) of 2-year entry on student outcomes that combines the two distinct complier margins into a single weighted average:<sup>29</sup>

$$\beta_2 = \underbrace{LATE_2}_{\text{Net effect of 2-year entry}} = \omega \underbrace{LATE_{2\leftarrow 0}}_{\text{Democratization effect}} + (1 - \omega) \underbrace{LATE_{2\leftarrow 4}}_{\text{Diversion effect}} \quad (2)$$

The weight  $\omega$  captures the share of  $Z_2$  compliers who are on the  $2\leftarrow 0$  democratization margin,

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<sup>28</sup>See Kirkeboen et al. (2016) for a higher education setting with observable measures of these relevant counterfactuals, thanks to a centralized admissions system that requires applicants to submit rank-ordered preference lists over programs. The college application and enrollment process is far more decentralized in the United States, usually prohibiting identification of a given student’s next-preferred alternative to a given program.

<sup>29</sup>Heckman and Urzua (2010), Hull (2018), and Kline and Walters (2016) provide related derivations, as do Angrist and Imbens (1995) for the case of ordered multivalued treatments.

and this share is identified by the reduction in  $Pr(\text{no college})$  induced by  $Z_2$  as a fraction of the increase in  $Pr(D_2)$ . The distinct  $2\leftarrow 0$  democratization and  $2\leftarrow 4$  diversion treatment effects are not separately identified, however, leaving these likely opposing impacts of 2-year enrollment shrouded behind the identified net effect that pools them together.

In many settings, the pooled net effect is a parameter of interest in its own right; here,  $LATE_2$  captures the aggregate impact of 2-year entry on all students induced by the instrument, which may correspond to policy-relevant variation like closer access to a 2-year college campus, subsidized 2-year tuition, etc. Decomposing the net effect into its potentially opposing impacts on students from each margin, however, allows for a more comprehensive assessment of the impacts and potential unintended consequences of such policies. Equation (2) reveals that diverse combinations of democratization and diversion effects could all yield the same net effect, with very different policy implications. To take two illustrative cases, consider that the same positive  $LATE_2$  value could be generated from a moderately positive  $LATE_{2\leftarrow 0}$  plus a zero  $LATE_{2\leftarrow 4}$ , or alternatively a large positive  $LATE_{2\leftarrow 0}$  plus a large negative  $LATE_{2\leftarrow 4}$ . The first case features modest average gains for democratized students and zero average impact on diverted students; in light of lower costs at 2-year colleges relative to their 4-year counterparts, this case could potentially justify broad investment in 2-year college access as a cost-effective engine of upward mobility. The second case features large average gains for democratized students but large average losses for diverted students. This case would demand caution in broadly expanding 2-year access, perhaps in favor of targeted policies towards the types of students more likely to be on the democratization margin, minimizing the mass of compliers diverted from direct 4-year entry.

With two treatment margins of interest and only one instrument, the preceding 2SLS framework is fundamentally underidentified. A natural next step would be to consider multivariate 2SLS with two endogenous treatments when a second instrument is available, e.g. an exogenous  $Z_4$  that makes starting at a 4-year college more attractive. Writing the second stage equation in the same form as the OLS specification in (1), with the no-college treatment  $D_0$  and the 4-year entry treatment  $D_4$  separately measured relative to 2-year entry as the excluded category, would seem to deliver a  $2\leftarrow 0$  democratization effect via  $-\beta_0$  and a  $2\leftarrow 4$  diversion effect via  $-\beta_4$ :

$$\begin{aligned} Y &= \kappa + \beta_0 D_0 + \beta_4 D_4 + \epsilon \\ D_0 &= \alpha_0 + \alpha_2 Z_2 + \alpha_4 Z_4 + \eta_0 \\ D_4 &= \gamma_0 + \gamma_2 Z_2 + \gamma_4 Z_4 + \eta_4 \end{aligned} \tag{3}$$

In fact, Kirkeboen et al. (2016) show that the multivariate 2SLS framework in (3) does not generally identify well-defined causal parameters, even with one instrument per endogenous treatment, except in special cases like homogeneous treatment effects across all individuals. Instead, each of the 2SLS estimands  $\beta_0$  and  $\beta_4$  is a linear combination of multiple potential outcome comparisons mixed across distinct treatment margins and distinct complier subpopulations, as I derive explicitly in Appendix

B.<sup>30</sup> In a world of treatment effect heterogeneity, these linear combinations do not generally identify an average impact of one choice versus another among that treatment margin’s compliers, or even economically interpretable net effects as in the single treatment model of Equation (2).

Empirically, several pieces of evidence point to systematic heterogeneity in treatment effects across students on the margin of 2-year college enrollment, hampering the ability of a traditional multivariate 2SLS approach like (3) to recover interpretable parameters and motivating the development of a new approach that accommodates such heterogeneity. First, Table 3 presents results from overidentification tests that reject constant treatment effects across individuals. Column (1) shows estimates of the  $-\beta_0$  democratization effect and  $-\beta_4$  diversion effect from the baseline 2SLS model in (3), which is just-identified under constant effects using the two instruments of a student’s distance to the nearest 2-year campus ( $Z_2$ ) and 4-year campus ( $Z_4$ ), controlling for the covariates detailed in Section 5.2. Generating additional “instruments” by squaring and interacting  $Z_2$  and  $Z_4$  in column (2) of Table 3, and interacting  $Z_2$  and  $Z_4$  with covariates in column (3), yields overidentification test results that consistently reject the baseline model, suggesting that  $\beta_0$  and  $\beta_4$  are not constant parameters and instead vary systematically across students.<sup>31</sup> Second, the alternative identification approach developed in the remainder of this section can identify differences in observable characteristics across the compliers along different treatment margins. The implementation of this exercise in Table 6 shows that students democratized into college along the  $2 \leftarrow 0$  treatment margin are a markedly different subpopulation compared to diverted students along the  $2 \leftarrow 4$  margin, making it more difficult to assume these two distinct subpopulations would have identical, and thus interchangeable, treatment effects along a given margin, as the traditional 2SLS approach implicitly does. Finally, and most directly, the main results in Sections 6.3 and 6.4 indicate substantial heterogeneity in both democratization and diversion effects across observable student dimensions like gender and family income, making it difficult to rule out effect heterogeneity across unobserved dimensions as well.

## 4.2 Setting up the Separate Identification Approach: Notation and Instruments

To overcome the limitations of traditional multivariate 2SLS in the presence of effect heterogeneity, I now develop an alternative IV approach to separately identifying causal effects along multiple treatment margins that is robust to such heterogeneity. Let us first collect and augment the notation used throughout this section. I suppress the individual index  $i$  and implicitly condition on the control set  $X$ , detailed in Section 5. The three mutually exclusive and exhaustive treatments are  $D = 2$  (start college at a 2-year institution),  $D = 4$  (start college directly at a 4-year institution), and  $D = 0$  (no college). Define  $D_2, D_4, D_0$  as the binary indicators corresponding to each treatment,

<sup>30</sup>A similar result applies when interacting a single instrument with covariates in the attempt to generate additional sources of instrumental variation (Kline and Walters, 2016; Hull, 2018). See Pinto (2016) for a related discussion in the context of the multiple treatment arms of the Moving to Opportunity experiment.

<sup>31</sup>Of course, an alternative interpretation of the overidentification test is an assessment of instrument validity under a maintained assumption of constant treatment effects. The other pieces of evidence of heterogeneity discussed in this paragraph make such a premise difficult to maintain. Section 5.2 conducts instrument diagnostics that do not require first assuming constant treatment effects.

Table 3: Overidentification Tests of Treatment Effect Heterogeneity

	(1) Multivariate 2SLS Just-identified	(2) Multivariate 2SLS Overidentified	(3) Multivariate 2SLS Overidentified
First stage instruments	$Z_2, Z_4$	$Z_2, Z_4, Z_2^2, Z_4^2, Z_2 \times Z_4$	$Z_2, Z_4, Z_2 \times X, Z_4 \times X$
Years of schooling			
2←0 Democratization effect	1.74 (.28)	2.46 (.21)	1.85 (.15)
2←4 Diversion effect	-.90 (.21)	-1.54 (.15)	-.91 (.17)
Overidentification test $p$ -value		< .001	< .001
Bachelor's degree			
2←0 Democratization effect	.237 (.056)	.380 (.044)	.203 (.030)
2←4 Diversion effect	-.237 (.042)	-.397 (.032)	-.233 (.037)
Overidentification test $p$ -value		< .001	< .001
Quarterly earnings			
2←0 Democratization effect	905 (815)	1,870 (639)	2,108 (470)
2←4 Diversion effect	-1,651 (600)	-1,791 (467)	-4,251 (547)
Overidentification test $p$ -value		.063	< .001
Observations	590,392	590,392	590,392

Notes: The just-identified multivariate 2SLS estimates in column (1) come from a two stage least squares regression of each outcome on indicators for no college and 4-year entry, yielding democratization and diversion parameters relative to the omitted 2-year treatment, using 2-year distance ( $Z_2$ ) and 4-year distance ( $Z_4$ ) as instruments. The overidentified multivariate 2SLS estimates in column (2) come from the same specification as (1), but with three additional instruments: 2-year distance squared, 4-year distance squared, and 2-year distance times 4-year distance. The estimates in column (3) come from the same specification as (1), but with four additional instruments: 2-year distance interacted with gender and disadvantaged status (FRPL), and 4-year distance interacted with gender and disadvantaged status. All specifications include the baseline control set described in Section 5.2. Standard errors in parentheses, and  $p$ -values from Hansen's  $J$ -statistic overidentification test, are clustered at the high school campus by cohort level. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30.

noting that  $D_2 + D_4 + D_0 = 1$  for a given individual. Two continuous instruments influence treatment choices:  $Z_2$  (distance to the nearest 2-year college) and  $Z_4$  (distance to the nearest 4-year college). Denote potential treatment choice as  $D(z_2, z_4) \in \{0, 2, 4\}$ , i.e. the enrollment choice a student would make if exogenously assigned to instrument values  $(Z_2, Z_4) = (z_2, z_4)$ . Define the binary indicators  $D_0(z_2, z_4)$ ,  $D_2(z_2, z_4)$ ,  $D_4(z_2, z_4)$  analogously. The potential outcomes associated with these treatments are  $Y_0, Y_2, Y_4$ , i.e. the outcome a student would reap if exogenously assigned to treatment  $D = d \in \{0, 2, 4\}$ . We observe the realized outcome  $Y = Y_0D_0 + Y_2D_2 + Y_4D_4$ . The potential outcome contrasts  $Y_2 - Y_0$  (democratization effect) and  $Y_2 - Y_4$  (diversion effect) are our treatment-margin-specific causal effects of interest.

Throughout this section, I maintain the assumption of valid instrumental variation, i.e. the instruments are as good as randomly assigned and only affect outcomes through choices:

**Assumption IE (Independence and Exclusion):**  $(Z_2, Z_4) \perp (Y_0, Y_2, Y_4, \{D(z_2, z_4)\}_{\forall(z_2, z_4)})$ .

Relative to its standard invocation in the case of a binary instrument and binary treatment, Assumption IE simply expands the instrumental variation to two continuous dimensions  $(Z_2, Z_4)$  and expands the treatment options from two to three ( $D \in \{0, 2, 4\}$ ). Section 5 probes this assumption empirically.

### 4.3 Visualizing the Separate Identification Approach

In short, instead of attempting to use these instruments to recover multiple causal differences in one outcome equation like (3), with the undesirable consequence of mixing comparisons across distinct treatment margins and complier groups, the proposed approach first isolates the mean potential outcomes of each distinct complier group along each treatment margin of interest. Then, with these separately identified components in hand, appropriately differencing them delivers well-defined causal effects for compliers along each margin.

Section 4.4 derives these identification arguments in a general framework of potential choices and potential outcomes. To build intuition, however, first consider a more structured discrete choice index model that helps visualize the mechanics of the approach.<sup>32</sup> In this more structured model, individuals have latent indirect utilities for each mutually exclusive and exhaustive treatment option,

$$\begin{aligned} I_0 &= 0 \\ I_2 &= U_2 - \mu_2(Z_2) \\ I_4 &= U_4 - \mu_4(Z_4), \end{aligned}$$

where the utility of no college is normalized to zero.  $U_2$  is an individual's gross utility from 2-year entry (relative to no college), representing unobserved individual preference heterogeneity from the

<sup>32</sup>Appendix D shows that this index model satisfies the framework in Section 4.4 as a special case.

econometrician’s perspective.  $\mu_2(Z_2)$  is the cost of 2-year entry, shifted around by the continuous 2-year instrument  $Z_2$ , such that  $U_2 - \mu_2(Z_2)$  is the net utility of starting at a 2-year college. Likewise,  $U_4$  is unobserved preference heterogeneity for 4-year entry, weighed against its cost  $\mu_4(Z_4)$ , such that  $U_4 - \mu_4(Z_4)$  is the net utility of starting college in the 4-year sector.<sup>33</sup>  $\mu_2(\cdot)$  and  $\mu_4(\cdot)$  are strictly increasing, differentiable, and homogeneous across individuals.  $(U_2, U_4)$  vary continuously with full support across  $\mathbb{R}^2$ , but with otherwise unrestricted functional form. Each individual chooses the alternative with the highest indirect utility, implying the treatment choice equations

$$\begin{aligned} D_0(z_2, z_4) &= \mathbb{1}[I_0 > I_2, I_0 > I_4] = \mathbb{1}[U_2 < \mu_2(z_2), U_4 < \mu_4(z_4)] \\ D_2(z_2, z_4) &= \mathbb{1}[I_2 > I_0, I_2 > I_4] = \mathbb{1}[U_2 > \mu_2(z_2), U_4 - U_2 < \mu_4(z_4) - \mu_2(z_2)] \\ D_4(z_2, z_4) &= \mathbb{1}[I_4 > I_0, I_4 > I_2] = \mathbb{1}[U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4) - \mu_2(z_2)]. \end{aligned} \quad (4)$$

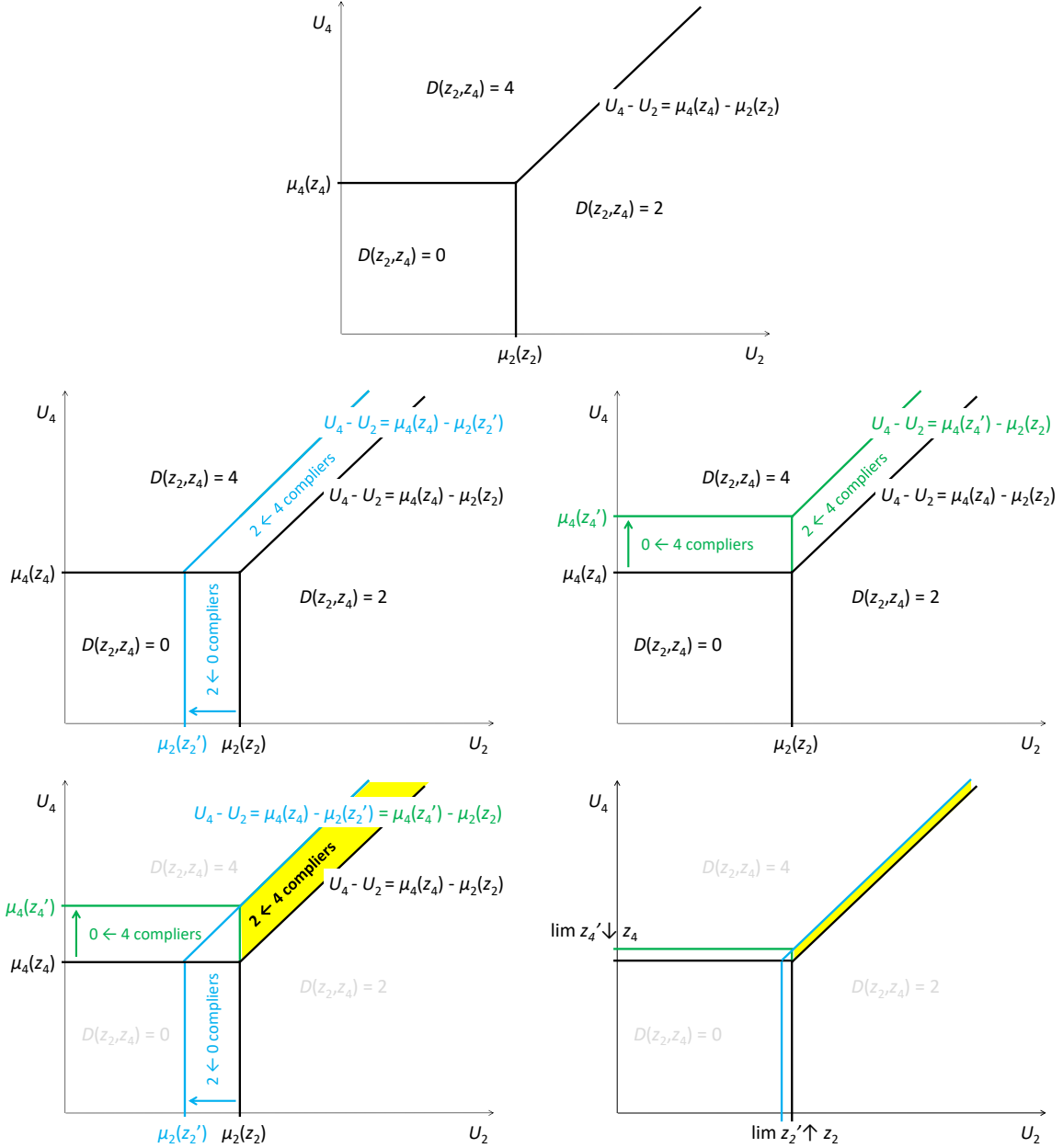
Figure 4 illustrates the usefulness of this structured choice model in visualizing the mechanics of the separate identification approach. First, the top panel of Figure 4 shows how the treatment choice equations partition the two-dimensional space of unobserved preference heterogeneity  $(U_2, U_4)$  for a given value of the instruments  $(z_2, z_4)$ . Individuals who choose  $D = 0$  (no college) have low preference values for both 2-year and 4-year enrollment relative to their costs, while those who choose  $D = 2$  (2-year entry) or  $D = 4$  (4-year entry) have relatively higher values of the corresponding  $U_j$ .

Next, the middle left panel of Figure 4 visualizes how a shift in the 2-year instrument, i.e. a reduction in the cost of 2-year entry, shifts the treatment partition to generate compliers along both the 2 $\leftarrow$ 0 democratization margin and the 2 $\leftarrow$ 4 diversion margin. A decrease in  $Z_2$  to  $z'_2 < z_2$ , while holding  $Z_4$  fixed at  $z_4$ , lowers the cost of 2-year enrollment to  $\mu_2(z'_2) < \mu_2(z_2)$ . This shifts the treatment partition to the left and expands the size of the  $D = 2$  region monotonically, as no individuals find 2-year entry *less* attractive as its cost decreases. This expansion of 2-year enrollment comes at the expense of both no college and direct 4-year entry, thus inducing democratized 2 $\leftarrow$ 0 compliers as well as diverted 2 $\leftarrow$ 4 compliers in the two regions swept over by the instrument-induced shift in the partition.

Recalling Equation (2), this single instrument shift is insufficient to disentangle the mean democratization effect on the outcomes of the 2 $\leftarrow$ 0 compliers from the mean diversion effect on the outcomes of the 2 $\leftarrow$ 4 compliers. The shift in  $Z_2$  does separately identify two key ingredients of these margin-specific treatment effects, however. First, the mean potential outcome of 2 $\leftarrow$ 0 compliers in their no-college counterfactual ( $Y_0$ ) is revealed by compositional changes in the outcomes

<sup>33</sup>In principle, one could allow  $\mu_2(\cdot)$  to also depend on  $Z_4$ , and  $\mu_4(\cdot)$  to also depend on  $Z_2$ . In that case, instead of working with shifts in each instrument directly to identify complier potential outcomes, as this section does, the index functions  $\mu_2(Z_2, Z_4)$  and  $\mu_4(Z_2, Z_4)$  would need to be nonparametrically identified in a first step, then manipulated to induce complier flows from conditional variation in the value of each index function while holding the other fixed (e.g. Lee and Salanié, 2018). My approach in Section 4.4 bypasses this demanding first step by deriving conditions on complier behavior that allow a set of easily-implemented local two stage least squares (2SLS) regressions with modified outcome variables to recover all of the ingredients necessary for identifying margin-specific treatment effects. The index model in (4) is sufficient, but not necessary, for these conditions on complier behavior to hold, as shown in Appendices D and E, respectively.

Figure 4: Visualizing the Separate Identification Approach



Notes: This figure visualizes the mechanics of the separate identification approach using a structured discrete choice model. The top panel shows how the treatment choice equations, given a particular pair of instrument values, partition the two-dimensional space of unobserved preference heterogeneity. The middle left panel illustrates a shift in  $Z_2$  inducing  $2 \leftarrow 0$  and  $2 \leftarrow 4$  compliers, and the middle right panel illustrates a shift in  $Z_4$  inducing  $0 \leftarrow 4$  and  $2 \leftarrow 4$  compliers. The bottom left panel overlays these two shifts to illustrate their overlapping compliers along the  $2 \leftarrow 4$  diversion margin, and the bottom right panel visualizes the convergence of this overlap as the discrete instrument shifts converge to marginal shifts.



of the  $D = 0$  treatment group. To see this, note that as the treatment partition sweeps to the left in the middle left panel of Figure 4, any change in the composition of the  $D = 0$  group is entirely driven by  $2 \leftarrow 0$  compliers leaving this group. Since  $Y_0$  is the observed outcome for individuals with  $D = 0$ , the observed change in the mean outcome  $Y$  within the  $D = 0$  treatment group is directly informative about the potential outcomes  $Y_0$  that democratized compliers would have realized, on average, had they stayed in their no-college counterfactual. Second, by analogous logic, notice that any change in the composition of the  $D = 4$  treatment group in the middle left panel of Figure 4 is entirely driven by diverted  $2 \leftarrow 4$  compliers leaving this group. The observed change in the mean outcome  $Y$  within the  $D = 4$  treatment group is then directly informative about the potential outcomes  $Y_4$  that diverted  $2 \leftarrow 4$  compliers would have realized, on average, had they stayed in their 4-year entry counterfactual.

Of course, knowing the mean  $Y_0$  for  $2 \leftarrow 0$  compliers and the mean  $Y_4$  for  $2 \leftarrow 4$  compliers is not sufficient for identifying democratization and diversion treatment effects. We also need the mean  $Y_2$  for each of these distinct complier groups. The middle left panel of Figure 4 shows why these are not separately identified by the shift in  $Z_2$ . Unlike the compositional changes in the  $D = 0$  and  $D = 4$  treatment groups, which were each driven by only one complier type, the compositional change in the  $D = 2$  group is driven by both complier types entering this treatment group simultaneously. With only one observable quantity—the  $Z_2$ -induced change in the mean outcome  $Y$  within the  $D = 2$  treatment group—we cannot separately identify the two unknowns that contribute to it: the mean  $Y_2$  of  $2 \leftarrow 0$  compliers vs. the mean  $Y_2$  of  $2 \leftarrow 4$  compliers.

The key to disentangling these two quantities is the 4-year instrument,  $Z_4$ , and its overlapping compliers along the  $2 \leftarrow 4$  diversion margin. The middle right panel of Figure 4 starts from the same baseline instrument values  $(z_2, z_4)$  as the  $Z_2$  shift, and thus the same initial treatment partition, but visualizes a shift in  $Z_4$  to  $z'_4 > z_4$  while holding  $Z_2$  fixed at  $z_2$ . This increases the cost of 4-year entry to  $\mu_4(z'_4) > \mu_4(z_4)$ , which shifts the partition upward and makes 4-year entry less attractive relative to its two alternatives of no college and 2-year entry. Crucially, unlike the shift in  $Z_2$ , the  $Z_4$ -induced change in the composition of the  $D = 2$  treatment group is driven solely by  $2 \leftarrow 4$  compliers entering this group. The observed change in the mean outcome  $Y$  within the  $D = 2$  treatment group induced by  $Z_4$  thus isolates the mean  $Y_2$  potential outcome of these  $2 \leftarrow 4$  compliers alone.

The bottom panels of Figure 4 put these pieces together to complete the visual argument. By overlaying the partial shift in  $Z_2$  and the partial shift in  $Z_4$ , both starting from the same baseline point  $(z_2, z_4)$ , the bottom left panel shows that these two instrument shifts generate overlapping  $2 \leftarrow 4$  compliers (shaded) near the margin of indifference between 2-year and 4-year entry, visualized in this structured choice model as the diagonal line defined by  $U_4 - U_2 = \mu_4(z_4) - \mu_2(z_2)$ . The bottom right panel shows that the shaded complier overlap of these two instrument shifts along the 2-4 indifference margin becomes identical in the limit as discrete shifts converge to marginal shifts, highlighting the usefulness of continuous instruments.<sup>34</sup> Hence, we can use the marginal  $Z_4$  shift

<sup>34</sup>With two discrete instruments, there would be no guarantee that the  $2 \leftarrow 4$  diversion compliers with respect to  $Z_2$

to separately identify the mean  $Y_2$  among marginal  $2\leftarrow 4$  compliers, which in turn can be used to back out what the mean  $Y_2$  among marginal  $2\leftarrow 0$  compliers must be to satisfy the weighted average identified by the marginal  $Z_2$  shift. Finally, with these four mean potential outcomes all separately identified, we can difference them to form the two margin-specific treatment effects of interest: the average  $Y_2 - Y_0$  democratization effect among  $2\leftarrow 0$  compliers, and the average  $Y_2 - Y_4$  diversion effect among  $2\leftarrow 4$  compliers.

While this structured discrete choice model helps build visual intuition for the identification procedure, it is more structure than necessary for disentangling margin-specific treatment effects with instrumental variables. The next subsection therefore presents the separate identification approach in a more general framework, with two objectives in mind: to clarify the particular assumptions about complier behavior that deliver point identification of margin-specific treatment effects in this setting, and to highlight the method’s straightforward implementation as a set of local 2SLS regressions with modified outcome variables.

## 4.4 Main Identification Results

To develop the separate identification approach in a more general framework, remove the imposition of the index model in (4), leaving the potential treatment function  $D(z_2, z_4)$  (and its binary variants  $D_0$ ,  $D_2$ , and  $D_4$ ) unstructured. Identifying margin-specific treatment effects will require two key restrictions on complier behavior for which the index model was sufficient but not necessary.

### 4.4.1 Unordered Partial Monotonicity

The first of these restrictions is a generalization of instrument monotonicity to multiple instruments and multiple treatments:

**Assumption UPM (Unordered Partial Monotonicity):**

For all  $z_2, z'_2, z_4$  with  $z'_2 < z_2$  and holding  $z_4$  fixed:

$$D_2(z'_2, z_4) \geq D_2(z_2, z_4), D_0(z'_2, z_4) \leq D_0(z_2, z_4), \text{ and } D_4(z'_2, z_4) \leq D_4(z_2, z_4)$$

for all individuals, with each inequality holding strictly for at least some individuals.

For all  $z_4, z'_4, z_2$  with  $z'_4 < z_4$  and holding  $z_2$  fixed:

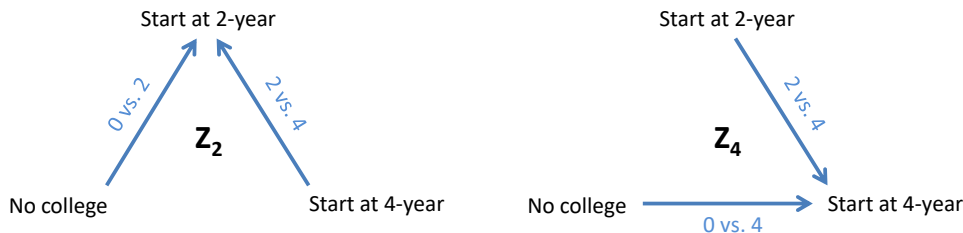
$$D_4(z_2, z'_4) \geq D_4(z_2, z_4), D_0(z_2, z'_4) \leq D_0(z_2, z_4), \text{ and } D_2(z_2, z'_4) \leq D_2(z_2, z_4)$$

for all individuals, with each inequality holding strictly for at least some individuals.

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and the  $2\leftarrow 4$  diversion compliers w.r.t.  $Z_4$  would overlap as closely as drawn in the bottom panels of Figure 4, e.g. if the discrete shift in  $\mu_4(Z_4)$  were substantially larger than the discrete shift in  $\mu_2(Z_2)$ . The triangular region in the center of the bottom left panel of Figure 4, moreover, shows that the  $2\leftarrow 4$  complier overlap in this model would always be imperfect with discrete shifts in  $Z_2$  and  $Z_4$ . Identifying margin-specific LATEs with discrete instruments would thus require additional assumptions about homogeneity in potential outcomes across these different complier groups, as discussed in the next subsection and further explored by Lee and Salanié (2020). Two continuous instruments, in contrast, help narrow in on precisely the indifference margin along which  $2\leftarrow 4$  compliers with respect to  $Z_2$  are *identical* to  $2\leftarrow 4$  compliers w.r.t.  $Z_4$  in this structured discrete choice model, as visualized in the bottom right panel of Figure 4, foreshadowing the generalized “Comparable Compliers” condition in the next subsection.

Figure 5: Unordered Partial Monotonicity



Notes: This figure visualizes the complier flows permitted by Assumption UPM. “ $Z_2$ ” denotes a marginal decrease in  $Z_2$  while holding  $Z_4$  fixed, and “ $Z_4$ ” denotes a marginal decrease in  $Z_4$  while holding  $Z_2$  fixed.

Assumption UPM retains the intuition of “no defiers” from the binary case: each instrument shift renders each treatment either weakly more attractive for all individuals, or weakly less attractive for all individuals, thus ruling out simultaneous flows of different individuals both into and out of a given treatment in response to a given instrument shift.<sup>35</sup> As Figure 5 illustrates, however, this does not limit each instrument to only inducing one type of complier: closer 2-year proximity ( $z'_2 < z_2$ ) induces both  $2 \leftarrow 0$  and  $2 \leftarrow 4$  compliers by rendering 2-year entry weakly more attractive ( $D_2(z'_2, z_4) \geq D_2(z_2, z_4)$ ) at the expense of no college ( $D_0(z'_2, z_4) \leq D_0(z_2, z_4)$ ) and 4-year entry ( $D_4(z'_2, z_4) \leq D_4(z_2, z_4)$ ). Likewise, closer 4-year proximity ( $z'_4 < z_4$ ) induces both  $4 \leftarrow 0$  and  $4 \leftarrow 2$  compliers by rendering 4-year entry more attractive ( $D_4(z_2, z'_4) \geq D_4(z_2, z_4)$ ) at the expense of no college ( $D_0(z_2, z'_4) \leq D_0(z_2, z_4)$ ) and 2-year entry ( $D_2(z_2, z'_4) \leq D_2(z_2, z_4)$ ).<sup>36</sup>

Notice that these complier flows are the same as those induced by the more structured index model in (4); Appendix E shows that Assumption UPM is strictly weaker, however, by considering a nonseparable index model that generalizes (4) and no longer satisfies the two-dimensional visualization in Figure 4, but still satisfies Assumption UPM. To summarize, one can generalize (4) to allow for individual-level heterogeneity in instrument sensitivity, i.e. allowing  $\mu_2(\cdot)$  and  $\mu_4(\cdot)$  to vary across individuals. As long as this heterogeneity is such that  $\mu_2(\cdot)$  and  $\mu_4(\cdot)$  are still strictly increasing in their arguments for a given individual, then instrument responses still run in the same directions those induced by (4), thus continuing to satisfy Assumption UPM.

Since the multiple treatments in this setting need not be ordered in any uniform way across

<sup>35</sup>Assumption UPM also embeds an instrument relevance condition by requiring that each instrument shift induce at least some individuals to switch into or out of each treatment.

<sup>36</sup>One potential violation of Assumption UPM would be an option value channel that causes 4-year proximity to induce  $2 \leftarrow 0$  compliers: the future prospect of upward transfer may inspire some non-college individuals into 2-year entry. Empirically, however, the first stage relationship between 4-year proximity and the probability of not attending college turns out to be quite small; this limits any influence of such an option value channel, since the mass of any  $2 \leftarrow 0$  compliers with respect to 4-year proximity would be bounded above by this small first stage share. Table A.1, moreover, shows that neither 2-year proximity nor 4-year proximity influence the probability of graduating from high school, consistent with limited forward-looking behavior among instrument compliers. A different type of violation of Assumption UPM could arise in the presence of capacity constraints, whereby an instrument-induced switch of one student out of a given sector allows another student to switch into that sector. This type of behavior is notationally ruled out by the exclusion of other students’ instrument values in the potential treatment functions. It is also empirically unlikely in this setting given that all 2-year colleges are open-enrollment, and the types of 4-year institutions attended by marginal students tend to be open-enrollment or have very inclusive admission policies.

individuals, Assumption UPM is closely related to the “unordered monotonicity” assumption of Heckman and Pinto (2018). Assumption UPM is weaker, however, in that it only concerns *partial* instrumental variation in  $Z_2$  while holding  $Z_4$  fixed, and likewise  $Z_4$  holding  $Z_2$  fixed, and is thus agnostic about complier flows when both  $Z_2$  and  $Z_4$  change value simultaneously.<sup>37</sup> Heckman and Pinto (2018) consider the case where unordered monotonicity holds across any shift in the value of a discrete instrument  $Z$ ; by considering each combination of  $(Z_2, Z_4)$  in the present setting as a distinct value of  $Z$ , my relaxation to unordered “partial” monotonicity limits the scope of the assumption to the subset of shifts in  $Z = (Z_2, Z_4)$  in which only one element of the vector changes value. To demonstrate the importance of this relaxation, consider that a simultaneous shift in 2-year distance ( $z'_2 < z_2$ ) and 4-year distance ( $z'_4 > z_4$ )—which could be visualized in the structured index model of Figure 4 as a single shift in the partition to the northwest—would induce not only  $2 \leftarrow 0$  compliers and  $2 \leftarrow 4$  compliers, but also  $0 \leftarrow 4$  compliers. Such behavior would violate Heckman and Pinto (2018)’s unordered monotonicity condition by inducing some students into a given treatment (in this example,  $D = 0$ ) at the same time that others are induced out of it. Assumption UPM, meanwhile, is fully consistent with these patterns, given its more limited imposition of unordered monotonicity on partial instrument shifts only.<sup>38</sup>

The payoff from Assumption UPM (in tandem with Assumption IE) is that it allows us to separately identify the masses and characteristics (including mean potential outcomes) of instrument compliers along each treatment margin, despite our inability to identify which specific individuals in the sample actually comprise these complier groups. Consider a decrease in  $Z_2$  from  $z_2$  to  $z'_2$ , while holding  $Z_4$  fixed at  $z_4$ . By Assumption UPM, this induces  $2 \leftarrow 0$  and  $2 \leftarrow 4$  compliers. Changes in the  $D = 0$  treatment group with respect to this shift therefore must be driven by  $2 \leftarrow 0$  compliers: using the shorthand  $Pr[D = 0 | Z_2 = z_2, Z_4 = z_4] \equiv Pr[D = 0 | z_2, z_4]$ , we have

$$\begin{aligned}
& Pr[D = 0 | z'_2, z_4] - Pr[D = 0 | z_2, z_4] \\
&= Pr[D(z'_2, z_4) = 0] - Pr[D(z_2, z_4) = 0] \\
&= Pr[D(z'_2, z_4) = 0, D(z_2, z_4) = 0] - (Pr[D(z'_2, z_4) = 0, D(z_2, z_4) = 0] + Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0]) \\
&= - Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0] \equiv -Pr[2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)].
\end{aligned}$$

The first equation is due to Assumption IE: conditioning on a given instrument value is as good as exogenously assigning that instrument value. The second equation is due to Assumption UPM: the group of individuals who choose  $D(z_2, z_4) = 0$  includes  $2 \leftarrow 0$  compliers, who would switch to  $D = 2$  in response to the reduction in  $Z_2$ , as well as non-responders, who would continue to choose  $D = 0$ .

<sup>37</sup>On the other hand, while Assumption UPM is written to apply to discrete or continuous instruments, some of the identification results in this section exploit marginal shifts in continuous instruments, which is an important way in which this approach is more demanding than Heckman and Pinto (2018)’s discrete instrument framework.

<sup>38</sup>If  $D$  were binary instead of multinomial, partial monotonicity would similarly relax the more stringent monotonicity condition of Imbens and Angrist (1994), who require  $D(z') \leq D(z)$  for all individuals, or  $D(z') \geq D(z)$  for all individuals, for any shift in  $Z$  from  $z$  to  $z'$ , which would include shifts in which multiple elements of the vector  $Z$  change value simultaneously. See Mogstad et al. (2020) for further discussion of partial monotonicity in the binary treatment case.

Meanwhile, the group of individuals who choose  $D(z'_2, z_4) = 0$  can only include non-responders w.r.t.  $(z'_2, z_4) \leftarrow (z_2, z_4)$ , since if  $D = 2$  still isn't attractive to them with a lower  $Z_2$  cost, it would not have been more attractive at a higher  $Z_2$  cost.

By the same logic, Appendix C shows that changes in the outcome-by-treatment interaction  $YD_0$  with respect to this decrease in  $Z_2$  must also be driven solely by  $2 \leftarrow 0$  compliers:

$$\begin{aligned} & E[YD_0|z'_2, z_4] - E[YD_0|z_2, z_4] \\ &= - E[Y_0|D(z'_2, z_4) = 2, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0] \\ &= - E[Y_0|2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]Pr[2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]. \end{aligned}$$

Putting these pieces together identifies our first mean potential outcome of interest:

$$\frac{E[YD_0|z'_2, z_4] - E[YD_0|z_2, z_4]}{E[D_0|z'_2, z_4] - E[D_0|z_2, z_4]} = E[Y_0|2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]. \quad (5)$$

Estimating the Wald (1940)-esque ratio on the left side of (5) has a straightforward implementation as a 2SLS regression of  $YD_0$  on  $D_0$ , instrumenting for  $D_0$  with  $Z_2$  and conditioning on  $Z_4 = z_4$ .<sup>39</sup> Intuitively, since  $YD_0 = Y_0$  when  $D_0 = 1$ , and  $YD_0 = 0$  otherwise, the  $Z_2$ -induced change in the distribution of  $YD_0$ , scaled by the change in  $D_0$ , reveals information about the distribution of  $Y_0$  among compliers switching out of the  $D = 0$  treatment group. By Assumption UPM, these must be  $2 \leftarrow 0$  compliers, so the information gleaned about  $Y_0$  is specific to this group of compliers.<sup>40</sup>

Since the same partial shift in  $Z_2$  also induces  $2 \leftarrow 4$  compliers, nearly identical arguments (detailed in Appendix C) applied to  $YD_4$  instead of  $YD_0$  lead to the identification of our second mean potential outcome of interest, this time among diversion compliers:

$$\frac{E[YD_4|z'_2, z_4] - E[YD_4|z_2, z_4]}{E[D_4|z'_2, z_4] - E[D_4|z_2, z_4]} = E[Y_4|2 \leftarrow 4 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]. \quad (6)$$

Again, since  $YD_4 = Y_4$  when  $D_4 = 1$ , and  $YD_4 = 0$  otherwise, the  $Z_2$ -induced change in the distribution of  $YD_4$  reveals information about the distribution of  $Y_4$  among compliers switching

<sup>39</sup>Note that this separate identification approach can identify other features of the marginal distributions of complier potential outcomes, not simply means, by replacing  $Y$  with appropriate indicator functions of  $Y$ , e.g.  $\mathbb{1}(Y \leq y)$ .

<sup>40</sup>Instead of working with  $YD_0$ , one could alternatively work with selected outcomes; a rewriting of (5) yields

$$E[Y|D = 0, z'_2, z_4] = E[Y_0|2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)] - \frac{E[Y|D = 0, z'_2, z_4] - E[Y|D = 0, z_2, z_4]}{(E[D_0|z'_2, z_4] - E[D_0|z_2, z_4])/E[D_0|z_2, z_4]}.$$

In words, the mean selected outcome among the  $D = 0$  treatment group at  $(z'_2, z_4)$  is equal to the unselected complier potential outcome mean of interest adjusted by a selection term, which is proportional to the instrument-induced compositional change in the observed outcome within the selected treatment group. This formulation has the flavor of a nonparametric control function (e.g. Heckman and Robb, 1985; Blundell and Powell, 2003; Wooldridge, 2015; Brinch et al., 2017; Kline and Walters, 2019), and as such suggests a simple test of selection: if the instrument induces no compositional change in the mean selected outcome, i.e. if the selection term is zero, then the mean complier potential outcome of interest is identified directly from the conditional mean  $E[Y|D = 0, z_2, z_4]$  with no selection adjustment. Otherwise, the sign of the selection term helps inform whether the average  $D = 0$  treatment group member at  $(z'_2, z_4)$  tends to be positively or negatively selected on their potential outcome level  $Y_0$  relative to the  $2 \leftarrow 0$  compliers of interest.

out of the  $D = 4$  treatment group. By Assumption UPM, these must be  $2 \leftarrow 4$  compliers, so the information gleaned about  $Y_4$  is specific to this group of compliers.

The story is more complicated for  $YD_2$ , since Assumption UPM allows  $Z_2$ -induced changes in the  $D = 2$  treatment group to be driven by both  $2 \leftarrow 0$  and  $2 \leftarrow 4$  compliers. Appendix C shows:

$$\begin{aligned} & E[YD_2|z'_2, z_4] - E[YD_2|z_2, z_4] \\ &= E[Y_2|2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)] Pr[2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)] \quad (7) \\ &+ E[Y_2|2 \leftarrow 4 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)] Pr[2 \leftarrow 4 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]. \end{aligned}$$

$Pr[2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]$ , as shown above, is identified by  $-(Pr[D = 0|z'_2, z_4] - Pr[D = 0|z_2, z_4])$ , and  $Pr[2 \leftarrow 4 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]$  is likewise identified by  $-(Pr[D = 4|z'_2, z_4] - Pr[D = 4|z_2, z_4])$ . But this still leaves (7) as one equation with two unknowns.

Without further assumptions, then, instrumental variation in  $Z_2$  alone is insufficient to identify margin-specific treatment effects, which requires disentangling the mean  $Y_2$  among  $2 \leftarrow 0$  democratization compliers from the mean  $Y_2$  among  $2 \leftarrow 4$  diversion compliers. One possible approach would be to equate these two unknown quantities by assumption, as explored by Lee and Salanié (2020); then (7) would feature only one mean potential outcome, thus identified.<sup>41</sup> Such a homogeneity assumption across compliers along *different* treatment margins may be reasonable in some settings, but it would be unreasonably strong in this one: Table 6 below shows that students democratized into college along the  $2 \leftarrow 0$  treatment margin tend to have substantially lower test scores than diverted students along the  $2 \leftarrow 4$  margin, making it difficult to assume these two distinct complier subpopulations would have equal mean values of the potential outcome level  $Y_2$ . This useful comparison of complier characteristics is identified by replacing  $Y$  with a predetermined student covariate  $W$  in (5), which describes  $2 \leftarrow 0$  compliers, and likewise replacing  $Y$  with  $W$  in (6), which describes  $2 \leftarrow 4$  compliers, and then comparing the two.

Instead of assuming homogeneity across compliers along different treatment margins, we can turn to partial variation in the other instrument,  $Z_4$ , which also induces compliers along the  $2 \leftarrow 4$  diversion margin under Assumption UPM. Specifically, consider an increase in  $Z_4$  from  $z_4$  to  $z'_4$ , holding  $Z_2$  fixed at  $z_2$ , where the base values  $(z_2, z_4)$  are the same as those in the  $Z_2$  shift studied above. By Assumption UPM, this increase in  $Z_4$  induces  $2 \leftarrow 4$  and  $0 \leftarrow 4$  compliers, implying that any compositional changes in the  $D = 2$  treatment group with respect to this shift must be driven by  $2 \leftarrow 4$  compliers alone. Analogous to the previous arguments involving  $Z_2$ , Appendix C shows the following result for  $Z_4$ :

$$\frac{E[YD_2|z_2, z'_4] - E[YD_2|z_2, z_4]}{E[D_2|z_2, z'_4] - E[D_2|z_2, z_4]} = E[Y_2|2 \leftarrow 4 \text{ complier w.r.t. } (z_2, z'_4) \leftarrow (z_2, z_4)]. \quad (8)$$

The intuition for this result is also analogous to the  $Z_2$  results above: since  $YD_2 = Y_2$  when  $D_2 = 1$ , and  $YD_2 = 0$  otherwise, the  $Z_4$ -induced change in the distribution of  $YD_2$  reveals information about

<sup>41</sup>A simple generalization of this approach would be to trace out the schedule of democratization and diversion effects implied by different hypothesized values of the difference between the two unknown means in (7).

the distribution of  $Y_2$  among compliers switching into the  $D = 2$  treatment group. By Assumption UPM, these must be  $2 \leftarrow 4$  compliers, so the information gleaned about  $Y_2$  is specific to this group.

#### 4.4.2 Comparable Compliers

At first glance, (8) might appear to be the *deus ex machina* that neatly completes our identification agenda by disentangling the two mean potential outcomes of interest in (7). In the end, it will fulfill this role, but not without a final assumption and a sharper scope. Closer inspection of (8) shows that it actually involves a slightly different conditioning set than its counterpart in (7): notice that (8) involves  $2 \leftarrow 4$  compliers w.r.t. to the partial shift in  $Z_4$ ,  $(z_2, z'_4) \leftarrow (z_2, z_4)$ , whereas its counterpart in (7) involves  $2 \leftarrow 4$  compliers w.r.t. to the partial shift in  $Z_2$ ,  $(z'_2, z_4) \leftarrow (z_2, z_4)$ . To be clear, both of these conditioning sets are comprised of students who would choose  $D = 4$  when assigned to the base instrument value  $(z_2, z_4)$ , and would switch to  $D = 2$  in response to 2-year college becoming relatively more accessible than 4-year college. The difference is simply which instrument caused the relative change: in one case,  $Z_2$  decreased while holding  $Z_4$  fixed, while in the other,  $Z_4$  increased while holding  $Z_2$  fixed.

As visualized in the bottom left panel of Figure 4 and discussed in footnote 34, these two groups of  $2 \leftarrow 4$  compliers need not be identical subpopulations when the shifts in  $Z_2$  and  $Z_4$  are discrete, since their overlap may be imperfect. Narrowing in on marginal shifts in  $Z_2$  and  $Z_4$ , however, did isolate exactly the same subpopulation of marginal  $2 \leftarrow 4$  compliers in the structured index model, as visualized in the bottom right panel of Figure 4. The structure in (4) is thus sufficient for (8) to disentangle (7) as the shifts in  $Z_2$  and  $Z_4$  become arbitrarily small, since the two conditioning sets of  $2 \leftarrow 4$  compliers involved become identical in the limit. As with Assumption UPM, however, the structure in (4) is not necessary: the nonseparable model in Appendix E generalizes (4) but still features identical  $2 \leftarrow 4$  compliers w.r.t. marginal shifts in  $Z_2$  and  $Z_4$ . The final assumption below therefore generalizes this “identical compliers” feature of the structured index model, stripping it down to the minimal requirement that  $2 \leftarrow 4$  compliers w.r.t. marginal shifts in  $Z_2$  and  $Z_4$  from the same base value have comparable mean  $Y_2$  potential outcomes:

**Assumption CC (Comparable Compliers):** For all base values  $(z_2, z_4)$ ,

$$\lim_{z'_2 \uparrow z_2} E[Y_2 | D(z'_2, z_4) = 2, D(z_2, z_4) = 4] = \lim_{z'_4 \downarrow z_4} E[Y_2 | D(z_2, z'_4) = 2, D(z_2, z_4) = 4].$$

To understand the content of Assumption CC, consider all students who live in a given location, and thus face the same distance costs to the nearest 2-year and 4-year options  $(z_2, z_4)$ . A subset of these students are planning to start college at a 4-year institution, given these distances ( $D(z_2, z_4) = 4$ ). The left side of the equation in Assumption CC considers the further subset of such 4-year entrants who would switch to 2-year entry if the nearest 2-year campus were slightly closer ( $D(z'_2, z_4) = 2$ ). The right side of Assumption CC also considers 4-year entrants at  $(z_2, z_4)$  who would switch to 2-year entry, if the nearest 4-year campus were slightly farther ( $D(z_2, z'_4) = 2$ ).

In the structured index model of (4), these two sets of students would perfectly coincide, and would therefore necessarily have the same mean  $Y_2$ . Assumption CC preserves this equality of mean potential outcomes, but does not require that it result from a structured index model like (4), and does not require that the two sets of compliers comprise the same common set of individuals.

To emphasize that the only difference between the two sets of students involved in Assumption CC is the particular instrument used to induce their switch from 4 to 2, another way to write the assumption is

$$\begin{aligned} & E[Y_2 | \text{Marginal 2-4 complier w.r.t. } \mathbf{Z}_2 \text{ at } (z_2, z_4)] \\ &= E[Y_2 | \text{Marginal 2-4 complier w.r.t. } \mathbf{Z}_4 \text{ at } (z_2, z_4)]. \end{aligned}$$

This formulation helps clarify what Assumption CC does *not* impose. First, it does not make any claims of comparability between compliers along different treatment margins: Assumption CC solely concerns diversion compliers, i.e. students along the 2-4 treatment margin, leaving them free to differ systematically from democratization compliers along the 2-0 margin. Second, Assumption CC does not require comparability between 2-4 diversion compliers induced by instrument shifts of large and differing magnitudes: its scope is limited to infinitesimal changes in  $Z_2$  and  $Z_4$ . Finally, Assumption CC does not require comparability between 2-4 diversion compliers who face different initial costs of 2-year and 4-year entry: it only considers individuals who share the same base value of  $(z_2, z_4)$  and are on the margin of indifference between  $D_2$  and  $D_4$  given this cost schedule.

Assumption CC is automatically satisfied in a broad class of index models, including (4) and even its nonseparable generalization in Appendix E. In the unstructured framework of this subsection, however, Assumption CC does not quite come for free; Appendix F offers a counterexample of a nonseparable model that satisfies Assumptions IE and UPM but not CC. Intuitively, imagine that some (but not all) of the students who are on the margin between 2-year and 4-year entry at a given  $(z_2, z_4)$  point are completely insensitive to 2-year distance, but still sensitive to 4-year distance. Then these students will not be 2-4 compliers w.r.t.  $Z_2$ , but will be 2-4 compliers w.r.t.  $Z_4$ , breaking the exact overlap of the two complier groups involved in Assumption CC. If, furthermore, these  $Z_2$ -insensitive students are systematically different from the other marginal 2-4 students at  $(z_2, z_4)$  in terms of their mean potential outcomes, then Assumption CC may not hold.

Fortunately, it is straightforward to test for such differences empirically using observable student covariates. If  $(Z_2, Z_4)$  are as good as randomly assigned relative to some pre-determined student characteristic  $W$ , then we can replace  $Y$  with  $W$  in (6) to identify

$$\frac{E[WD_4 | z'_2, z_4] - E[WD_4 | z_2, z_4]}{E[D_4 | z'_2, z_4] - E[D_4 | z_2, z_4]} = E[W | 2 \leftarrow 4 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)], \quad (9)$$

and likewise replace  $Y$  with  $W$  in (8) to identify

$$\frac{E[WD_2 | z_2, z'_4] - E[WD_2 | z_2, z_4]}{E[D_2 | z_2, z'_4] - E[D_2 | z_2, z_4]} = E[W | 2 \leftarrow 4 \text{ complier w.r.t. } (z_2, z'_4) \leftarrow (z_2, z_4)], \quad (10)$$



then compare the two for marginal shifts in  $Z_2$  and  $Z_4$ . This exercise does not require Assumption CC, since (6) and (8) result from Assumptions IE and UPM alone.<sup>42</sup> It therefore offers a useful empirical diagnostic for assessing the validity of Assumption CC in any given setting.<sup>43</sup> Table 6 below conducts this exercise with 10th grade standardized test scores, which are strong predictors of student outcomes, and finds that marginal 2←4 compliers w.r.t.  $Z_2$  are statistically identical to marginal 2←4 compliers w.r.t.  $Z_4$ , bolstering the credibility of Assumption CC in this setting.

#### 4.4.3 Putting the Pieces Together: Margin-Specific Marginal Treatment Effects

Assumptions IE, UPM, and CC together deliver all the ingredients required for identifying margin-specific treatment effects. To match the marginal scope of Assumption CC, narrow the discrete instrument differences in (5) to partial derivatives by making the change in  $Z_2$  arbitrarily small:

$$\begin{aligned} \lim_{z'_2 \rightarrow z_2} \frac{E[YD_0|z'_2, z_4] - E[YD_0|z_2, z_4]}{E[D_0|z'_2, z_4] - E[D_0|z_2, z_4]} &= \lim_{z'_2 \rightarrow z_2} \frac{\frac{E[YD_0|z'_2, z_4] - E[YD_0|z_2, z_4]}{z'_2 - z_2}}{\frac{E[D_0|z'_2, z_4] - E[D_0|z_2, z_4]}{z'_2 - z_2}} = \frac{\frac{\partial E[YD_0|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_0|z_2, z_4]}{\partial Z_2}} \quad (11) \\ &= \lim_{z'_2 \rightarrow z_2} E[Y_0 | D(z'_2, z_4) = 2, D(z_2, z_4) = 0] \equiv E[Y_0 | \text{Marginal 2-0 complier w.r.t. } Z_2 \text{ at } (z_2, z_4)]. \end{aligned}$$

Likewise, the marginal version of (6) is

$$\frac{\frac{\partial E[YD_4|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_4|z_2, z_4]}{\partial Z_2}} = E[Y_4 | \text{Marginal 2-4 complier w.r.t. } Z_2 \text{ at } (z_2, z_4)], \quad (12)$$

the marginal version of (7) is

$$\begin{aligned} \frac{\partial E[YD_2|z_2, z_4]}{\partial Z_2} &= E[Y_2 | \text{Marginal 2-0 complier w.r.t. } Z_2 \text{ at } (z_2, z_4)] \left( - \frac{\partial E[D_0|z_2, z_4]}{\partial Z_2} \right) \\ &\quad + E[Y_2 | \text{Marginal 2-4 complier w.r.t. } Z_2 \text{ at } (z_2, z_4)] \left( - \frac{\partial E[D_4|z_2, z_4]}{\partial Z_2} \right), \quad (13) \end{aligned}$$

and the marginal version of (8) is

$$\frac{\frac{\partial E[YD_2|z_2, z_4]}{\partial Z_4}}{\frac{\partial E[D_2|z_2, z_4]}{\partial Z_4}} = E[Y_2 | \text{Marginal 2-4 complier w.r.t. } Z_4 \text{ at } (z_2, z_4)]. \quad (14)$$

<sup>42</sup>The framework in this section is therefore overidentified in the sense that if equality of (9) and (10) is rejected, one could weaken Assumption CC to only hold conditional on  $W$ .

<sup>43</sup>This test also does not require the shifts in  $Z_2$  and  $Z_4$  to be infinitesimal; if continuous instruments are unavailable, one could try to justify a discrete version of Assumption CC (or suggest a rejection of it) by comparing the observable characteristics of 2←4 compliers w.r.t. discrete shifts in  $Z_2$  vs.  $Z_4$ , subject to the discussion in footnote 34.

Applying Assumption CC to (12) and (14) therefore yields

$$\begin{aligned} \frac{\frac{\partial E[YD_2|z_2, z_4]}{\partial Z_4}}{\frac{\partial E[D_2|z_2, z_4]}{\partial Z_4}} - \frac{\frac{\partial E[YD_4|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_4|z_2, z_4]}{\partial Z_2}} &= E[Y_2 - Y_4 | \text{Marginal 2-4 complier at } (z_2, z_4)] \\ &\equiv MTE_{2\leftarrow 4}(z_2, z_4), \end{aligned}$$

and applying it to (13) and (14), in tandem with (11), yields

$$\begin{aligned} \frac{\frac{\partial E[YD_2|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_0|z_2, z_4]}{\partial Z_2}} - \frac{\frac{\partial E[YD_2|z_2, z_4]}{\partial Z_4}}{\frac{\partial E[D_2|z_2, z_4]}{\partial Z_4}} \frac{\frac{\partial E[D_4|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_0|z_2, z_4]}{\partial Z_2}} - \frac{\frac{\partial E[YD_0|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_0|z_2, z_4]}{\partial Z_2}} &= E[Y_2 - Y_0 | \text{Marginal 2-0 complier at } (z_2, z_4)] \\ &\equiv MTE_{2\leftarrow 0}(z_2, z_4). \end{aligned}$$

These margin-specific marginal treatment effects,  $MTE_{2\leftarrow 0}(z_2, z_4)$  and  $MTE_{2\leftarrow 4}(z_2, z_4)$ , are simply the continuous instrument analogues to the discrete “sub-LATEs” from equation (2). After identifying  $MTE_{2\leftarrow 0}(z_2, z_4)$  and  $MTE_{2\leftarrow 4}(z_2, z_4)$  at each  $(z_2, z_4)$  evaluation point in the support of the instruments, any discrete sub-LATE of interest within the instrument support can be formed by integrating the relevant MTE over the domain of the discrete instrument shift of interest (Heckman and Vytlacil, 2005).

Finally, the net effect of 2-year entry, which pools 2-0 and 2-4 compliers together into a single weighted average effect, is identified by the local instrumental variables estimand (Heckman and Vytlacil, 1999) involving  $Y$ ,  $D_2$ , and  $Z_2$ ,

$$MTE_2(z_2, z_4) = \frac{\frac{\partial E[Y|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_2|z_2, z_4]}{\partial Z_2}},$$

and the share of 2-0 compliers (i.e. the weight  $\omega$  in the weighted average effect) is identified by

$$\omega(z_2, z_4) = \frac{-\frac{\partial E[D_0|z_2, z_4]}{\partial Z_2}}{\frac{\partial E[D_2|z_2, z_4]}{\partial Z_2}}.$$

Putting all of these separately identified pieces together delivers the decomposition of interest:

$$\underbrace{MTE_2}_{\text{Net effect of 2-year entry}} = \omega \underbrace{MTE_{2\leftarrow 0}}_{\text{Democratization effect}} + (1 - \omega) \underbrace{MTE_{2\leftarrow 4}}_{\text{Diversion effect}}, \quad (15)$$

where each component is identified at each point in the instrument support with nonzero first-stage derivatives.

## 5 Estimation and Instrument Diagnostics

### 5.1 Locally Linear Specification

All of the ingredients that go into Equation (15) are partial derivatives of the conditional expectations of  $\{D_0, D_2, D_4, Y, YD_0, YD_2, YD_4\}$  with respect to the instruments  $(Z_2, Z_4)$ , evaluated at a given point in the support of  $(Z_2, Z_4)$ . In many empirical applications, these instruments may only satisfy Assumptions IE, UPM, and CC conditional on a control set  $X$ . All of the preceding arguments still apply after conditioning on each  $X = x$ , but the curse of dimensionality quickly sets in as  $X$  becomes high-dimensional and includes continuous variables, as it does in my setting.

To reduce this dimensionality problem, I assume that the conditional expectations of interest are well-approximated by flexible locally linear functions around  $(z_2, z_4)$  evaluation points in which the variables in the control set  $X$  enter additively but with coefficients that are allowed to vary arbitrarily across different  $(z_2, z_4)$  evaluation points (e.g. Hastie and Tibshirani, 1993). That is, for a given variable  $T \in \{D_0, D_2, D_4, Y, YD_0, YD_2, YD_4\}$ , the estimated coefficients at each  $(z_2, z_4)$  evaluation point solve a kernel-weighted least squares problem:

$$\begin{pmatrix} \hat{\beta}_0^T(z_2, z_4) \\ \hat{\beta}_2^T(z_2, z_4) \\ \hat{\beta}_4^T(z_2, z_4) \\ \hat{\beta}_x^T(z_2, z_4) \end{pmatrix} = \underset{\beta_0, \beta_2, \beta_4, \beta_x}{\operatorname{argmin}} \sum_{i=1}^N K\left(\frac{Z_{2i} - z_2}{h}, \frac{Z_{4i} - z_4}{h}\right) (T_i - \beta_0 - \beta_2 Z_{2i} - \beta_4 Z_{4i} - X_i' \beta_x)^2,$$

where  $K(\cdot)$  is a two-dimensional kernel with bandwidth  $h$ . This specification offers a flexible compromise between two extremes: fully nonparametric estimation across all dimensions of  $(Z_2, Z_4, X)$ , which is infeasible in this setting, and a globally linear specification that would constrain the  $\beta$  slope coefficients to remain constant across all  $(z_2, z_4)$  evaluation points, which is a strong but common restriction in IV estimation.

Forming the potential outcome and treatment effect estimates then proceeds by the analogy principle, plugging in the local slope coefficients  $\hat{\beta}_2^T(z_2, z_4)$  and  $\hat{\beta}_4^T(z_2, z_4)$  in place of the local partial derivatives  $\frac{\partial E[T|Z_2=z_2, Z_4=z_4]}{\partial Z_2}$  and  $\frac{\partial E[T|Z_2=z_2, Z_4=z_4]}{\partial Z_4}$  involved in each expression, e.g.

$$\hat{E}[Y_0 | \text{Marginal 2-0 complier at } (z_2, z_4)] = \frac{\hat{\beta}_2^{YD_0}(z_2, z_4)}{\hat{\beta}_2^{D_0}(z_2, z_4)}.$$

These plug-in estimators are numerically equivalent to 2SLS estimators with modified outcome variables: continuing the example above, we would arrive at the same estimate of  $\hat{E}[Y_0 | \text{Marginal 2-0 complier at } (z_2, z_4)]$  through a 2SLS regression of  $YD_0$  on  $D_0$  instrumented with  $Z_2$ , controlling linearly for  $Z_4$  and  $X$  in a local kernel-weighted region around the evaluation point  $(z_2, z_4)$ .

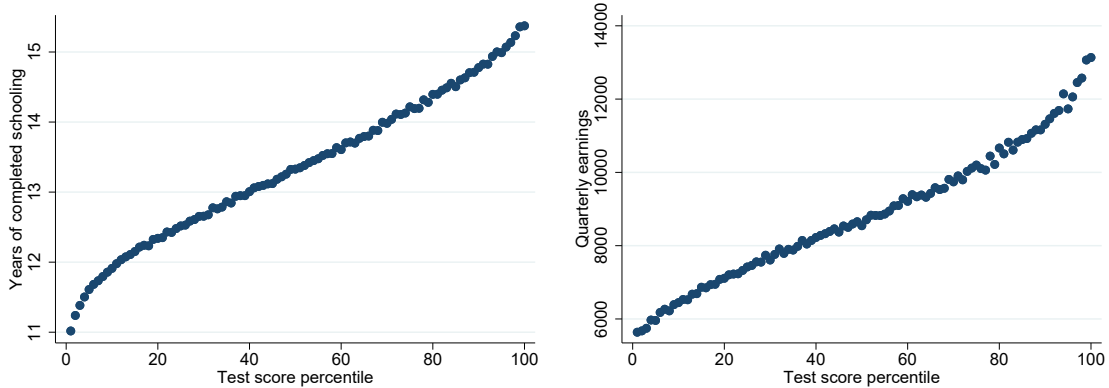
I use a two-dimensional Epanechnikov (parabolic) kernel with 40-mile bandwidth to weight observations in the locally linear regressions; Table 8 below shows that the point estimates are similar when using smaller bandwidths but are less precisely estimated. I report the main results evaluated at the mean values of  $(Z_2, Z_4)$ , while Section 6.5 explores heterogeneity and selection

Table 4: Instrument Diagnostics: Raw and Controlled Relationships with Student Covariates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: Relationships with 2-year distance										
	Dependent variable: $Z_2$ , miles to the nearest 2-year college									
Test score percentile (0 to 1)	.992 (.121)						-.434 (.088)	-.308 (.071)	-.079 (.059)	-.047 (.058)
Female		-.252 (.022)					-.110 (.019)	-.038 (.016)	-.014 (.014)	-.014 (.014)
Hispanic			-2.644 (.154)				-1.551 (.134)	-.614 (.100)	-.449 (.088)	-.472 (.082)
Black			-3.293 (.140)				-2.442 (.133)	-.217 (.105)	.040 (.092)	.014 (.089)
Asian			-4.255 (.153)				-2.915 (.153)	-1.038 (.119)	-.342 (.091)	-.305 (.090)
Disadvantaged (FRPL)				-.891 (.109)			.303 (.074)	.205 (.059)	-.015 (.051)	-.033 (.041)
Cohort year					-.135 (.079)		-.115 (.072)	-.138 (.062)	-.140 (.055)	-.141 (.055)
$Z_4$ , miles to nearest 4-year college						.314 (.011)	.299 (.011)	.236 (.013)	.069 (.014)	.069 (.014)
$R^2$	.0009	.0003	.039	.003	.0007	.202	.218	.464	.603	.604
Panel B: Relationships with 4-year distance										
	Dependent variable: $Z_4$ , miles to the nearest 4-year college									
Test score percentile (0 to 1)	1.710 (.195)						-.064 (.139)	-.292 (.113)	-.070 (.105)	.053 (.102)
Female		-.267 (.032)					-.067 (.027)	.004 (.021)	.018 (.019)	.015 (.019)
Hispanic			-4.311 (.225)				-2.899 (.200)	-.751 (.131)	-.394 (.120)	-.715 (.111)
Black			-3.339 (.235)				-1.454 (.224)	-.167 (.172)	.412 (.155)	.173 (.154)
Asian			-4.687 (.259)				-2.148 (.262)	-1.515 (.190)	-.466 (.175)	-.395 (.165)
Disadvantaged (FRPL)				-1.457 (.168)			.404 (.111)	.580 (.087)	.494 (.086)	.225 (.065)
Cohort year					-.022 (.119)		.078 (.109)	.011 (.087)	-.030 (.082)	-.034 (.082)
$Z_2$ , miles to nearest 2-year college						.644 (.020)	.616 (.021)	.429 (.023)	.143 (.029)	.140 (.028)
$R^2$	.0014	.0002	0.037	0.004	.000009	.202	.215	.526	.601	.605
Local labor market controls								✓	✓	✓
Urbanization controls									✓	✓
Neighborhood quality controls										✓
$N$	556,719	556,719	556,719	556,719	556,719	556,719	556,719	556,719	556,719	556,719

Notes: Test score percentiles in the top row of each panel are measured from 0 to 1 for readability. Standard errors in parentheses are clustered at the high school campus by cohort level. Observations are locally weighted around the mean values of the instruments to match the exact sample as the main causal effect estimates in Section 6. Column (8) controls for each of the 62 commuting zones in Texas and a cubic polynomial in the neighborhood-level oil and gas employment share. Column (9) adds controls for each of the 12 neighborhood-level NCES urbanization locale codes (e.g. midsize city, large suburb, fringe town, remote rural, etc.). Column (10) adds a cubic polynomial in the neighborhood quality index constructed in Section 3.2.

Figure 6: Predictive Power of 10th Grade Test Scores on Long-Run Outcomes



Notes: Years of completed schooling are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30. Test score percentile construction is described in Section 3.2.

patterns across different instrument evaluation points. Inference is conducted via block bootstrap at each evaluation point with clusters at the high school campus by cohort level, which corresponds to the level at which the instruments vary and allows for arbitrary error correlations among students in the same high school class.

## 5.2 Instrument Diagnostics

In my setting, 2-year and 4-year college proximity are unlikely to satisfy Assumption IE unconditionally, given that different types of families with high school aged students sort systematically into different types of locations. The first five columns of Table 4 confirm this: regressing 2-year distance (top panel) and 4-year distance (bottom panel) on individual student covariates in the main evaluation sample shows that higher ability students tend to live farther away from each type of college, while female, non-white, and low-income students tend to live closer.

One could reasonably argue, however, that different types of families with children do not sort into locations on the basis of 2-year and 4-year college distance per se. Instead, families sort on more fundamental factors like local labor markets, preferences for different levels of urbanization, and neighborhood quality, which themselves happen to correlate with college distances. The remaining columns of Table 4 show that controlling for these “neighborhood fundamentals” tends to substantially weaken, and in many cases statistically eliminate, the relationships between college distances and student covariates. Column (8) controls for each of the 62 commuting zones in Texas and the neighborhood-level oil and gas employment share to proxy for local labor markets; column (9) adds controls for each of the 12 neighborhood-level NCES urbanization locale codes (e.g. midsize city, large suburb, fringe town, remote rural, etc.); and column (10) adds a cubic in the neighborhood quality index constructed in Section 3.2. The lack of any conditional relationship between distances and the test score measure in the first row of each panel in Table 4 is especially important, given the remarkably strong power of this ability measure to predict college enrollment choices, as illustrated in Figure 1, and long-run outcomes, as illustrated in Figure 6.

A few of the other covariates in Table 4, however, retain economically small but statistically significant relationships with 2-year and/or 4-year distance after controlling for neighborhood fundamentals. Table 5 therefore explores the robustness of the first stage and reduced form estimates, as well as the ability balance result, to the inclusion of these covariates as additional controls. The first four columns of Table 5 proceed in the same fashion as the last four columns of Table 4, beginning with uncontrolled regressions of each panel’s dependent variable on 2-year distance and 4-distance (now divided by 10 for more readable coefficients), and then sequentially adding the baseline controls for local labor markets, neighborhood urbanization, and neighborhood quality. While the first stage coefficients in Panel B are fairly stable across all specifications, the changes in the reduced form coefficients in Panel C across columns (1) through (4) demonstrate the importance of controlling for neighborhood fundamentals. Adding student demographic controls in column (5), however, does not affect the estimates as much, despite the large increases in  $R$ -squared. Finally, the estimates change little (besides another large increase in  $R$ -squared) when tacking on the highly predictive test score control in column (6), which corroborates the balance results in Panel A.

Taken together, these diagnostics suggest that controls for local labor markets, urbanization, and neighborhood quality help purge the raw distance instruments of confounding relationships with student potential, with only a supporting role played by controls for individual student demographics. I therefore proceed with the control set defined by column (5) in Table 5, leaving the highly predictive test score measure as an excluded covariate available for describing compliers in Table 6 and validating the main results in Table 8.

The first stage estimates in Panel B of Table 5 also align with Assumption UPM. The coefficients on 2-year distance, multiplied by  $-1$ , show that decreasing  $Z_2$  while holding  $Z_4$  fixed increases 2-year entry at the expense of both 4-year entry and non-enrollment.<sup>44</sup> Likewise, the coefficients on 4-year distance show that increasing  $Z_4$  while holding  $Z_2$  fixed increases 2-year entry and non-enrollment at the expense of 4-year entry. Figure 7 further shows that the distance instruments induce meaningful variation in enrollment behavior by plotting the estimated propensity score distributions of 2-year entry with respect to 2-year distance (left panel) and 4-year distance (right panel), evaluated at the mean values of the other distance dimension and the controls.

Finally, Table 6 empirically probes the validity of Assumption CC by describing the observable abilities of each complier type. The upper row in both columns shows that 2–4 diversion compliers with respect to  $Z_2$  tend to come from the middle of the high school ability distribution, with a mean test score percentile of 53.5. The bottom row in the left column reports the mean test score percentile among 2–4 diversion compliers with respect to  $Z_4$ , which is independently identified without making any assumption about the similarity of these two groups. In fact, the two complier means are statistically indistinguishable, lending empirical credence to Assumption CC’s requirement that 2–4 diversion compliers w.r.t.  $Z_2$  and  $Z_4$  have equal mean  $Y_2$  potential outcomes. In contrast, the right column of Table 6 shows that democratization compliers along the 2–0 treatment margin tend to have much lower high school test scores than 2–4 diversion compliers, reinforcing the motivation

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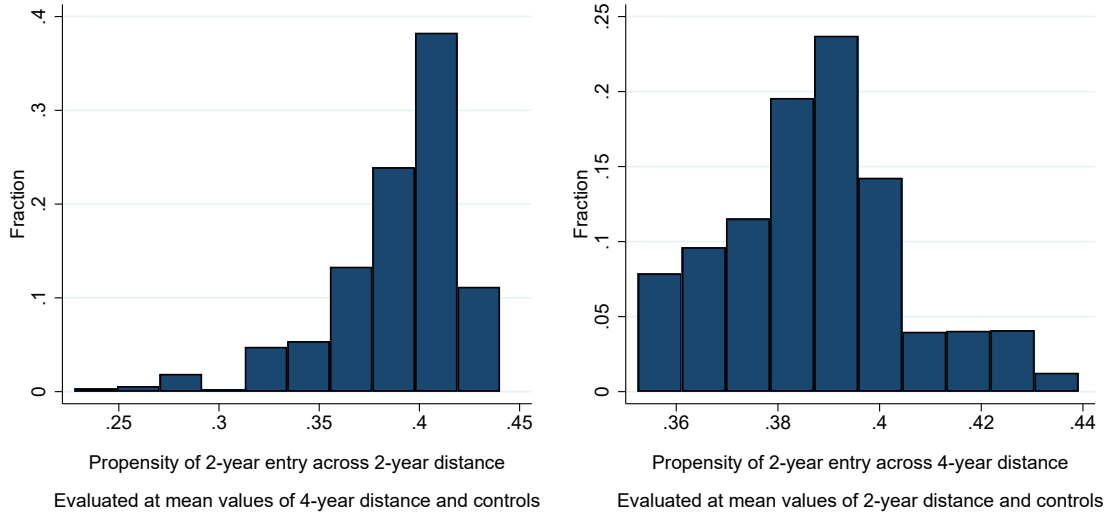
<sup>44</sup>The coefficients on  $D_0$  are excluded from Table 5 to save space, but are easily inferred given  $D_0 = 1 - D_2 - D_4$ .

Table 5: Instrument Diagnostics: Balance, First Stages, and Reduced Forms

	(1)	(2)	(3)	(4)	(5)	(6)
<u>Panel A: Balance Test</u>						
	Dependent variable: test score percentile (0 to 1)					
$Z_2$ : miles/10	.005 (.001)	-.003 (.002)	.001 (.002)	.001 (.002)	-.001 (.001)	
$Z_4$ : miles/10	.006 (.001)	-.003 (.001)	-.003 (.001)	.001 (.001)	.001 (.001)	
$R^2$	.002	.020	.025	.040	.101	
<u>Panel B: First Stages</u>						
	Dependent variable: $D_2$ (start at 2-year college)					
$Z_2$ : miles/10	-.041 (.002)	-.042 (.002)	-.043 (.003)	-.044 (.003)	-.043 (.003)	-.043 (.003)
$Z_4$ : miles/10	.025 (.002)	.020 (.002)	.015 (.002)	.018 (.002)	.019 (.002)	.018 (.002)
$R^2$	.004	.013	.017	.019	.027	.038
	Dependent variable: $D_4$ (start at 4-year college)					
$Z_2$ : miles/10	.014 (.002)	.006 (.003)	.016 (.003)	.019 (.003)	.015 (.003)	.016 (.002)
$Z_4$ : miles/10	-.026 (.002)	-.034 (.002)	-.028 (.002)	-.023 (.002)	-.025 (.002)	-.026 (.002)
$R^2$	.004	.019	.021	.031	.069	.158
<u>Panel C: Reduced Forms</u>						
	Dependent variable: Years of schooling					
$Z_2$ : miles/10	-.027 (.012)	-.098 (.015)	-.039 (.016)	-.026 (.013)	-.040 (.011)	-.036 (.009)
$Z_4$ : miles/10	-.031 (.009)	-.106 (.010)	-.086 (.011)	-.046 (.009)	-.052 (.008)	-.055 (.007)
$R^2$	.001	.013	.015	.037	.093	.223
	Dependent variable: Bachelor's degree					
$Z_2$ : miles/10	-.004 (.002)	-.018 (.003)	-.004 (.003)	-.001 (.002)	-.005 (.002)	-.004 (.002)
$Z_4$ : miles/10	-.008 (.002)	-.023 (.002)	-.018 (.002)	-.010 (.002)	-.011 (.002)	-.012 (.001)
$R^2$	.001	.012	.015	.035	.075	.151
	Dependent variable: Quarterly earnings					
$Z_2$ : miles/10	16.7 (29.2)	-94.0 (25.8)	-41.3 (28.2)	-25.1 (23.6)	-30.1 (20.6)	-24.7 (20.1)
$Z_4$ : miles/10	137.2 (21.6)	-144.7 (19.6)	-156.0 (20.9)	-97.7 (18.3)	-82.1 (15.4)	-85.4 (14.4)
$R^2$	.001	.029	.031	.039	.105	.142
Local labor market controls		✓	✓	✓	✓	✓
Urbanization controls			✓	✓	✓	✓
Neighborhood quality controls				✓	✓	✓
Student demographic controls					✓	✓
Test score controls						✓
$N$	556,719	556,719	556,719	556,719	556,719	556,719

Notes: Test score percentiles are measured from 0 to 1 for comparing coefficient magnitudes to specifications with binary outcomes. Standard errors in parentheses are clustered at the high school campus by cohort level. Observations are locally weighted around the mean values of the instruments to match the exact sample as the main causal effect estimates in Section 6. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30. Column (2) controls for each of the 62 commuting zones in Texas and a cubic polynomial in the neighborhood-level oil and gas employment share. Column (3) adds controls for each of the 12 neighborhood-level NCES urbanization locale codes (e.g. midsize city, large suburb, fringe town, remote rural, etc.). Column (4) adds a cubic polynomial in the neighborhood quality index constructed in Section 3.2. Column (5) adds categorical controls for gender, free/reduced price lunch status, race, and cohort. Column (6) adds a cubic polynomial in test score percentile.

Figure 7: Conditional Distributions of Estimated 2-Year Entry Propensity Scores



Notes: The left panel plots the distribution of the estimated propensity score of 2-year entry as a function of 2-year distance, estimated via the locally linear specification described in Section 5.1 and evaluated at the mean values of 4-year distance and the control set described in Section 5.2. The right panel plots the distribution of the estimated propensity score of 2-year entry as a function of 4-year distance, evaluated at the mean values of 2-year distance and the control set.

Table 6: Describing Compliers

Comparable compliers: Compliers along the <i>same</i> treatment margin, induced by <i>different</i> instruments		Distinct compliers: Compliers along <i>different</i> treatment margins, induced by the <i>same</i> instrument	
Mean test score percentile		Mean test score percentile	
2-4 complier w.r.t. $Z_2$	53.5 (2.7)	2-4 complier w.r.t. $Z_2$	53.5 (2.7)
2-4 complier w.r.t. $Z_4$	54.0 (2.9)	2-0 complier w.r.t. $Z_2$	31.8 (2.3)

Notes: Locally weighted observations: 556,719. Test score percentiles in this table are measured from 1 to 100. Standard errors in parentheses are block bootstrapped at the high school campus by cohort level. All estimates are evaluated at the mean values of the instruments.



Table 7: Causal Effect Estimates

	$MTE_2$	=	$\omega$	$MTE_{2\leftarrow 0}$	+	$(1 - \omega)$	$MTE_{2\leftarrow 4}$	$H_0 : MTE_{2\leftarrow 0} = MTE_{2\leftarrow 4}$
	Net effect		Democratization share	Democratization effect		Diversion share	Diversion effect	Test of equal effects across treatment margins
Years of schooling	.928 (.245)		.653 (.050)	1.72 (.202)		.347 (.050)	-.567 (.339)	$p < .001$
Bachelor's degree	.104 (.044)		.653 (.050)	.257 (.035)		.347 (.050)	-.184 (.084)	$p < .001$
Quarterly earnings	697 (434)		.653 (.050)	1,323 (544)		.347 (.050)	-483 (845)	$p = .095$

Notes: Locally weighted observations: 556,719. All estimates are evaluated at the mean values of the instruments. Standard errors in parentheses, and  $t$ -statistics for tests of equal effects across margins, are block bootstrapped at the high school campus by cohort level. Complier shares are the same across outcomes due to common first stage equations. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30.

for the separate identification approach and its accommodation of unrestricted heterogeneity across compliers along *different* treatment margins.

## 6 Results

### 6.1 Main Results

Table 7 presents the main results.<sup>45</sup> The first column shows the net effect of 2-year entry on each outcome, which pools the effects on 2 $\leftarrow$ 0 democratization compliers and 2 $\leftarrow$ 4 diversion compliers into a single weighted average. On net, 2-year college access boosts educational attainment and earnings: for the “average” complier induced into 2-year entry by closer access, completed schooling increases by roughly one year, bachelor’s degree attainment increases by 10.4 percentage points, and earnings per quarter around age 30 increase by a marginally significant 697 dollars. These extra earnings correspond to a 10.2 percent premium relative to the pooled counterfactual complier potential outcome mean of 6,828 dollars per quarter.

The next four columns of Table 7 decompose these net effects into the two potentially opposing channels of democratization and diversion. Roughly two-thirds (.653) of compliers would not have otherwise attended college, and these democratized 2-year entrants experience significant gains in all outcomes compared to their counterfactual of not attending any college. They complete 1.7 more years of schooling, and are 26 percentage points more likely to earn a bachelor’s degree. Table A.2 shows that very few democratized students are able to transfer to a 4-year institution

<sup>45</sup>Main estimates are evaluated at the mean values of the instruments. Section 6.5 below explores heterogeneity in the local estimates across the range of 2-year college proximity. Averaging the entire two-dimensional grid of estimates across the empirical distribution of the instruments yields average marginal treatment effects (AMTEs) that are similar to the reported MTE estimates evaluated at the mean.

and complete a BA within four years of college entry, but the democratization effect rises steadily as these students are given a progressively longer observation window to transfer and eventually complete degrees. Table A.2 also shows that nearly all of these degrees are in non-STEM fields, with the democratization effect on completing a BA in STEM just 1.5 percentage points, in line with the fact that the average democratization complier is only at the 32nd percentile of the high school test score distribution (Table 6).

Moving to earnings, the average student democratized into 2-year entry from non-enrollment earns 1,323 dollars more per quarter around age 30, which is a 22 percent premium over their no-college counterfactual mean of 6,140 dollars per quarter. Considering that the net tuition price of attending a 2-year college for the average student in the U.S. is approximately zero after grant aid,<sup>46</sup> this represents a healthy private return to 2-year entry along the democratization margin. From a social perspective, the average cost of educating a full-time community college student is roughly 10 thousand dollars per year of enrollment, so it takes only about  $10,000 / (1,323 * 4) \approx 2$  years of (undiscounted) higher earnings to recoup each year of upfront social investment.

Diverted students, on the other hand, make up the other third (0.347) of compliers, and they end up with lower average outcomes as a result of starting college at a 2-year instead of a 4-year institution. Diverted students complete roughly half a year less of total education and are 18 percentage points less likely to complete a bachelor's degree relative to their counterfactual of starting directly at a 4-year institution, leading to a negative but statistically imprecise impact on earnings around age 30. Table A.2 shows that the magnitude of the BA effect doubles when moving from a 6-year observation window to a 10-year observation window, and diversion has little impact on bachelor's degree completion in STEM fields. Thus, a large fraction of the BA degrees lost to diversion come from students who would have had long time-to-degrees even after starting directly in the 4-year sector, and very few of these students would have majored in STEM.<sup>47</sup> Still, taking the imprecise earnings estimate at face value, a prospective student along the diversion margin comparing the average net tuition price of 2-year entry ( $\sim 0$  dollars per year) to the average net tuition price of public 4-year entry ( $\sim 3,500$  dollars per year) would have to severely discount the future to rationalize losing roughly 500 dollars in earnings every quarter in exchange for the upfront savings of  $\sim 3,500$  dollars per year enrolled in a 2-year instead of a 4-year institution. The social calculation is quite similar, given that annual educational expenditures per student at public community colleges ( $\sim 10,000$  dollars) and public baccalaureate institutions ( $\sim 13,500$ ) also differ by about 3,500 dollars.

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<sup>46</sup>Net price statistics throughout this section come from College Board (2018).

<sup>47</sup>Further exploration of the mechanisms driving diversion effects remains an important avenue for future work. See Monaghan and Attewell (2015) for a propensity score matching approach that suggests the importance of credit loss during 2-year to 4-year transfer, and Xu (2018) for evidence suggesting adverse impacts of 2-year colleges' greater reliance on part-time adjunct faculty relative to 4-year institutions.

Table 8: Causal Effect Estimates: Robustness Checks

	(1)	(2)	(3)	(4)	(5)
	Baseline	No	Add test	Bandwidth	Bandwidth
	specification	clustering	score control	35 miles	30 miles
2-0 Democratization share	.653 (.050)	.653 (.023)	.638 (.048)	.649 (.053)	.655 (.059)
Years of schooling					
2-0 Democratization effect	1.72 (.202)	1.72 (.135)	1.69 (.198)	1.69 (.214)	1.68 (.229)
2-4 Diversion effect	-.567 (.339)	-.567 (.193)	-.655 (.312)	-.627 (.362)	-.650 (.387)
Bachelor's degree					
2-0 Democratization effect	.257 (.035)	.257 (.030)	.256 (.036)	.252 (.038)	.252 (.040)
2-4 Diversion effect	-.184 (.084)	-.184 (.050)	-.203 (.078)	-.194 (.089)	-.194 (.092)
Quarterly earnings					
2-0 Democratization effect	1,323 (544)	1,323 (469)	1,288 (557)	1,535 (575)	1,653 (767)
2-4 Diversion effect	-483 (845)	-483 (617)	-696 (810)	-538 (893)	-755 (1,016)
Locally weighted obs.	556,719	556,719	556,719	542,271	526,707

Notes: All estimates are evaluated at the mean values of the instruments. Standard errors in parentheses are block bootstrapped at the high school campus by cohort level, except in column (2), where bootstrapping is at the individual student level. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30.

## 6.2 Robustness Checks and Comparisons to Other Approaches

Table 8 conducts several robustness checks to probe the sensitivity of the results to alternative specifications. Column (1) transposes the baseline point estimates and standard errors from Table 7 for comparison. Column (2) shows how the standard errors change when bootstrapping at the individual student level rather than clustering at the high school campus by cohort level. Column (3) adds a cubic polynomial in the excluded test score measure to the control set. Column (4) decreases the local regression bandwidth from 40 to 35 miles, and column (5) further reduces it to 30 miles. None of these alternative specifications lead to meaningful changes in the estimates.

Table 9 compares the main estimates to those resulting from other identification approaches. Column (1) transposes the main nonparametric IV estimates from Table 7. Column (2) estimates the controlled OLS specification from Section 3.6 using the same local observation weighting as the main IV specification in column (1). The main diversion IV estimates are meaningfully smaller in magnitude than those implied by controlled OLS, suggesting that unobserved differences between 2-year and 4-year entrants bias the OLS diversion estimates towards larger negative magnitudes. Column (3) presents results from the multivariate 2SLS specification corresponding to this setting:

Table 9: Causal Effect Estimates: Comparisons to Other Approaches

	(1)	(2)	(3)
	Nonparametric IV approach	Controlled OLS	Multivariate 2SLS
Years of schooling			
2-0 Democratization effect	1.72 (.202)	1.48 (.007)	2.21 (.208)
2-4 Diversion effect	-.567 (.339)	-1.34 (.008)	-1.49 (.171)
Bachelor's degree			
2-0 Democratization effect	.257 (.035)	.150 (.001)	.349 (.041)
2-4 Diversion effect	-.184 (.084)	-.356 (.002)	-.358 (.036)
Quarterly earnings			
2-0 Democratization effect	1,323 (544)	1,067 (18)	2,452 (616)
2-4 Diversion effect	-483 (845)	-1,441 (24)	-2,612 (531)
Observations	556,719	556,719	556,719

Notes: Column (1) reproduces the main estimates from Table 7. OLS estimates in column (2) come from the same specification as the controlled OLS regressions described in Section 3.6 and presented in Table 2, but now locally weighted in the same way as the main IV estimates in column (1) to ensure identical samples across the columns, i.e. with an Epanechnikov (parabolic) kernel with 40-mile bandwidth around the mean values of the instruments. Analogously, multivariate 2SLS estimates in column (3) come from the same specification as the just-identified multivariate 2SLS specification described at the end of Section 4.1 and presented in column (1) of Table 3, but now locally weighted in the same way as the main IV estimates in column (1) to ensure identical samples across the columns, i.e. with an Epanechnikov (parabolic) kernel with 40-mile bandwidth around the mean values of the instruments. Standard errors in parentheses are clustered at the high school campus by cohort level. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30.

a 2SLS regression of outcomes on indicators for no college and 4-year entry, yielding democratization versus diversion comparisons relative to the omitted 2-year treatment, using the same instruments, control set, and local observation weighting as the main nonparametric IV approach in column (1). As shown in Appendix B, the multivariate 2SLS estimands fuse together multiple treatment margins across multiple complier subpopulations, making them difficult to interpret when treatment effects are heterogeneous. Under the strong assumption of constant treatment effects across individuals, the estimands of the nonparametric IV approach and the multivariate 2SLS approach would coincide; instead, the substantial differences in the estimates between columns (1) and (3) provide evidence against this homogeneity assumption.

Table 10: Causal Effect Estimates: Women vs. Men

Women							
	$MTE_2$	=	$\omega$	$MTE_{2\leftarrow 0}$	+	$(1 - \omega)$	$MTE_{2\leftarrow 4}$
	Net effect		Democratization share	Democratization effect		Diversion share	Diversion effect
Years of schooling	1.05 (.245)		.649 (.050)	2.04 (.222)		.351 (.050)	-.785 (.355)
Bachelor's degree	.123 (.047)		.649 (.050)	.324 (.043)		.351 (.050)	-.249 (.087)
Quarterly earnings	1,579 (444)		.649 (.050)	2,869 (563)		.351 (.050)	-804 (942)

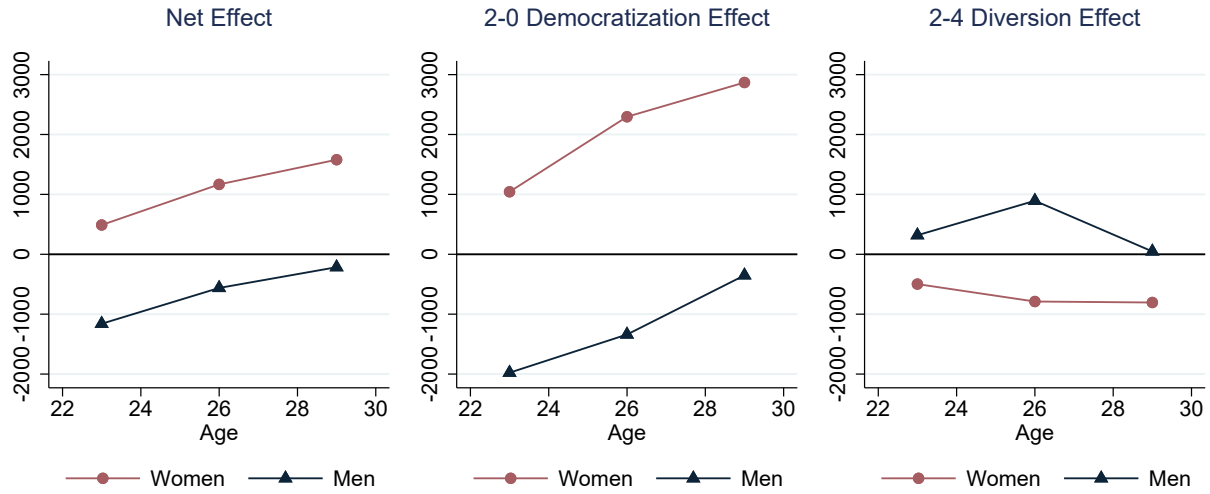
Men							
	$MTE_2$	=	$\omega$	$MTE_{2\leftarrow 0}$	+	$(1 - \omega)$	$MTE_{2\leftarrow 4}$
	Net effect		Democratization share	Democratization effect		Diversion share	Diversion effect
Years of schooling	.784 (.321)		.659 (.065)	1.30 (.302)		.341 (.065)	-.215 (.485)
Bachelor's degree	.082 (.060)		.659 (.065)	.166 (.047)		.341 (.065)	-.080 (.128)
Quarterly earnings	-216 (761)		.659 (.065)	-352 (1,114)		.341 (.065)	48 (1,311)

Notes: Locally weighted observations: 287,976 (women), 268,743 (men). All estimates are evaluated at the mean values of the instruments. Standard errors in parentheses are block bootstrapped at the high school campus by cohort level. Complier shares are the same across outcomes due to common first stage equations. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30.

### 6.3 Heterogeneity by Gender

Table 10 stratifies the main results by gender. Men and women have nearly identical complier shares along each enrollment margin, but the similarities end there: women drive the main results with effects of larger magnitude than men for every outcome along every margin. While men experience positive gains in educational attainment along the 2–0 democratization margin, their 2–4 diversion losses are small and insignificant, and male earnings appear relatively unaffected by 2-year entry along both margins. Women, meanwhile, experience large gains in educational attainment and significant earnings returns to 2-year entry among 2–0 democratization compliers who otherwise would not have attended college, consistent with the large OLS literature documenting a female premium in the returns to 2-year college enrollment relative to nonattendance (Belfield and Bailey, 2011, 2017). Diverted women, on the other hand, experience significant losses in educational attainment and a modestly large (though imprecise) decline in earnings relative to their 4-year

Figure 8: Earnings Effect Profiles by Gender



Notes: This figure plots marginal treatment effect estimates of 2-year entry on quarterly earnings averaged within three different age windows: 22-24, 25-27, and 28-30. All estimates are evaluated at the mean values of the instruments.

entry counterfactual.

To gauge the evolution of male and female earnings effects across the early-career lifecycle, Figure 8 estimates mean quarterly earnings effects separately across the three age windows of 22-24, 25-27, and 28-30 (pooled for greater precision), then plots these estimates to yield dynamic effect profiles by gender. The left and middle panels provide context for the roughly zero earnings effects around age 30 for men on net and along the 2-0 democratization margin, showing that these null effects are actually preceded by negative returns at earlier ages: men on the margin between 2-year entry and no college who do enroll end up taking their entire 20s to overtake the earnings of those who do not enroll. Extrapolating from these profiles suggests that marginal men will start to reap positive returns to 2-year entry in their 30s, while women already begin experiencing positive effects on net and along the democratization margin in the early 20s and enjoy steadily increasing effects over at least the next decade.<sup>48</sup> Concerning the diversion margin, the rightmost panel of Figure 8 shows that the weak earnings effects along the 2-4 diversion margin do not have a detectable age trend, suggesting that diversion impacts on earnings may not grow larger over time.

#### 6.4 Impacts on Disadvantaged Students and Implications for Upward Mobility

Table 11 limits the sample to disadvantaged students, as measured by eligibility for subsidized meals in high school. Low-income students are a key constituency in policy debates over community colleges, since they are disproportionately more likely to enroll in 2-year rather than 4-year institutions and are likely the most sensitive to policies that reduce 2-year entry costs. The second

<sup>48</sup>Recall similar gender differences in the raw earnings profiles of Figure 3. Exploring the mechanisms behind these gender differentials, including mediation through field of study and occupational choice, remains an important avenue for future work.

Table 11: Causal Effect Estimates: Disadvantaged Students

	$MTE_2$ Net effect	=	$\omega$ Democratiz- ation share	+	$MTE_{2\leftarrow 0}$ Democratiz- ation effect	+	$(1 - \omega)$ Diversion share	$MTE_{2\leftarrow 4}$ Diversion effect
Years of schooling	.857 (.279)		.807 (.063)		1.04 (.219)		.193 (.063)	.089 (.982)
Bachelor's degree	.083 (.045)		.807 (.063)		.100 (.033)		.193 (.063)	.014 (.244)
Quarterly earnings	1,371 (692)		.807 (.063)		1,728 (808)		.193 (.063)	-123 (2,254)

Notes: Locally weighted observations: 197,257. Disadvantaged is an indicator for free or reduced price lunch eligibility in 10th grade. All estimates are evaluated at the mean values of the instruments. Standard errors in parentheses are block bootstrapped at the high school campus by cohort level. Complier shares are the same across outcomes due to common first stage equations. Academic outcomes are measured at age 28. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30.

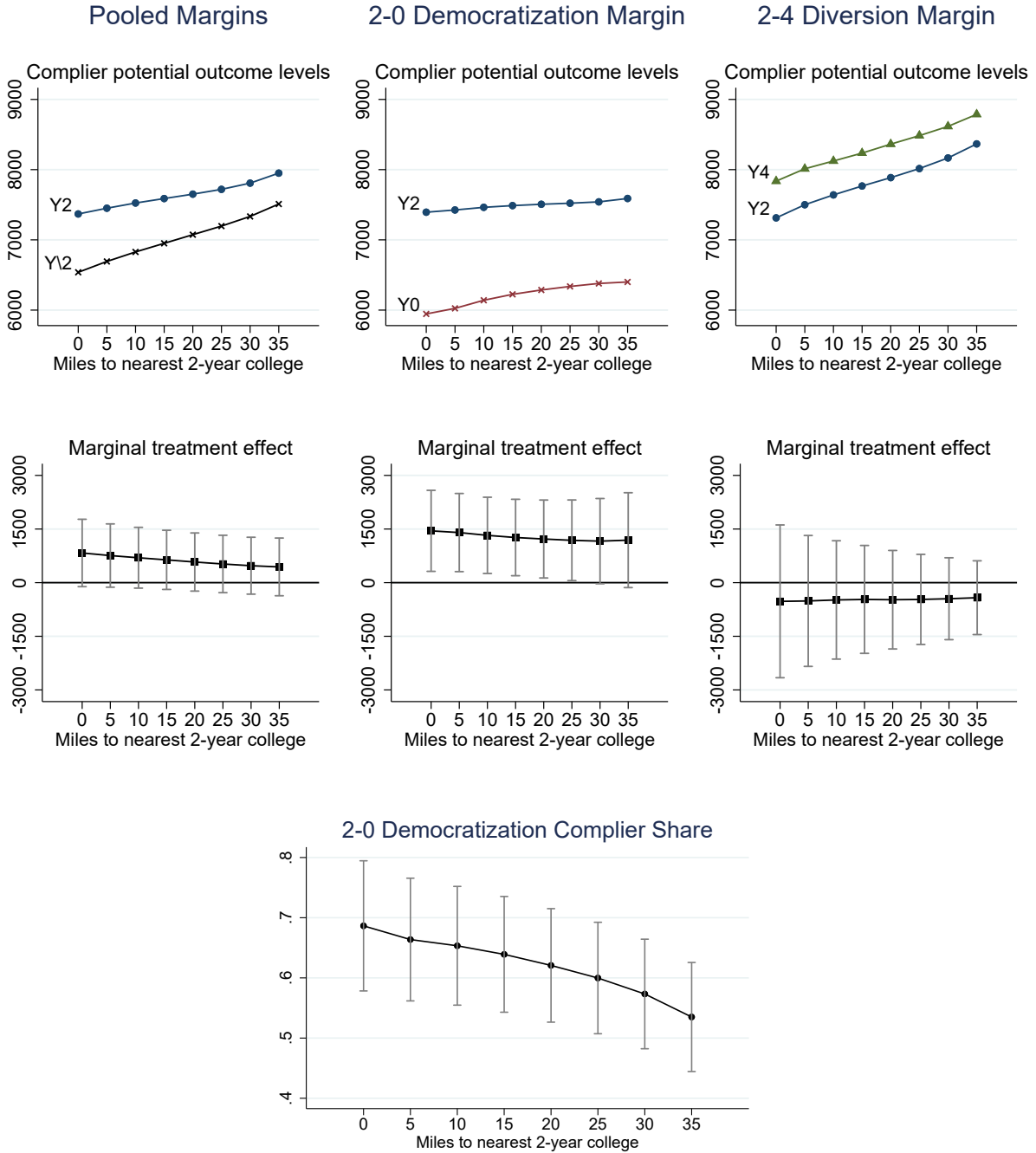
column of Table 11 shows that when 2-year access expands, disadvantaged students are overwhelmingly on the 2–0 democratization margin: 81 percent of disadvantaged students who are induced into 2-year entry thanks to closer access would not have otherwise attended any college, while just 19 percent are diverted from immediate 4-year entry.

The results in the third column of Table 11 show that disadvantaged students “democratized” into higher education along the 2–0 margin experience smaller-than-average gains in educational attainment, but slightly larger-than-average earnings returns. This suggests that 2-year college enrollment may involve other labor market benefits for disadvantaged students beyond modest increases in formal educational attainment, such as better access to employer networks, short course sequences teaching readily-employable skills, and improved job matching. Taken together, these results suggest that boosting the upward earnings mobility of disadvantaged youth need not require large increases in years of formal postsecondary schooling or a narrow focus on bachelor’s degree attainment; simply attracting more disadvantaged students into 2-year colleges may confer meaningful earnings benefits through other channels, and identifying these specific channels remains an important avenue for future work.

## 6.5 Selection Patterns

Stratifying the results across the range of 2-year proximity permits exploration of selection patterns and helps probe the external validity of the local IV estimates. Since the separate identification approach directly identifies complier mean potential outcomes along each treatment margin, Figure 9 first plots these mean potential outcome levels in the top panel, stratifying across the usable support of 2-year distance while holding 4-year distance fixed at its mean. Moving from right to left, as 2-year distance decreases, the mean potential earnings levels of marginally-induced compliers

Figure 9: Selection Patterns



Notes: Each estimate is evaluated at a given 2-year distance value holding 4-year distance fixed at its mean. Quarterly earnings are measured in real 2010 U.S. dollars and averaged within person over ages 28-30. 95 percent confidence intervals are estimated via block bootstrap at the high school campus by cohort level.



decrease along all treatment margins. This selection-on-levels pattern implies that progressive expansions of 2-year college access tend to bring in progressively lower-potential students, with a more pronounced slope on the diversion margin than the democratization margin.

The middle panel of Figure 9 takes differences of the potential outcomes in the top panel to form the marginal treatment effects of interest. The estimates at the mean 2-year distance of 10 miles correspond to the main results in Table 7, while stratifying across other 2-year proximity values permits exploration of selection-on-gains patterns and external validity. The 95 percent confidence intervals cannot reject that the effects along all margins are flat across the usable support of 2-year proximity. If anything, the net effect of 2-year entry increases slightly as 2-year distance decreases over this range, i.e. as 2-year access further increases. This is not driven by meaningful slopes in the 2–0 or 2–4 marginal treatment effects, but rather by a changing composition of marginal compliers: as 2-year distance decreases to the left, the bottom panel of Figure 9 shows that the share of compliers who are on the 2–0 democratization margin increases. The large confidence intervals preclude a precise conclusion, but such a pattern would imply that as 2-year access progressively expands, the net returns increase thanks to a growing share of compliers democratized into higher education from non-enrollment rather than diverted from 4-year college entry.

## 6.6 Policy Simulations

All of the preceding IV estimates are specific to compliers who would change their initial college enrollment behavior in response to changes in college proximities. These estimates can help forecast the consequences of policies that increase students’ physical access to 2-year colleges, like building new campuses in previously underserved areas. With additional assumptions of external validity, these estimates may also help forecast the impacts of a wider range of 2-year access policies, like tuition subsidies or targeted outreach programs. I use the IV estimates to conduct two policy simulations as illustrations towards these ends. First, I remain within the college proximity setting and explore the implications of marginally decreasing 2-year college distance on earnings gaps by gender and by family income. Second, under the additional assumption of external validity of the distance-based estimates, I quantify how the magnitudes, and even signs, of net effects across different 2-year access policies depend crucially on what fraction of policy-induced 2-year entrants are diverted from 4-year college entry.

To carry out the first simulation, consider a decrease in 2-year college distance resulting from building a new local 2-year campus. How does this affect local earnings gaps between men and women, and between students from low-income and higher-income backgrounds?<sup>49</sup> The expected reduced form effect on quarterly earnings among women is a net increase of 7.87 dollars per mile reduction in 2-year distance, while men experience roughly no change in earnings (an insignificant decrease of 78 cents); hence, expanding access to 2-year colleges by decreasing distance serves to reduce the overall gender earnings gap, with larger reductions expected for larger decreases in

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<sup>49</sup>For ease of exposition, all estimates used in the policy simulations in this section are evaluated from the starting point of mean 2-year and 4-year distances, corresponding to the results in previous sections.

distance. The larger reduced form effect for women is driven by both a larger first stage effect (2-year entry is more responsive to 2-year distance for women than men) and a larger marginal treatment effect (marginal women induced into 2-year entry earn a bigger return than marginal men). Similarly, reducing distance to 2-year colleges decreases the overall earnings gap between low-income students (those eligible for subsidized meals in high school) and their higher-income counterparts. The marginal reduced form effect on quarterly earnings among low-income students is a net increase of 6.54 dollars per mile reduction in 2-year distance, while higher-income students gain only about two dollars per mile reduced. Like the gender gap, this reduction in the family income gap is driven both by a larger first stage effect for low-income students and a larger marginal treatment effect.

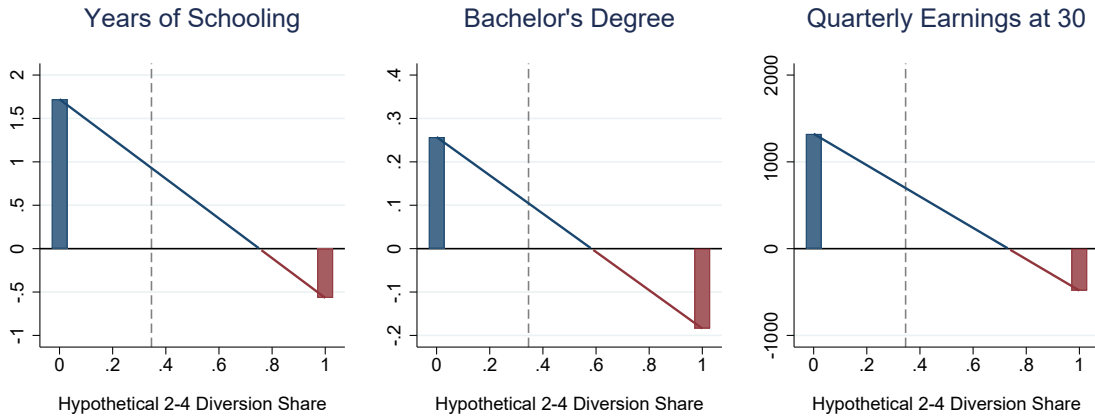
To illustrate the second type of policy simulation, note that the net effects of other policies that expand 2-year college access, beyond proximity changes, are also likely comprised of a share-weighted average of the democratization effect among 2–0 compliers (new 2-year entrants who otherwise would not have enrolled in college) and the diversion effect among 2–4 compliers (new 2-year entrants who otherwise would have started at 4-year institutions). Assuming that the main democratization and diversion treatment effect estimates from Table 7 are externally valid with respect to other policy changes, the net effects of such policies on student outcomes can be forecasted given information on the share of policy compliers who are on the 2–4 diversion margin, which can be calculated from initial policy-induced changes in enrollment shares without waiting years to observe long-run outcomes.<sup>50</sup>

Figure 10 visualizes the entire range of net effects forecasted for different hypothetical policies, with each policy indexed by its diversion share. A hypothetical policy with a diversion share of zero yields a net effect equal to the democratization effect from Table 7, since all compliers would be along the democratization margin; a diversion share of one yields a net effect equal to the diversion effect from Table 7, since all compliers would be along the diversion margin; and every hypothetical policy in between is simply a convex combination of these two effects, with the policy’s diversion share serving as the weight. To take the setting of this paper as an example, the dashed vertical line marks the 35% diversion share corresponding to marginal reductions in 2-year college distance, such that the y-axis value at the intersection of the dashed line and the diagonal solid line equals the net effect estimate reported in Table 7. Another policy example is the Tennessee Promise Program, which (as discussed in the Introduction) began offering free 2-year college tuition to recent Tennessee high school graduates in 2014 and has since spurred a huge number of similar programs across the United States. Figure 11 plots the raw time series patterns of public 2-year and 4-year college enrollment around the implementation of the program. The raw post-policy decrease in 4-year enrollment divided by the increase in 2-year enrollment suggests a diversion share around 30%, which applied to Figure 10 would forecast similar long-run net effects as the distance variation used in this paper.

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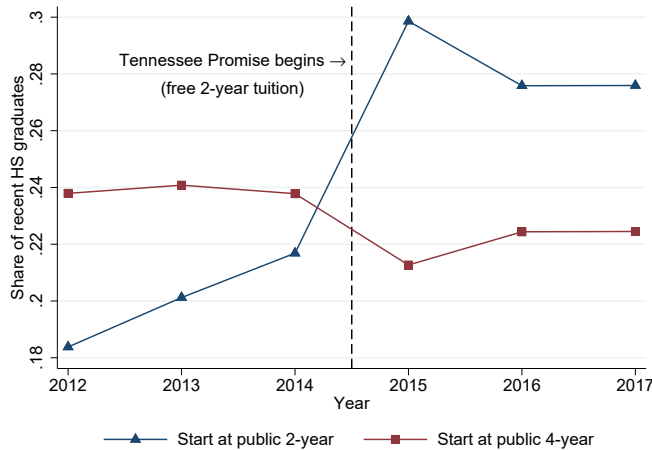
<sup>50</sup>Specifically, as discussed in Section 4.1, the diversion share is identified by the policy-induced reduction in 4-year enrollment as a fraction of the policy-induced increase in 2-year enrollment.

Figure 10: Net Effects of Hypothetical Policies



Notes: This figure plots the net effects of hypothetical 2-year college access policies indexed by their share of compliers who are along the 2-4 diversion margin, assuming the main 2-0 democratization and 2-4 diversion effect estimates in Table 7 are externally valid. A diversion share of zero yields a hypothetical net effect equal to the democratization effect from Table 7; a diversion share of one yields a net effect equal to the diversion effect from Table 7; and every hypothetical policy in between is simply a convex combination of these two effects, weighted by the diversion share. The dashed vertical line marks the 35% diversion share corresponding to marginal reductions in 2-year college distance, such that the y-axis value at the intersection of the dashed line and the diagonal solid line equals the net effect estimate reported in Table 7.

Figure 11: College Enrollment Patterns and the Tennessee Promise Program



Notes: This figure plots enrollment shares in public 2-year and public 4-year colleges among recent high school graduates in Tennessee around the implementation of the Tennessee Promise Program. Data source: Tennessee Higher Education Commission.

Importantly, moving further rightward on the x-axes of Figure 10 suggests the net effects of 2-year access policies begin to turn negative as the diversion share reaches roughly .75, with bachelor's degree completion turning negative even sooner. These hypothetical net effects are inherently speculative and come with many caveats, since they rely on strong assumptions of external validity. More generally, however, Figure 10 offers a useful framework for thinking about the long-run impacts of community college access policies, highlighting the tradeoff between democratizing new students into higher education and diverting college-bound students from direct 4-year entry.

## 7 Conclusion

Policymakers often look to 2-year community colleges as policy levers for extending higher education to a broader share of Americans. This paper has empirically explored the consequences of expanding access to 2-year colleges among students of traditional college-going age, mindful of the potential tradeoff between attracting new students into higher education and diverting those already bound for college away from immediate 4-year enrollment.

Decomposing the net impacts of 2-year college access into effects along these two distinct enrollment margins presents a methodological challenge, since standard instrumental variables methods are not generally equipped to disentangle such effects. I show how a separate identification approach, guided by the flows of different compliers to different instruments, can secure identification of causal effects along these distinct complier margins. I apply the method using linked administrative data spanning the state of Texas, leveraging instrumental variation in 2-year and 4-year college proximities net of controls for local labor markets, neighborhood urbanization, and neighborhood quality. I verify that this residual proximity variation is balanced across excluded test scores that strongly predict enrollment choices and outcomes, and I show that the assumption of comparable compliers along the diversion margin with respect to marginal shifts in 2-year versus 4-year proximity has empirical support through equal mean test scores across these two complier groups.

The empirical results indicate that broadly expanding access to 2-year colleges does boost educational attainment and earnings on net, but decomposing these net effects reveals substantial heterogeneity along several dimensions: students diverted from 4-year entry face lower outcomes, those who would not have otherwise attended college experience large gains, women experience larger effects along both margins compared to men, and disadvantaged students reap large earnings returns to 2-year entry with little offsetting diversion. Taken together, these results suggest that broad expansions of 2-year college access have different implications for the upward mobility of different types of students, leaving open the potential for more targeted policies to achieve equal or greater net impacts with fewer unintended consequences.

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## Appendix: For Online Publication

### A Proof of Binary 2SLS Decomposition

This appendix section derives the binary two-stage least squares (2SLS) decomposition in Equation (2) from Section 4.1, showing that binary 2SLS estimates a weighted average of local average treatment effects along the 2-0 (2-year entry vs. no college) and 2-4 (2-year entry vs. 4-year entry) complier margins.<sup>51</sup> Recall the 2SLS specification:

$$\begin{aligned} Y &= \beta_0 + \beta_2 D_2 + \epsilon \\ D_2 &= \alpha_0 + \alpha_2 Z_2 + \eta, \end{aligned}$$

where  $Y$  is a student outcome,  $D_2$  is an indicator for 2-year college entry, and  $Z_2$  is an exogenous and excludable binary instrument that induces students into 2-year entry from the alternative treatments of no college ( $D_0$ ) and 4-year entry ( $D_4$ ). In this system,  $\beta_2$  is the familiar Wald (1940) estimand:

$$\beta_2 = \frac{E[Y|Z_2 = 1] - E[Y|Z_2 = 0]}{E[D_2|Z_2 = 1] - E[D_2|Z_2 = 0]}.$$

Decompose  $E[Y|Z_2 = 1]$  in the numerator using the fact that  $Y = Y_0 D_0 + Y_2 D_2 + Y_4 D_4$ , where  $Y_j$  is the potential outcome associated with treatment  $j \in \{0, 2, 4\}$ :

$$\begin{aligned} E[Y|Z_2 = 1] &= E[Y_0 D_0 + Y_2 D_2 + Y_4 D_4 | Z_2 = 1] \\ &= E[Y_0 | D_0 = 1, Z_2 = 1] Pr(D_0 = 1 | Z_2 = 1) \\ &\quad + E[Y_2 | D_2 = 1, Z_2 = 1] Pr(D_2 = 1 | Z_2 = 1) \\ &\quad + E[Y_4 | D_4 = 1, Z_2 = 1] Pr(D_4 = 1 | Z_2 = 1). \end{aligned}$$

Letting  $D(z_2) \in \{0, 2, 4\}$  denote the potential choice an individual would make if exogenously assigned to  $Z_2 = z_2 \in \{0, 1\}$ , by instrument independence and exclusion this becomes

$$\begin{aligned} E[Y|Z_2 = 1] &= E[Y_0 | D(1) = 0] Pr(D(1) = 0) \\ &\quad + E[Y_2 | D(1) = 2] Pr(D(1) = 2) \\ &\quad + E[Y_4 | D(1) = 4] Pr(D(1) = 4). \end{aligned}$$

The monotonicity assumption that  $Z_2$  induces students into  $D_2$  from  $D_0$  and  $D_4$  permits the following five complier types:  $\{D(0) = 0, D(1) = 0\}$ ,  $\{D(0) = 0, D(1) = 2\}$ ,  $\{D(0) = 2, D(1) = 2\}$ ,  $\{D(0) = 4, D(1) = 4\}$ , and  $\{D(0) = 4, D(1) = 2\}$ . Hence we can further decompose:

$$\begin{aligned} E[Y|Z_2 = 1] &= E[Y_0 | D(0) = 0, D(1) = 0] Pr(D(0) = 0, D(1) = 0) \\ &\quad + E[Y_2 | D(0) = 0, D(1) = 2] Pr(D(0) = 0, D(1) = 2) \\ &\quad + E[Y_2 | D(0) = 2, D(1) = 2] Pr(D(0) = 2, D(1) = 2) \\ &\quad + E[Y_2 | D(0) = 4, D(1) = 2] Pr(D(0) = 4, D(1) = 2) \\ &\quad + E[Y_4 | D(0) = 4, D(1) = 4] Pr(D(0) = 4, D(1) = 4). \end{aligned}$$

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<sup>51</sup>Heckman and Urzua (2010), Kline and Walters (2016), and Hull (2018) provide related derivations, as do Angrist and Imbens (1995) for the case of ordered multivalued treatments.

These permitted complier types also decompose  $E[Y|Z_2 = 0]$  into

$$\begin{aligned}
E[Y|Z_2 = 0] &= E[Y_0 D_0 | Z_2 = 0] + E[Y_2 D_2 | Z_2 = 0] + E[Y_4 D_4 | Z_2 = 0] \\
&= E[Y_0 | D_0 = 1, Z_2 = 0] Pr(D_0 = 1 | Z_2 = 0) \\
&\quad + E[Y_2 | D_2 = 1, Z_2 = 0] Pr(D_2 = 1 | Z_2 = 0) \\
&\quad + E[Y_4 | D_4 = 1, Z_2 = 0] Pr(D_4 = 1 | Z_2 = 0) \\
&= E[Y_0 | D(0) = 0, D(1) = 0] Pr(D(0) = 0, D(1) = 0) \\
&\quad + E[Y_0 | D(0) = 0, D(1) = 2] Pr(D(0) = 0, D(1) = 2) \\
&\quad + E[Y_2 | D(0) = 2, D(1) = 2] Pr(D(0) = 2, D(1) = 2) \\
&\quad + E[Y_4 | D(0) = 4, D(1) = 4] Pr(D(0) = 4, D(1) = 4) \\
&\quad + E[Y_4 | D(0) = 4, D(1) = 2] Pr(D(0) = 4, D(1) = 2).
\end{aligned}$$

Subtracting  $E[Y|Z_2 = 1] - E[Y|Z_2 = 0]$  eliminates the always-taker and never-taker groups, leaving only the instrument compliers:

$$\begin{aligned}
E[Y|Z_2 = 1] - E[Y|Z_2 = 0] &= E[Y_2 | D(0) = 0, D(1) = 2] Pr(D(0) = 0, D(1) = 2) \\
&\quad - E[Y_0 | D(0) = 0, D(1) = 2] Pr(D(0) = 0, D(1) = 2) \\
&\quad + E[Y_2 | D(0) = 4, D(1) = 2] Pr(D(0) = 4, D(1) = 2) \\
&\quad - E[Y_4 | D(0) = 4, D(1) = 2] Pr(D(0) = 4, D(1) = 2) \\
&= E[Y_2 - Y_0 | D(0) = 0, D(1) = 2] Pr(D(0) = 0, D(1) = 2) \\
&\quad + E[Y_2 - Y_4 | D(0) = 4, D(1) = 2] Pr(D(0) = 4, D(1) = 2).
\end{aligned}$$

To identify the two complier probabilities  $Pr(D(0) = 0, D(1) = 2)$  and  $Pr(D(0) = 4, D(1) = 2)$ , recall from above that independence and monotonicity of the instrument imply

$$\begin{aligned}
Pr(D_0 | Z_2 = 0) &= Pr(D(0) = 0) = Pr(D(0) = 0, D(1) = 0) + Pr(D(0) = 0, D(1) = 2) \\
Pr(D_0 | Z_2 = 1) &= Pr(D(1) = 0) = Pr(D(0) = 0, D(1) = 0) \\
\implies Pr(D_0 | Z_2 = 0) - Pr(D_0 | Z_2 = 1) &= Pr(D(0) = 0, D(1) = 2)
\end{aligned}$$

$$\begin{aligned}
Pr(D_4 | Z_2 = 0) &= Pr(D(0) = 4) = Pr(D(0) = 4, D(1) = 4) + Pr(D(0) = 4, D(1) = 2) \\
Pr(D_4 | Z_2 = 1) &= Pr(D(1) = 4) = Pr(D(0) = 4, D(1) = 4) \\
\implies Pr(D_4 | Z_2 = 0) - Pr(D_4 | Z_2 = 1) &= Pr(D(0) = 4, D(1) = 2).
\end{aligned}$$

This yields

$$\begin{aligned}
E[Y|Z_2 = 1] - E[Y|Z_2 = 0] &= E[Y_2 - Y_0 | D(0) = 0, D(1) = 2] (E[D_0 | Z_2 = 0] - E[D_0 | Z_2 = 1]) \\
&\quad + E[Y_2 - Y_4 | D(0) = 4, D(1) = 2] (E[D_4 | Z_2 = 0] - E[D_4 | Z_2 = 1]),
\end{aligned}$$

and plugging this back into the Wald expression yields the result:

$$\begin{aligned}
\beta_2 &= \frac{E[Y|Z_2 = 1] - E[Y|Z_2 = 0]}{E[D_2 | Z_2 = 1] - E[D_2 | Z_2 = 0]} \\
&= \frac{E[Y_2 - Y_0 | D(0) = 0, D(1) = 2] (E[D_0 | Z_2 = 0] - E[D_0 | Z_2 = 1])}{E[D_2 | Z_2 = 1] - E[D_2 | Z_2 = 0]} \\
&\quad + \frac{E[Y_2 - Y_4 | D(0) = 4, D(1) = 2] (E[D_4 | Z_2 = 0] - E[D_4 | Z_2 = 1])}{E[D_2 | Z_2 = 1] - E[D_2 | Z_2 = 0]} \\
&= \omega E[Y_2 - Y_0 | D(0) = 0, D(1) = 2] + (1 - \omega) E[Y_2 - Y_4 | D(0) = 4, D(1) = 2] \\
&= \omega LATE_{2 \leftarrow 0} + (1 - \omega) LATE_{2 \leftarrow 4},
\end{aligned}$$

where the weights

$$\omega \equiv -\frac{E[D_0|Z_2 = 1] - E[D_0|Z_2 = 0]}{E[D_2|Z_2 = 1] - E[D_2|Z_2 = 0]}, \quad (1 - \omega) = -\frac{E[D_4|Z_2 = 1] - E[D_4|Z_2 = 0]}{E[D_2|Z_2 = 1] - E[D_2|Z_2 = 0]}$$

result from the fact that  $D_0 + D_2 + D_4 = 1$ .

## B What Does Multivariate 2SLS Identify?

This appendix section derives and decomposes the multivariate two-stage least squares (2SLS) estimands in (3) under Assumptions IE, UPM, and CC.<sup>52</sup> For efficient notation, write this specification as

$$\begin{aligned} Y &= \gamma + \beta_0 D_0 + \beta_4 D_4 + \epsilon \\ E[D_0|Z] &= \alpha_0^0 + \alpha_0^2 Z_2 + \alpha_0^4 Z_4 \\ E[D_4|Z] &= \alpha_4^0 + \alpha_4^2 Z_2 + \alpha_4^4 Z_4. \end{aligned}$$

$D_2 = 1$  is the omitted treatment case in the outcome equation, making  $-\beta_0$  comparable to  $MTE_{2 \leftarrow 0}$  and  $-\beta_4$  comparable to  $MTE_{2 \leftarrow 4}$ .  $Z_2$  and  $Z_4$  are continuous, and the entire specification is local to a given evaluation point  $(z_2, z_4)$  such that the linear first stages are arbitrarily close to exact for small partial shifts in  $Z_2$  and  $Z_4$ . Plug these first stage conditional expectations into the reduced form:

$$\begin{aligned} E[Y|Z] &= \gamma + \beta_0(\alpha_0^0 + \alpha_0^2 Z_2 + \alpha_0^4 Z_4) + \beta_4(\alpha_4^0 + \alpha_4^2 Z_2 + \alpha_4^4 Z_4) + E[\epsilon|Z] \\ &= \underbrace{\gamma + \beta_0 \alpha_0^0 + \beta_4 \alpha_4^0}_{\equiv \alpha_y^0} + \underbrace{(\beta_0 \alpha_0^2 + \beta_4 \alpha_4^2)}_{\equiv \alpha_y^2} Z_2 + \underbrace{(\beta_0 \alpha_0^4 + \beta_4 \alpha_4^4)}_{\equiv \alpha_y^4} Z_4 \\ &= \alpha_y^0 + \alpha_y^2 Z_2 + \alpha_y^4 Z_4 \end{aligned}$$

where  $E[\epsilon|Z] = 0$  by Assumption IE. Note that

$$\begin{pmatrix} \alpha_y^2 \\ \alpha_y^4 \end{pmatrix} = \begin{pmatrix} \alpha_0^2 & \alpha_4^2 \\ \alpha_0^4 & \alpha_4^4 \end{pmatrix} \times \begin{pmatrix} \beta_0 \\ \beta_4 \end{pmatrix},$$

so we can solve for  $\beta_0$  and  $\beta_4$  as

$$\begin{aligned} \begin{pmatrix} \beta_0 \\ \beta_4 \end{pmatrix} &= \begin{pmatrix} \alpha_0^2 & \alpha_4^2 \\ \alpha_0^4 & \alpha_4^4 \end{pmatrix}^{-1} \times \begin{pmatrix} \alpha_y^2 \\ \alpha_y^4 \end{pmatrix} = \frac{1}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4} \begin{pmatrix} \alpha_4^4 & -\alpha_4^2 \\ -\alpha_0^4 & \alpha_0^2 \end{pmatrix} \times \begin{pmatrix} \alpha_y^2 \\ \alpha_y^4 \end{pmatrix} \\ \beta_0 &= \frac{\alpha_4^4 \alpha_y^2 - \alpha_4^2 \alpha_y^4}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4}, \quad \beta_4 = \frac{\alpha_0^2 \alpha_y^4 - \alpha_0^4 \alpha_y^2}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4}. \end{aligned}$$

<sup>52</sup>See Kirkeboen et al. (2016) for a related derivation involving discrete instruments, a less restrictive monotonicity condition, and no comparable compliers assumption, which yields more complicated estimands due to additional margins of instrument compliance. See also Kline and Walters (2016) and Hull (2018) for related derivations involving one binary instrument interacted with a stratifying covariate.

Using the complier mean potential outcome identification results of Section 4.4, we can decompose the reduced form w.r.t.  $Z_2$  into

$$\begin{aligned}
\alpha_y^2 &= \frac{\partial E[Y|Z]}{\partial Z_2} = \frac{\partial E[YD_0|Z]}{\partial Z_2} + \frac{\partial E[YD_2|Z]}{\partial Z_2} + \frac{\partial E[YD_4|Z]}{\partial Z_2} \\
&= E[Y_0|2-0] \frac{\partial E[D_0|Z]}{\partial Z_2} + E[Y_2|2-0] \left( -\frac{\partial E[D_0|Z]}{\partial Z_2} \right) + E[Y_2|2-4] \left( -\frac{\partial E[D_4|Z]}{\partial Z_2} \right) + E[Y_4|2-4] \frac{\partial E[D_4|Z]}{\partial Z_2} \\
&= -\frac{\partial E[D_0|Z]}{\partial Z_2} (E[Y_2|2-0] - E[Y_0|2-0]) - \frac{\partial E[D_4|Z]}{\partial Z_2} (E[Y_2|2-4] - E[Y_4|2-4]) \\
&= -\alpha_0^2 MTE_{2\leftarrow 0} - \alpha_4^2 MTE_{2\leftarrow 4}
\end{aligned}$$

where  $E[Y_0|2-0]$ , for example, is shorthand for

$$\lim_{z_2' \uparrow z_2} E[Y_0|D(z_2', z_4) = 2, D(z_2, z_4) = 0] = E[Y_0|\text{Marginal 2-0 complier w.r.t. } Z_2 \text{ at } (z_2, z_4)],$$

and dependence on the local evaluation point  $(z_2, z_4)$  is suppressed in the notation of each element. Likewise with respect to  $Z_4$ , we have

$$\begin{aligned}
\alpha_y^4 &= \frac{\partial E[Y|Z]}{\partial Z_4} = \frac{\partial E[YD_0|Z]}{\partial Z_4} + \frac{\partial E[YD_2|Z]}{\partial Z_4} + \frac{\partial E[YD_4|Z]}{\partial Z_4} \\
&= E[Y_0|4-0] \frac{\partial E[D_0|Z]}{\partial Z_4} + E[Y_2|2-4 \text{ w.r.t. } Z_4] \frac{\partial E[D_2|Z]}{\partial Z_4} \\
&\quad + E[Y_4|2-4 \text{ w.r.t. } Z_4] \left( -\frac{\partial E[D_2|Z]}{\partial Z_4} \right) + E[Y_4|4-0] \left( -\frac{\partial E[D_0|Z]}{\partial Z_4} \right)
\end{aligned}$$

where  $E[Y_0|4-0]$ , for example, is shorthand for

$$\lim_{z_4' \uparrow z_4} E[Y_0|D(z_2, z_4') = 4, D(z_2, z_4) = 0] = E[Y_0|\text{Marginal 4-0 complier w.r.t. } Z_4 \text{ at } (z_2, z_4)].$$

By Assumption CC, we can equate  $E[Y_2|2-4 \text{ w.r.t. } Z_4] = E[Y_2|2-4 \text{ w.r.t. } Z_2]$  at a given evaluation point and thus write this mean complier potential outcome in shorthand as  $E[Y_2|2-4]$ . Assumption CC in the main text is silent about the relationship between  $E[Y_4|2-4 \text{ w.r.t. } Z_4]$  and  $E[Y_4|2-4 \text{ w.r.t. } Z_2]$ , however, since no restrictions are needed on these  $Y_4$  potential outcomes to secure identification of the desired treatment effects in the separate identification approach of this paper. To simplify the 2SLS decomposition, however, let us make a slightly stronger comparable compliers assumption and equate these mean  $Y_4$  potential outcomes across 2-4 compliers w.r.t.  $Z_2$  vs.  $Z_4$ , as with  $Y_2$ . Hence we equate  $E[Y_4|2-4 \text{ w.r.t. } Z_4] = E[Y_4|2-4 \text{ w.r.t. } Z_2] \equiv E[Y_4|2-4]$ , which simplifies the expression for  $\alpha_y^4$  to

$$\begin{aligned}
\alpha_y^4 &= -\frac{\partial E[D_0|Z]}{\partial Z_4} (E[Y_4|4-0] - E[Y_0|4-0]) + \frac{\partial E[D_2|Z]}{\partial Z_4} (E[Y_2|2-4] - E[Y_4|2-4]) \\
&= -\alpha_0^4 MTE_{4\leftarrow 0} - (\alpha_0^4 + \alpha_4^4) MTE_{2\leftarrow 4},
\end{aligned}$$

again suppressing dependence on the local evaluation point  $(z_2, z_4)$  and using the fact that

$$\frac{\partial E[D_2|Z]}{\partial Z_4} = \frac{\partial E[1 - D_0 - D_4|Z]}{\partial Z_4} = -\frac{\partial E[D_0|Z]}{\partial Z_4} - \frac{\partial E[D_4|Z]}{\partial Z_4} = -\alpha_0^4 - \alpha_4^4.$$

Plugging these results into the expressions above for  $\beta_0$  and  $\beta_4$  yields:

$$\begin{aligned}\beta_0 &= \frac{\alpha_4^4(-\alpha_0^2 MTE_{2\leftarrow 0} - \alpha_4^2 MTE_{2\leftarrow 4}) - \alpha_4^2(-\alpha_0^4 MTE_{4\leftarrow 0} - (\alpha_0^4 + \alpha_4^4)MTE_{2\leftarrow 4})}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4} \\ &= -\frac{\alpha_0^2 \alpha_4^4 MTE_{2\leftarrow 0} - \alpha_4^2 \alpha_0^4 (MTE_{4\leftarrow 0} + MTE_{2\leftarrow 4})}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4}, \\ \beta_4 &= \frac{\alpha_0^2(-\alpha_0^4 MTE_{4\leftarrow 0} - (\alpha_0^4 + \alpha_4^4)MTE_{2\leftarrow 4}) - \alpha_0^4(-\alpha_0^2 MTE_{2\leftarrow 0} - \alpha_4^2 MTE_{2\leftarrow 4})}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4} \\ &= -\frac{(\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4 + \alpha_0^2 \alpha_0^4)MTE_{2\leftarrow 4} + (-\alpha_0^2 \alpha_0^4)(MTE_{2\leftarrow 0} - MTE_{4\leftarrow 0})}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4}.\end{aligned}$$

Finally, defining the weights

$$\theta_0 \equiv \frac{\alpha_0^2 \alpha_4^4}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4}, \quad \theta_4 \equiv \frac{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4 + \alpha_0^2 \alpha_0^4}{\alpha_0^2 \alpha_4^4 - \alpha_4^2 \alpha_0^4}$$

yields the main result of this appendix section:

$$\begin{aligned}-\beta_0 &= \theta_0 MTE_{2\leftarrow 0} + (1 - \theta_0)(MTE_{4\leftarrow 0} + MTE_{2\leftarrow 4}) \\ -\beta_4 &= \theta_4 MTE_{2\leftarrow 4} + (1 - \theta_4)(MTE_{2\leftarrow 0} - MTE_{4\leftarrow 0}).\end{aligned}$$

Each local multivariate 2SLS estimand in this setting is thus a linear combination of the marginal treatment effect of interest and a biasing term involving effects for compliers along the other two treatment margins. In the special case of constant treatment effects across all individuals, note that  $MTE_{4\leftarrow 0} + MTE_{2\leftarrow 4} = (Y_4 - Y_0) + (Y_2 - Y_4) = Y_2 - Y_0$  and  $MTE_{2\leftarrow 0} - MTE_{4\leftarrow 0} = (Y_2 - Y_0) - (Y_4 - Y_0) = Y_2 - Y_4$ , which confirms that 2SLS identifies the effects of interest in the absence of effect heterogeneity. With heterogeneous effects, however,  $MTE_{4\leftarrow 0} + MTE_{2\leftarrow 4} \neq MTE_{2\leftarrow 0}$  and  $MTE_{2\leftarrow 0} - MTE_{4\leftarrow 0} \neq MTE_{2\leftarrow 4}$  in general, since each of these treatment effects conditions on a different complier subpopulation. Each multivariate 2SLS estimand therefore does not generally recover a well-defined treatment effect for any well-defined complier population.

## C Proofs for Section 4.4

This appendix section proves the identification results in (5), (6), (7), and (8) from Section 4.4. Consider a decrease in  $Z_2$  from  $z_2$  to  $z'_2$  while holding  $Z_4$  fixed at  $z_4$ . By Assumption UPM, this induces  $2\leftarrow 0$  and  $2\leftarrow 4$  compliers. Changes in  $D_0$  with respect to this shift therefore must be driven by  $2\leftarrow 0$  compliers, and changes in  $D_4$  must be driven by  $2\leftarrow 4$  compliers. To prove (5):

$$\begin{aligned}E[YD_0|z_2, z_4] &= E[Y_0|D_0 = 1, z_2, z_4]Pr[D_0 = 1|z_2, z_4] \\ &= E[Y_0|D(z_2, z_4) = 0]Pr[D(z_2, z_4) = 0] \\ &= [E[Y_0|D(z'_2, z_4) = 0, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 0|D(z_2, z_4) = 0] \\ &\quad + E[Y_0|D(z'_2, z_4) = 2, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 2|D(z_2, z_4) = 0]]Pr[D(z_2, z_4) = 0] \\ &= E[Y_0|D(z'_2, z_4) = 0, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 0, D(z_2, z_4) = 0] \\ &\quad + E[Y_0|D(z'_2, z_4) = 2, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0],\end{aligned}$$

where the second equation is due to Assumption IE and the third equation decomposes the mass of individuals with  $D(z_2, z_4) = 0$  into the complier groups w.r.t.  $(z'_2, z_4) \leftarrow (z_2, z_4)$  allowed by Assumption UPM. Likewise, Assumptions IE and UPM imply

$$\begin{aligned}E[YD_0|z'_2, z_4] &= E[Y_0|D(z'_2, z_4) = 0]Pr[D(z'_2, z_4) = 0] \\ &= E[Y_0|D(z'_2, z_4) = 0, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 0, D(z_2, z_4) = 0].\end{aligned}$$

Hence

$$\begin{aligned} & E[YD_0|z'_2, z_4] - E[YD_0|z_2, z_4] \\ &= - E[Y_0|D(z'_2, z_4) = 2, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0]. \end{aligned}$$

The main text showed that

$$Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0] = - (Pr[D = 0|z'_2, z_4] - Pr[D = 0|z_2, z_4]),$$

yielding (5):

$$\begin{aligned} \frac{E[YD_0|z'_2, z_4] - E[YD_0|z_2, z_4]}{E[D_0|z'_2, z_4] - E[D_0|z_2, z_4]} &= E[Y_0|D(z'_2, z_4) = 2, D(z_2, z_4) = 0] \\ &\equiv E[Y_0|2 \leftarrow 0 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]. \end{aligned}$$

We can proceed analogously for  $D_4$ :

$$\begin{aligned} E[YD_4|z_2, z_4] &= E[Y_4|D(z_2, z_4) = 4]Pr[D(z_2, z_4) = 4] \\ &= (E[Y_4|D(z'_2, z_4) = 4, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 4|D(z_2, z_4) = 4] \\ &\quad + E[Y_4|D(z'_2, z_4) = 2, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 2|D(z_2, z_4) = 4])Pr[D(z_2, z_4) = 4] \\ &= E[Y_4|D(z'_2, z_4) = 4, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 4, D(z_2, z_4) = 4] \\ &\quad + E[Y_4|D(z'_2, z_4) = 2, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 4] \end{aligned}$$

$$\begin{aligned} E[YD_4|z'_2, z_4] &= E[Y_4|D(z'_2, z_4) = 4]Pr[D(z'_2, z_4) = 4] \\ &= E[Y_4|D(z'_2, z_4) = 4, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 4, D(z_2, z_4) = 4] \end{aligned}$$

$$\begin{aligned} E[YD_4|z'_2, z_4] - E[YD_4|z_2, z_4] &= - E[Y_4|D(z'_2, z_4) = 2, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 4] \\ &= E[Y_4|D(z'_2, z_4) = 2, D(z_2, z_4) = 4] (Pr[D(z'_2, z_4) = 4] - Pr[D(z_2, z_4) = 4]), \end{aligned}$$

which yields (6):

$$\begin{aligned} \frac{E[YD_4|z'_2, z_4] - E[YD_4|z_2, z_4]}{E[D_4|z'_2, z_4] - E[D_4|z_2, z_4]} &= E[Y_4|D(z'_2, z_4) = 2, D(z_2, z_4) = 4] \\ &\equiv E[Y_4|2 \leftarrow 4 \text{ complier w.r.t. } (z'_2, z_4) \leftarrow (z_2, z_4)]. \end{aligned}$$

Turning to  $D_2$ ,

$$\begin{aligned} E[YD_2|z_2, z_4] &= E[Y_2|D(z_2, z_4) = 2]Pr[D(z_2, z_4) = 2] \\ &= E[Y_2|D(z'_2, z_4) = 2, D(z_2, z_4) = 2]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 2] \end{aligned}$$

$$\begin{aligned} E[YD_2|z'_2, z_4] &= E[Y_2|D(z'_2, z_4) = 2]Pr[D(z'_2, z_4) = 2] \\ &= E[Y_2|D(z'_2, z_4) = 2, D(z_2, z_4) = 2]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 2] \\ &\quad + E[Y_2|D(z'_2, z_4) = 2, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0] \\ &\quad + E[Y_2|D(z'_2, z_4) = 2, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 4], \end{aligned}$$

which yields the pooled expression in (7):

$$\begin{aligned} E[YD_2|z'_2, z_4] - E[YD_2|z_2, z_4] &= E[Y_2|D(z'_2, z_4) = 2, D(z_2, z_4) = 0]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 0] \\ &\quad + E[Y_2|D(z'_2, z_4) = 2, D(z_2, z_4) = 4]Pr[D(z'_2, z_4) = 2, D(z_2, z_4) = 4]. \end{aligned}$$



Finally, we turn to  $Z_4$ . From the same initial evaluation point  $(z_2, z_4)$ , consider an increase in  $Z_4$  from  $z_4$  to  $z'_4$ , while holding  $Z_2$  fixed at  $z_2$ . By Assumption UPM, this induces  $2 \leftarrow 4$  and  $0 \leftarrow 4$  compliers. Changes in  $D_2$  with respect to this shift therefore must only involve  $2 \leftarrow 4$  compliers:

$$\begin{aligned} E[YD_2|z_2, z_4] &= E[Y_2|D(z_2, z_4) = 2]Pr[D(z_2, z_4) = 2] \\ &= E[Y_2|D(z_2, z'_4) = 2, D(z_2, z_4) = 2]Pr[D(z_2, z'_4) = 2, D(z_2, z_4) = 2] \end{aligned}$$

$$\begin{aligned} E[YD_2|z_2, z'_4] &= E[Y_2|D(z_2, z'_4) = 2]Pr[D(z_2, z'_4) = 2] \\ &= E[Y_2|D(z_2, z'_4) = 2, D(z_2, z_4) = 2]Pr[D(z_2, z'_4) = 2, D(z_2, z_4) = 2] \\ &\quad + E[Y_2|D(z_2, z'_4) = 2, D(z_2, z_4) = 4]Pr[D(z_2, z'_4) = 2, D(z_2, z_4) = 4] \end{aligned}$$

$$\begin{aligned} E[YD_2|z_2, z'_4] - E[YD_2|z_2, z_4] &= E[Y_2|D(z_2, z'_4) = 2, D(z_2, z_4) = 4]Pr[D(z_2, z'_4) = 2, D(z_2, z_4) = 4] \\ &= E[Y_2|D(z_2, z'_4) = 2, D(z_2, z_4) = 4] (Pr[D(z_2, z'_4) = 2] - Pr[D(z_2, z_4) = 2]), \end{aligned}$$

which yields (8):

$$\begin{aligned} \frac{E[YD_2|z_2, z'_4] - E[YD_2|z_2, z_4]}{E[D_2|z_2, z'_4] - E[D_2|z_2, z_4]} &= E[Y_2|D(z_2, z'_4) = 2, D(z_2, z_4) = 4] \\ &\equiv E[Y_2|2 \leftarrow 4 \text{ complier w.r.t. } (z_2, z'_4) \leftarrow (z_2, z_4)]. \end{aligned}$$

## D The Index Model Is Sufficient for Assumptions UPM and CC

This appendix section shows how the index model in Section 4.3 satisfies Assumptions UPM and CC, such that the more general identification results in Section 4.4 also result in the index model as a special case. Recall the choice equations from (4):

$$\begin{aligned} D_0(z_2, z_4) &= \mathbf{1}[U_2 < \mu_2(z_2), U_4 < \mu_4(z_4)] \\ D_2(z_2, z_4) &= \mathbf{1}[U_2 > \mu_2(z_2), U_4 - U_2 < \mu_4(z_4) - \mu_2(z_2)] \\ D_4(z_2, z_4) &= \mathbf{1}[U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4) - \mu_2(z_2)]. \end{aligned}$$

### D.1 Assumption UPM

To prove that the first part of Assumption UPM holds in this model, fix an arbitrary base point  $(z_2, z_4)$  and consider a decrease in  $Z_2$  to  $z'_2 < z_2$  while holding  $Z_4$  fixed at  $z_4$ . We must show that  $D_0(z'_2, z_4) \leq D_0(z_2, z_4)$ ,  $D_2(z'_2, z_4) \geq D_2(z_2, z_4)$ , and  $D_4(z'_2, z_4) \leq D_4(z_2, z_4)$  for all individuals, with each inequality holding strictly for at least some individuals.

By (4), whether an individual would choose a given treatment at a given instrument value depends entirely on her values of  $(U_2, U_4)$ . We can therefore completely characterize the set of individuals with  $D_0(z_2, z_4) = 1$  as  $\mathcal{I}_0(z_2, z_4) = \{(U_2, U_4) : U_2 < \mu_2(z_2), U_4 < \mu_4(z_4)\}$ , and the set of individuals with  $D_0(z'_2, z_4) = 1$  as  $\mathcal{I}_0(z'_2, z_4) = \{(U_2, U_4) : U_2 < \mu_2(z'_2), U_4 < \mu_4(z_4)\}$ . Since  $\mu_2(\cdot)$  is strictly increasing, any individual satisfying  $U_2 < \mu_2(z'_2)$  also satisfies  $U_2 < \mu_2(z_2)$ , which implies  $\mathcal{I}_0(z'_2, z_4) \subset \mathcal{I}_0(z_2, z_4)$  and thus  $D_0(z'_2, z_4) \leq D_0(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $2 \leftarrow 0$  compliers with  $\{(U_2, U_4) : U_2 \in (\mu_2(z'_2), \mu_2(z_2)), U_4 < \mu_4(z_4)\}$ .

Those choosing  $D_2(z_2, z_4) = 1$  are  $\mathcal{I}_2(z_2, z_4) = \{(U_2, U_4) : U_2 > \mu_2(z_2), U_4 - U_2 < \mu_4(z_4) - \mu_2(z_2)\}$ . Likewise  $\mathcal{I}_2(z'_2, z_4) = \{(U_2, U_4) : U_2 > \mu_2(z'_2), U_4 - U_2 < \mu_4(z_4) - \mu_2(z'_2)\}$ . Since  $\mu_2(\cdot)$  is strictly increasing, any individual satisfying  $U_2 > \mu_2(z_2)$  also satisfies  $U_2 > \mu_2(z'_2)$ , and any individual satisfying  $U_4 - U_2 < \mu_4(z_4) - \mu_2(z_2)$  also satisfies  $U_4 - U_2 < \mu_4(z_4) - \mu_2(z'_2)$ , which implies  $\mathcal{I}_2(z_2, z_4) \subset \mathcal{I}_2(z'_2, z_4)$  and thus  $D_2(z'_2, z_4) \geq D_2(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $2 \leftarrow 0$  compliers with  $\{(U_2, U_4) : U_2 \in (\mu_2(z'_2), \mu_2(z_2)), U_4 < \mu_4(z_4)\}$  and  $2 \leftarrow 4$  compliers with  $\{(U_2, U_4) : U_4 - U_2 \in (\mu_4(z_4) - \mu_2(z_2), \mu_4(z_4) - \mu_2(z'_2)), U_4 > \mu_4(z_4)\}$ .

Those choosing  $D_4(z_2, z_4) = 1$  are  $\mathcal{I}_4(z_2, z_4) = \{(U_2, U_4) : U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4) - \mu_2(z_2)\}$ . Likewise  $\mathcal{I}_4(z'_2, z_4) = \{(U_2, U_4) : U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4) - \mu_2(z'_2)\}$ . Since  $\mu_2(\cdot)$  is strictly increasing, any individual satisfying  $U_4 - U_2 > \mu_4(z_4) - \mu_2(z'_2)$  also satisfies  $U_4 - U_2 > \mu_4(z_4) - \mu_2(z_2)$ , which implies  $\mathcal{I}_4(z'_2, z_4) \subset \mathcal{I}_4(z_2, z_4)$  and thus  $D_4(z'_2, z_4) \leq D_4(z_2, z_4)$  for all individuals, with the inequality holding strictly for 2 $\leftarrow$ 4 compliers with  $\{(U_2, U_4) : U_4 - U_2 \in (\mu_4(z_4) - \mu_2(z_2), \mu_4(z_4) - \mu_2(z'_2)), U_4 > \mu_4(z_4)\}$ .

To prove that the second part of Assumption UPM holds in this model, fix an arbitrary base point  $(z_2, z_4)$  and consider an increase in  $Z_4$  to  $z'_4 > z_4$  (to match the direction of the visualized shift in Figure 4) while holding  $Z_2$  fixed at  $z_2$ . We must show that  $D_0(z_2, z'_4) \geq D_0(z_2, z_4)$ ,  $D_2(z_2, z'_4) \geq D_2(z_2, z_4)$ , and  $D_4(z_2, z'_4) \leq D_4(z_2, z_4)$  for all individuals, with each inequality holding strictly for at least some individuals.

Those choosing  $D_0(z_2, z'_4) = 1$  are  $\mathcal{I}_0(z_2, z'_4) = \{(U_2, U_4) : U_2 < \mu_2(z_2), U_4 < \mu_4(z'_4)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 < \mu_4(z_4)$  also satisfies  $U_4 < \mu_4(z'_4)$ , which implies  $\mathcal{I}_0(z_2, z_4) \subset \mathcal{I}_0(z_2, z'_4)$  and thus  $D_0(z_2, z'_4) \geq D_0(z_2, z_4)$  for all individuals, with the inequality holding strictly for 0 $\leftarrow$ 4 compliers with  $\{(U_2, U_4) : U_2 < \mu_2(z_2), U_4 \in (\mu_4(z_4), \mu_4(z'_4))\}$ .

Those choosing  $D_2(z_2, z'_4) = 1$  are  $\mathcal{I}_2(z_2, z'_4) = \{(U_2, U_4) : U_2 > \mu_2(z_2), U_4 - U_2 < \mu_4(z'_4) - \mu_2(z_2)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 - U_2 < \mu_4(z_4) - \mu_2(z_2)$  also satisfies  $U_4 - U_2 < \mu_4(z'_4) - \mu_2(z_2)$ , which implies  $\mathcal{I}_2(z_2, z_4) \subset \mathcal{I}_2(z_2, z'_4)$  and thus  $D_2(z_2, z'_4) \geq D_2(z_2, z_4)$  for all individuals, with the inequality holding strictly for 2 $\leftarrow$ 4 compliers with  $\{(U_2, U_4) : U_2 > \mu_2(z_2), U_4 - U_2 \in (\mu_4(z_4) - \mu_2(z_2), \mu_4(z'_4) - \mu_2(z_2))\}$ .

Those choosing  $D_4(z_2, z'_4) = 1$  are  $\mathcal{I}_4(z_2, z'_4) = \{(U_2, U_4) : U_4 > \mu_4(z'_4), U_4 - U_2 > \mu_4(z'_4) - \mu_2(z_2)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 > \mu_4(z'_4)$  also satisfies  $U_4 > \mu_4(z_4)$ , and any individual satisfying  $U_4 - U_2 > \mu_4(z'_4) - \mu_2(z_2)$  also satisfies  $U_4 - U_2 > \mu_4(z_4) - \mu_2(z_2)$ , which implies  $\mathcal{I}_4(z_2, z'_4) \subset \mathcal{I}_4(z_2, z_4)$  and thus  $D_4(z_2, z'_4) \leq D_4(z_2, z_4)$  for all individuals, with the inequality holding strictly for 0 $\leftarrow$ 4 compliers with  $\{(U_2, U_4) : U_2 < \mu_2(z_2), U_4 \in (\mu_4(z_4), \mu_4(z'_4))\}$  and 2 $\leftarrow$ 4 compliers with  $\{(U_2, U_4) : U_2 > \mu_2(z_2), U_4 - U_2 \in (\mu_4(z_4) - \mu_2(z_2), \mu_4(z'_4) - \mu_2(z_2))\}$ . This proves that the index model in (4) is sufficient for Assumption UPM.

## D.2 Assumption CC

To prove that the index model is sufficient for Assumption CC, first consider the left side of Assumption CC, which in the index model translates to

$$\begin{aligned} \lim_{z'_2 \uparrow z_2} E[Y_2 | D(z'_2, z_4) = 2, D(z_2, z_4) = 4] &= \lim_{z'_2 \uparrow z_2} E[Y_2 | U_4 - U_2 \in (\mu_4(z_4) - \mu_2(z_2), \mu_4(z_4) - \mu_2(z'_2)), U_4 > \mu_4(z_4)] \\ &= E[Y_2 | U_4 - U_2 = \mu_4(z_4) - \mu_2(z_2), U_4 > \mu_4(z_4)], \end{aligned} \quad (16)$$

where exact indifference with  $U_4 - U_2 = \mu_4(z_4) - \mu_2(z_2)$  is assumed to be decided in favor of  $D(z_2, z_4) = 4$ . Now consider the right side of Assumption CC, which in the index model translates to

$$\begin{aligned} \lim_{z'_4 \downarrow z_4} E[Y_2 | D(z_2, z'_4) = 2, D(z_2, z_4) = 4] &= \lim_{z'_4 \downarrow z_4} E[Y_2 | U_4 - U_2 \in (\mu_4(z_4) - \mu_2(z_2), \mu_4(z'_4) - \mu_2(z_2)), U_2 > \mu_2(z_2)] \\ &= E[Y_2 | U_4 - U_2 = \mu_4(z_4) - \mu_2(z_2), U_2 > \mu_2(z_2)]. \end{aligned} \quad (17)$$

The conditioning set in (16) can be written as  $U_4 = U_2 + \mu_4(z_4) - \mu_2(z_2) > \mu_4(z_4)$ , which implies  $U_2 > \mu_2(z_2)$ . Hence a verbose version of (16) is  $E[Y_2 | U_4 - U_2 = \mu_4(z_4) - \mu_2(z_2), U_2 > \mu_2(z_2), U_4 > \mu_4(z_4)]$ . The conditioning set in (17) can be written as  $U_2 = U_4 - \mu_4(z_4) + \mu_2(z_2) > \mu_2(z_2)$ , which implies  $U_4 > \mu_4(z_4)$ . Hence a verbose version of (17) is  $E[Y_2 | U_4 - U_2 = \mu_4(z_4) - \mu_2(z_2), U_2 > \mu_2(z_2), U_4 > \mu_4(z_4)]$ . Therefore

$$\begin{aligned} \lim_{z'_2 \uparrow z_2} E[Y_2 | D(z'_2, z_4) = 2, D(z_2, z_4) = 4] &= [Y_2 | U_4 - U_2 = \mu_4(z_4) - \mu_2(z_2), U_2 > \mu_2(z_2), U_4 > \mu_4(z_4)] \\ &= \lim_{z'_4 \downarrow z_4} E[Y_2 | D(z_2, z'_4) = 2, D(z_2, z_4) = 4], \end{aligned}$$

i.e. the index model is sufficient for Assumption CC.

## E A Nonseparable Model Satisfying Assumptions UPM and CC

This appendix section shows that the converse of the previous appendix section does not hold: the index model in Section 4.3 is not necessary for Assumptions UPM and CC. I consider a nonseparable model that strictly nests (4) and no longer satisfies the two-dimensional visualization in Figure 4, but still satisfies Assumptions UPM and CC.

The key generalization from the separable index model in (4) will be to allow for unobservable individual-level heterogeneity in the cost (instrument response) functions, i.e. nonseparability. As a useful preamble, however, note that (4) can accommodate such heterogeneity if it affects both  $\mu_2(\cdot)$  and  $\mu_4(\cdot)$  with equal sign and magnitude. To see this, consider the following variation on the index model,

$$\begin{aligned} I_0 &= 0 \\ I_2 &= U_2 - V\mu_2(Z_2) \\ I_4 &= U_4 - V\mu_4(Z_4), \end{aligned} \tag{18}$$

where  $V > 0$  is a random variable that varies unobservably across individuals. This implies the choice equations

$$\begin{aligned} D_0(z_2, z_4) &= \mathbb{1}[U_2 < V\mu_2(z_2), U_4 < V\mu_4(z_4)] \\ D_2(z_2, z_4) &= \mathbb{1}[U_2 > V\mu_2(z_2), U_4 - U_2 < V\mu_4(z_4) - V\mu_2(z_2)] \\ D_4(z_2, z_4) &= \mathbb{1}[U_4 > V\mu_4(z_4), U_4 - U_2 > V\mu_4(z_4) - V\mu_2(z_2)]. \end{aligned}$$

By dividing through by  $V > 0$ , we can see that this model is isomorphic to a separable index model given by

$$\begin{aligned} \tilde{I}_0 &= 0 \\ \tilde{I}_2 &= \tilde{U}_2 - \mu_2(Z_2) \\ \tilde{I}_4 &= \tilde{U}_4 - \mu_4(Z_4), \end{aligned}$$

where each tilde'd variable is its original value in (18) divided by  $V$ . Since dividing by  $V > 0$  preserves each individual's relative ranking of  $I_0$ ,  $I_2$ , and  $I_4$  for every given instrument value  $(z_2, z_4)$ , the model in (18) is weakly separable, i.e. it can be renormalized as a separable model yielding identical choice behavior.

What is important in strictly generalizing from (4), then, is that the unobserved heterogeneity in instrument responses be differential across  $\mu_2(\cdot)$  and  $\mu_4(\cdot)$ . Thus consider the following model,

$$\begin{aligned} I_0 &= 0 \\ I_2 &= U_2 - V_2\mu_2(Z_2) \\ I_4 &= U_4 - V_4\mu_4(Z_4), \end{aligned}$$

where  $V_2 > 0$  and  $V_4 > 0$  are random variables that vary unobservably across individuals. This model nests the weakly separable case above as  $V_2 = V_4 = V$ , and it nests (4) as  $V_2 = V_4 = 1$ . Unlike those models, however, this one does not generally admit a separable representation when  $V_2 \neq V_4$ . Dividing through by  $V_4 > 0$ , for example, still leaves the following nonseparable representation that we will work with for the remainder of this section, with some abuse of notation that redefines the quantities divided by  $V_4$ :

$$\begin{aligned} I_0 &= 0 \\ I_2 &= U_2 - V\mu_2(Z_2) \\ I_4 &= U_4 - \mu_4(Z_4). \end{aligned} \tag{19}$$

$V \equiv V_2/V_4 > 0$  thus captures individual-level heterogeneity in relative responsiveness to  $Z_2$  vs.  $Z_4$ . That is, individuals with high values of  $V$  are relatively more sensitive to changes in  $Z_2$  than changes in  $Z_4$ , compared to individuals with low values of  $V$ . This third dimension of choice heterogeneity is shut down by weakly separable models like (4) and (18): those models allow all individuals to respond differently to  $Z_2$  relative to  $Z_4$ , since  $\mu_2(\cdot)$  and  $\mu_4(\cdot)$  can differ from each other, but this relative responsiveness must be

homogeneous across individuals, since  $\mu_2(\cdot)$  and  $\mu_4(\cdot)$  do not differ across individuals. The nonseparable model in (19) thus strictly generalizes those separable models by allowing for such heterogeneity.

## E.1 Assumption UPM

This subsection shows that the nonseparable model in (19) still satisfies Assumption UPM. As long as  $V > 0$  for all individuals, the logic of the proof in Appendix D.1 still goes through, since all arguments using the fact that  $\mu_2(\cdot)$  is strictly increasing for each individual still apply to  $V\mu_2(\cdot)$ . Thus we proceed with a proof with nearly identical structure to that in D.1. The choice equations implied by (19) are

$$\begin{aligned} D_0(z_2, z_4) &= \mathbf{1}[U_2 < V\mu_2(z_2), U_4 < \mu_4(z_4)] \\ D_2(z_2, z_4) &= \mathbf{1}[U_2 > V\mu_2(z_2), U_4 - U_2 < \mu_4(z_4) - V\mu_2(z_2)] \\ D_4(z_2, z_4) &= \mathbf{1}[U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4) - V\mu_2(z_2)]. \end{aligned}$$

To prove that the first part of Assumption UPM holds in this model, fix an arbitrary base point  $(z_2, z_4)$  and consider a decrease in  $Z_2$  to  $z'_2 < z_2$  while holding  $Z_4$  fixed at  $z_4$ . We must show that  $D_0(z'_2, z_4) \leq D_0(z_2, z_4)$ ,  $D_2(z'_2, z_4) \geq D_2(z_2, z_4)$ , and  $D_4(z'_2, z_4) \leq D_4(z_2, z_4)$  for all individuals, with each inequality holding strictly for at least some individuals.

Whether an individual would choose a given treatment at a given instrument value depends entirely on her values of  $(U_2, U_4, V)$ . We can therefore completely characterize the set of individuals with  $D_0(z_2, z_4) = 1$  as  $\mathcal{I}_0(z_2, z_4) = \{(U_2, U_4, V) : U_2 < V\mu_2(z_2), U_4 < \mu_4(z_4)\}$ , and the set of individuals with  $D_0(z'_2, z_4) = 1$  as  $\mathcal{I}_0(z'_2, z_4) = \{(U_2, U_4, V) : U_2 < V\mu_2(z'_2), U_4 < \mu_4(z_4)\}$ . Since  $V\mu_2(\cdot)$  is strictly increasing, any individual satisfying  $U_2 < V\mu_2(z'_2)$  also satisfies  $U_2 < V\mu_2(z_2)$ , which implies  $\mathcal{I}_0(z'_2, z_4) \subset \mathcal{I}_0(z_2, z_4)$  and thus  $D_0(z'_2, z_4) \leq D_0(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $2 \leftarrow 0$  compliers with  $\{(U_2, U_4, V) : U_2 \in (V\mu_2(z'_2), V\mu_2(z_2)), U_4 < \mu_4(z_4)\}$ .

Those choosing  $D_2(z_2, z_4) = 1$  are  $\mathcal{I}_2(z_2, z_4) = \{(U_2, U_4, V) : U_2 > V\mu_2(z_2), U_4 - U_2 < \mu_4(z_4) - V\mu_2(z_2)\}$ . Likewise  $\mathcal{I}_2(z'_2, z_4) = \{(U_2, U_4, V) : U_2 > V\mu_2(z'_2), U_4 - U_2 < \mu_4(z_4) - V\mu_2(z'_2)\}$ . Since  $V\mu_2(\cdot)$  is strictly increasing, any individual satisfying  $U_2 > V\mu_2(z_2)$  also satisfies  $U_2 > V\mu_2(z'_2)$ , and any individual satisfying  $U_4 - U_2 < \mu_4(z_4) - V\mu_2(z_2)$  also satisfies  $U_4 - U_2 < \mu_4(z_4) - V\mu_2(z'_2)$ , which implies  $\mathcal{I}_2(z_2, z_4) \subset \mathcal{I}_2(z'_2, z_4)$  and thus  $D_2(z'_2, z_4) \geq D_2(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $2 \leftarrow 0$  compliers with  $\{(U_2, U_4, V) : U_2 \in (V\mu_2(z'_2), V\mu_2(z_2)), U_4 < \mu_4(z_4)\}$  and  $2 \leftarrow 4$  compliers with  $\{(U_2, U_4, V) : U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z_4) - V\mu_2(z'_2)), U_4 > \mu_4(z_4)\}$ .

Those choosing  $D_4(z_2, z_4) = 1$  are  $\mathcal{I}_4(z_2, z_4) = \{(U_2, U_4, V) : U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4) - V\mu_2(z_2)\}$ . Likewise  $\mathcal{I}_4(z'_2, z_4) = \{(U_2, U_4, V) : U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4) - V\mu_2(z'_2)\}$ . Since  $V\mu_2(\cdot)$  is strictly increasing, any individual satisfying  $U_4 - U_2 > \mu_4(z_4) - V\mu_2(z'_2)$  also satisfies  $U_4 - U_2 > \mu_4(z_4) - V\mu_2(z_2)$ , which implies  $\mathcal{I}_4(z'_2, z_4) \subset \mathcal{I}_4(z_2, z_4)$  and thus  $D_4(z'_2, z_4) \leq D_4(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $2 \leftarrow 4$  compliers with  $\{(U_2, U_4, V) : U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z_4) - V\mu_2(z'_2)), U_4 > \mu_4(z_4)\}$ .

To prove that the second part of Assumption UPM holds in this model, fix an arbitrary base point  $(z_2, z_4)$  and consider an increase in  $Z_4$  to  $z'_4 > z_4$  (to match the direction of the visualized shift in Figure 4) while holding  $Z_2$  fixed at  $z_2$ . We must show that  $D_0(z_2, z'_4) \geq D_0(z_2, z_4)$ ,  $D_2(z_2, z'_4) \geq D_2(z_2, z_4)$ , and  $D_4(z_2, z'_4) \leq D_4(z_2, z_4)$  for all individuals, with each inequality holding strictly for at least some individuals.

Those choosing  $D_0(z_2, z'_4) = 1$  are  $\mathcal{I}_0(z_2, z'_4) = \{(U_2, U_4, V) : U_2 < V\mu_2(z_2), U_4 < \mu_4(z'_4)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 < \mu_4(z_4)$  also satisfies  $U_4 < \mu_4(z'_4)$ , which implies  $\mathcal{I}_0(z_2, z_4) \subset \mathcal{I}_0(z_2, z'_4)$  and thus  $D_0(z_2, z'_4) \geq D_0(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $0 \leftarrow 4$  compliers with  $\{(U_2, U_4, V) : U_2 < V\mu_2(z_2), U_4 \in (\mu_4(z_4), \mu_4(z'_4))\}$ .

Those choosing  $D_2(z_2, z'_4) = 1$  are  $\mathcal{I}_2(z_2, z'_4) = \{(U_2, U_4, V) : U_2 > V\mu_2(z_2), U_4 - U_2 < \mu_4(z'_4) - V\mu_2(z_2)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 - U_2 < \mu_4(z_4) - V\mu_2(z_2)$  also satisfies  $U_4 - U_2 < \mu_4(z'_4) - V\mu_2(z_2)$ , which implies  $\mathcal{I}_2(z_2, z_4) \subset \mathcal{I}_2(z_2, z'_4)$  and thus  $D_2(z_2, z'_4) \geq D_2(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $2 \leftarrow 4$  compliers with  $\{(U_2, U_4, V) : U_2 > V\mu_2(z_2), U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z'_4) - V\mu_2(z_2))\}$ .

Those choosing  $D_4(z_2, z'_4) = 1$  are  $\mathcal{I}_4(z_2, z'_4) = \{(U_2, U_4, V) : U_4 > \mu_4(z'_4), U_4 - U_2 > \mu_4(z'_4) - V\mu_2(z_2)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 > \mu_4(z'_4)$  also satisfies  $U_4 > \mu_4(z_4)$ , and any individual satisfying  $U_4 - U_2 > \mu_4(z'_4) - V\mu_2(z_2)$  also satisfies  $U_4 - U_2 > \mu_4(z_4) - V\mu_2(z_2)$ , which implies

$\mathcal{I}_4(z_2, z'_4) \subset \mathcal{I}_4(z_2, z_4)$  and thus  $D_4(z_2, z'_4) \leq D_4(z_2, z_4)$  for all individuals, with the inequality holding strictly for  $0 \leftarrow 4$  compliers with  $\{(U_2, U_4, V) : U_2 < V\mu_2(z_2), U_4 \in (\mu_4(z_4), \mu_4(z'_4))\}$  and  $2 \leftarrow 4$  compliers with  $\{(U_2, U_4, V) : U_2 > V\mu_2(z_2), U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z'_4) - V\mu_2(z_2))\}$ . This proves that the nonseparable model in (19) satisfies Assumption UPM.

## E.2 Assumption CC

To prove that the nonseparable model in (19) satisfies Assumption CC, first consider the left side of Assumption CC, which in the nonseparable model translates to

$$\begin{aligned} & \lim_{z'_2 \uparrow z_2} E[Y_2 | D(z'_2, z_4) = 2, D(z_2, z_4) = 4] \\ &= \lim_{z'_2 \uparrow z_2} E[Y_2 | U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z_4) - V\mu_2(z'_2)), U_4 > \mu_4(z_4)] \\ &= E[Y_2 | U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_4 > \mu_4(z_4)], \end{aligned} \quad (20)$$

where exact indifference with  $U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2)$  is assumed to be decided in favor of  $D(z_2, z_4) = 4$ . Now consider the right side of Assumption CC, which in the nonseparable model translates to

$$\begin{aligned} & \lim_{z'_4 \downarrow z_4} E[Y_2 | D(z_2, z'_4) = 2, D(z_2, z_4) = 4] \\ &= \lim_{z'_4 \downarrow z_4} E[Y_2 | U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z'_4) - V\mu_2(z_2)), U_2 > V\mu_2(z_2)] \\ &= E[Y_2 | U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)]. \end{aligned} \quad (21)$$

The conditioning set in (20) can be written as  $U_4 = U_2 + \mu_4(z_4) - V\mu_2(z_2) > \mu_4(z_4)$ , which implies  $U_2 > V\mu_2(z_2)$ . Hence a verbose version of (20) is  $E[Y_2 | U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2), U_4 > \mu_4(z_4)]$ . The conditioning set in (21) can be written as  $U_2 = U_4 - \mu_4(z_4) + V\mu_2(z_2) > V\mu_2(z_2)$ , which implies  $U_4 > \mu_4(z_4)$ . Hence a verbose version of (21) is  $E[Y_2 | U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2), U_4 > \mu_4(z_4)]$ . Therefore

$$\begin{aligned} \lim_{z'_2 \uparrow z_2} E[Y_2 | D(z'_2, z_4) = 2, D(z_2, z_4) = 4] &= [Y_2 | U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2), U_4 > \mu_4(z_4)] \\ &= \lim_{z'_4 \downarrow z_4} E[Y_2 | D(z_2, z'_4) = 2, D(z_2, z_4) = 4], \end{aligned}$$

i.e. the nonseparable model in (19) satisfies Assumption CC.

## F A Nonseparable Model Satisfying UPM but Not CC

To show that Assumption CC does not quite come for free in the general framework Section 4.4, consider a generalization of the nonseparable model in (19) with the same structure,

$$\begin{aligned} I_0 &= 0 \\ I_2 &= U_2 - V\mu_2(Z_2) \\ I_4 &= U_4 - \mu_4(Z_4), \end{aligned}$$

but now allow the instrument response heterogeneity variable  $V \geq 0$  to take on the value of zero for some positive mass of students in the population, with  $0 < Pr[V = 0 | U_2, U_4] < 1$  for all  $(U_2, U_4)$ .

### F.1 Assumption UPM

Such a model still satisfies Assumption UPM. To see this, note first that for the subpopulation of individuals with  $V$  strictly positive, the proof in E.1 goes through exactly, so they satisfy Assumption UPM. For the

complementary subpopulation of individuals with  $V = 0$ , their implied choice equations are

$$\begin{aligned} D_0(z_2, z_4) &= D_0(z_4) = \mathbf{1}[U_2 < 0, U_4 < \mu_4(z_4)] \\ D_2(z_2, z_4) &= D_2(z_4) = \mathbf{1}[U_2 > 0, U_4 - U_2 < \mu_4(z_4)] \\ D_4(z_2, z_4) &= D_4(z_4) = \mathbf{1}[U_4 > \mu_4(z_4), U_4 - U_2 > \mu_4(z_4)]. \end{aligned}$$

That is, their potential treatment functions do not depend on  $Z_2$ . This means they satisfy the weak inequalities in first part of Assumption UPM by holding with equality— $D_0(z'_2, z_4) = D_0(z_2, z_4)$ ,  $D_2(z'_2, z_4) = D_2(z_2, z_4)$ , and  $D_4(z'_2, z_4) = D_4(z_2, z_4)$ —but they do not contribute any compliers to satisfy the requirement that each inequality hold strictly for at least some individuals. This does not lead to a violation of Assumption UPM, however, since other students with  $V > 0$  are available to fulfill this role for all possible instrument shifts given  $Pr[V > 0|U_2, U_4] > 0$  for all  $(U_2, U_4)$ .

To prove that the second part of Assumption UPM holds for the  $V = 0$  subpopulation, fix an arbitrary base point  $(z_2, z_4)$  and consider an increase in  $Z_4$  to  $z'_4 > z_4$  while holding  $Z_2$  fixed at  $z_2$ . We must show that  $D_0(z_2, z'_4) \geq D_0(z_2, z_4)$ ,  $D_2(z_2, z'_4) \geq D_2(z_2, z_4)$ , and  $D_4(z_2, z'_4) \leq D_4(z_2, z_4)$  for all individuals with  $V = 0$ . For this subpopulation,  $V$  is fixed and does not enter the choice equations, so whether an individual would choose a given treatment at a given instrument value depends entirely on her values of  $(U_2, U_4)$ .

Those choosing  $D_0(z_2, z'_4) = 1$  are  $\mathcal{I}_0(z_2, z'_4) = \{(U_2, U_4) : U_2 < 0, U_4 < \mu_4(z'_4)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 < \mu_4(z_4)$  also satisfies  $U_4 < \mu_4(z'_4)$ , which implies  $\mathcal{I}_0(z_2, z_4) \subset \mathcal{I}_0(z_2, z'_4)$  and thus  $D_0(z_2, z'_4) \geq D_0(z_2, z_4)$  for all individuals in the  $V = 0$  subpopulation, with the inequality holding strictly for  $0 \leftarrow 4$  compliers with  $\{(U_2, U_4) : U_2 < 0, U_4 \in (\mu_4(z_4), \mu_4(z'_4))\}$ .

Those choosing  $D_2(z_2, z'_4) = 1$  are  $\mathcal{I}_2(z_2, z'_4) = \{(U_2, U_4) : U_2 > 0, U_4 - U_2 < \mu_4(z'_4)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 - U_2 < \mu_4(z_4)$  also satisfies  $U_4 - U_2 < \mu_4(z'_4)$ , which implies  $\mathcal{I}_2(z_2, z_4) \subset \mathcal{I}_2(z_2, z'_4)$  and thus  $D_2(z_2, z'_4) \geq D_2(z_2, z_4)$  for all individuals in the  $V = 0$  subpopulation, with the inequality holding strictly for  $2 \leftarrow 4$  compliers with  $\{(U_2, U_4) : U_2 > 0, U_4 - U_2 \in (\mu_4(z_4), \mu_4(z'_4))\}$ .

Those choosing  $D_4(z_2, z'_4) = 1$  are  $\mathcal{I}_4(z_2, z'_4) = \{(U_2, U_4) : U_4 > \mu_4(z'_4), U_4 - U_2 > \mu_4(z'_4)\}$ . Since  $\mu_4(\cdot)$  is strictly increasing, any individual satisfying  $U_4 > \mu_4(z'_4)$  also satisfies  $U_4 > \mu_4(z_4)$ , and any individual satisfying  $U_4 - U_2 > \mu_4(z'_4)$  also satisfies  $U_4 - U_2 > \mu_4(z_4)$ , which implies  $\mathcal{I}_4(z_2, z'_4) \subset \mathcal{I}_4(z_2, z_4)$  and thus  $D_4(z_2, z'_4) \leq D_4(z_2, z_4)$  for all individuals in the  $V = 0$  subpopulation, with the inequality holding strictly for  $0 \leftarrow 4$  compliers with  $\{(U_2, U_4) : U_2 < 0, U_4 \in (\mu_4(z_4), \mu_4(z'_4))\}$  and  $2 \leftarrow 4$  compliers with  $\{(U_2, U_4) : U_2 > 0, U_4 - U_2 \in (\mu_4(z_4), \mu_4(z'_4))\}$ . This proves that the  $V = 0$  subpopulation satisfies Assumption UPM.

## F.2 Assumption CC

This model does not satisfy Assumption CC, however. Since individuals with  $V = 0$  are responsive to  $Z_4$  but not  $Z_2$ , their existence can break the exact overlap of marginal  $2 \leftarrow 4$  compliers w.r.t.  $Z_2$  vs.  $Z_4$  featured in the separable index model in (4) and the nonseparable model in (19). To see this, first note that the left side of Assumption CC in this model can only involve individuals with  $V > 0$ , since those with  $V = 0$  are never compliers w.r.t.  $Z_2$ . Thus

$$\begin{aligned} & \lim_{z'_2 \uparrow z_2} E[Y_2|D(z'_2, z_4) = 2, D(z_2, z_4) = 4] \\ &= \lim_{z'_2 \uparrow z_2} E[Y_2|V > 0, U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z_4) - V\mu_2(z'_2)), U_4 > \mu_4(z_4)] \\ &= E[Y_2|V > 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_4 > \mu_4(z_4)], \end{aligned} \tag{22}$$

where exact indifference with  $U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2)$  is assumed to be decided in favor of  $D(z_2, z_4) = 4$ . Now consider the right side of Assumption CC, which does involve individuals with  $V = 0$ ,

$$\begin{aligned} & \lim_{z'_4 \downarrow z_4} E[Y_2|D(z_2, z'_4) = 2, D(z_2, z_4) = 4] \\ &= \lim_{z'_4 \downarrow z_4} E[Y_2|U_4 - U_2 \in (\mu_4(z_4) - V\mu_2(z_2), \mu_4(z'_4) - V\mu_2(z_2)), U_2 > V\mu_2(z_2)] \\ &= E[Y_2|U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)], \end{aligned}$$

which we can decompose as a weighted average across the subpopulations with  $V > 0$  vs.  $V = 0$ ,

$$E[Y_2|V > 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)]Pr[V > 0|U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)] \\ + E[Y_2|V = 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)]Pr[V = 0|U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)].$$

As in E.2, the conditioning set  $V > 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_4 > \mu_4(z_4)$  is equivalent to  $V > 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)$ . Putting these pieces together, the difference between the left side and right side of Assumption CC in this model is

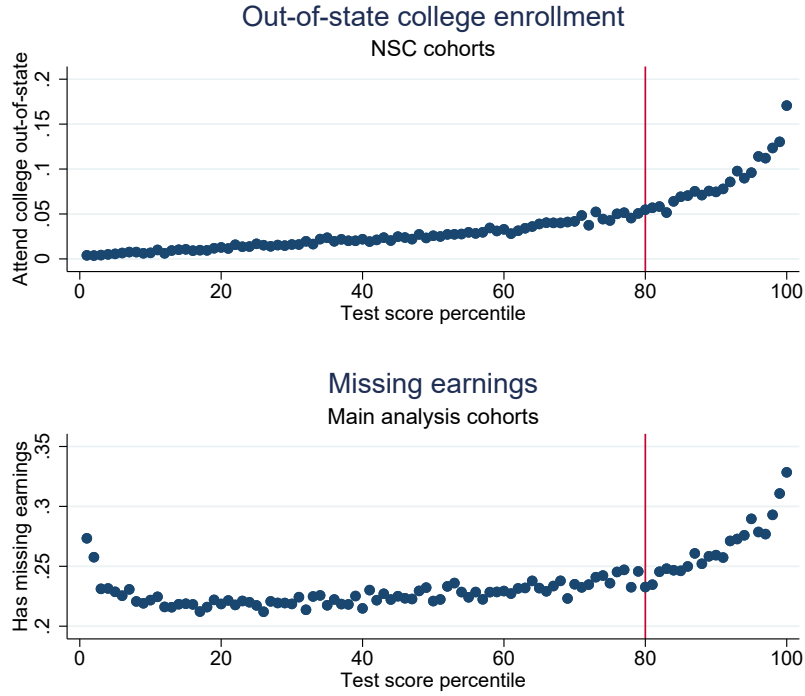
$$E[Y_2|V > 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_4 > \mu_4(z_4)] \\ - E[Y_2|V > 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)](1 - Pr[V = 0|U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)]) \\ - E[Y_2|V = 0, U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)]Pr[V = 0|U_4 - U_2 = \mu_4(z_4) - V\mu_2(z_2), U_2 > V\mu_2(z_2)],$$

which simplifies to

$$\{E[Y_2|V > 0, D(z_2, z'_4) = 2, D(z_2, z_4) = 4] - E[Y_2|V = 0, D(z_2, z'_4) = 2, D(z_2, z_4) = 4]\}Pr[V = 0|D(z_2, z'_4) = 2, D(z_2, z_4) = 4].$$

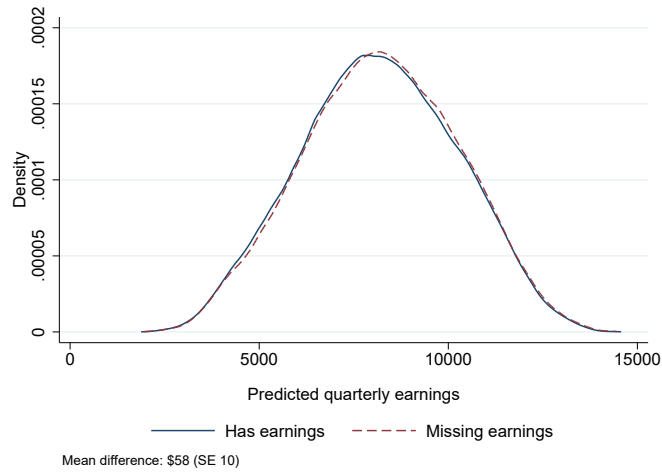
Thus, Assumption CC will fail to hold in this model if two conditions are both met. First, individuals with  $V = 0$  must be among  $2 \leftarrow 4$  compliers w.r.t.  $Z_4$  at  $(z_2, z_4)$ , i.e.  $Pr[V = 0|D(z_2, z'_4) = 2, D(z_2, z_4) = 4] > 0$ . Second, those compliers with  $V = 0$  must differ in their mean  $Y_2$  from their counterparts with  $V > 0$ , i.e.  $E[Y_2|V > 0, D(z_2, z'_4) = 2, D(z_2, z_4) = 4] \neq E[Y_2|V = 0, D(z_2, z'_4) = 2, D(z_2, z_4) = 4]$ .

Figure A.1: Out-of-State Enrollment and Missing Earnings among Top Scorers



Notes: The top panel of this figure plots the share of students within each 10th grade test score percentile (defined in Section 3.2) who enroll in college outside of Texas using the 2008-2009 cohorts with National Student Clearinghouse college enrollment coverage. The bottom panel plots the share of students within each test score percentile who have no Texas quarterly earnings records over ages 28-30 using the 2000-2004 main analysis cohorts.

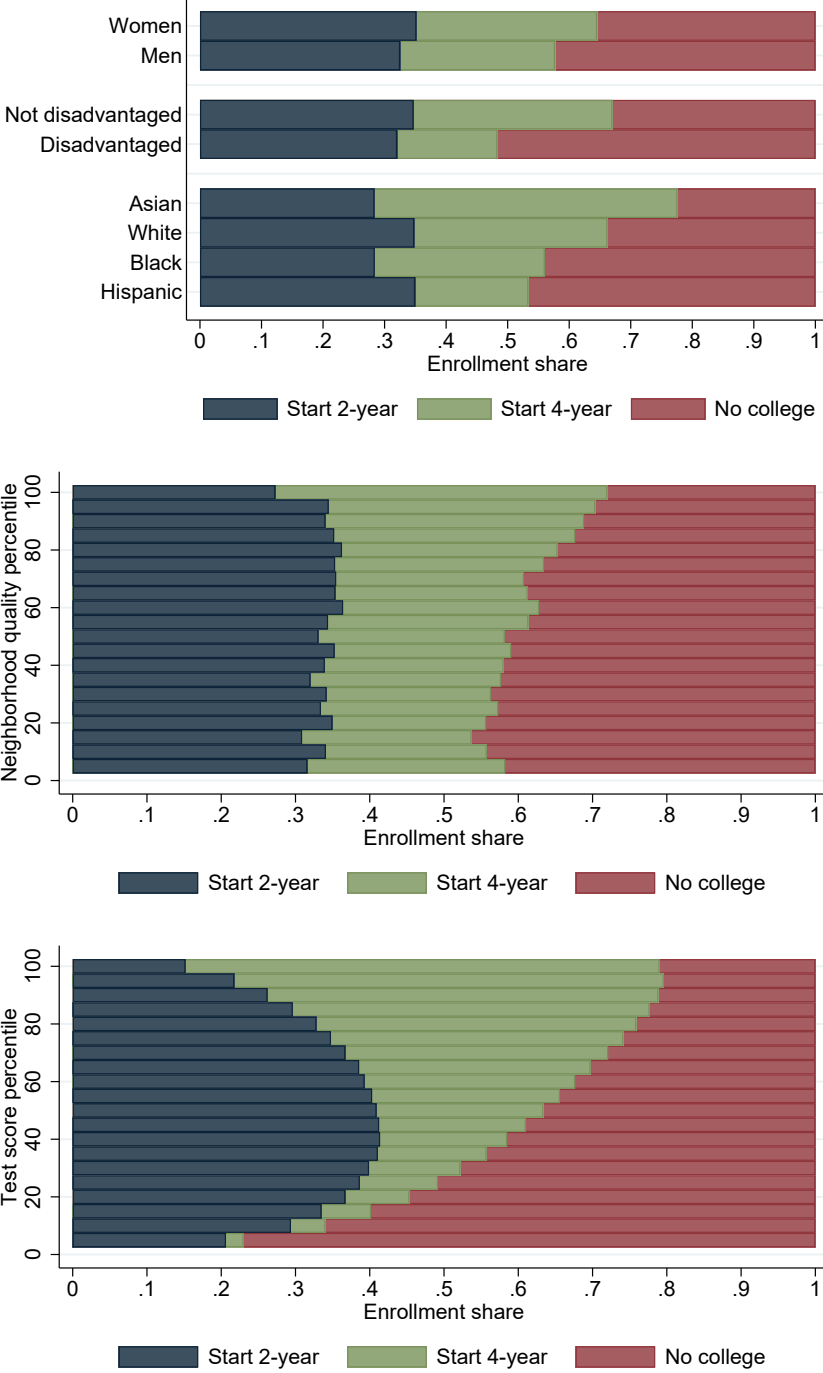
Figure A.2: Predicted Earnings Are Similar for Students with Observed and Missing Earnings



Notes: This figure plots the distributions of predicted mean quarterly earnings over ages 28-30 for students with and without observed earnings. Earnings are first projected on all covariates and instruments in Table 1 in the sample with valid earnings, then predicted in the full sample and plotted by earnings status.



Figure A.3: Sorting into College Enrollment Choices by Observables, 2000-2004 Analysis Cohorts



Notes: Disadvantaged is an indicator for free or reduced price lunch eligibility in 10th grade. Neighborhood quality and test score percentiles, defined in Section 3.2, are grouped into 5-unit bins.

Table A.1: High School Graduation and Out-of-State College Enrollment

	Graduate from high school	Enroll in college out-of-state
$Z_2$ : 2-year distance (miles/10)	.0013 (.0012)	-.00001 (.0006)
$Z_4$ : 4-year distance (miles/10)	.0001 (.001)	-.0011 (.0007)
$R^2$	.019	.017
$N$	590,392	362,011
Sample:	Main analysis cohorts	NSC cohorts
Baseline controls	✓	✓

Notes: NSC cohorts are those with National Student Clearinghouse college enrollment data. Standard errors in parentheses are clustered at the high school campus by cohort level. High school graduation is measured cumulatively through eight years after 10th grade. Out-of-state college enrollment is measured within two years of projected high school graduation due to NSC data availability.

Table A.2: Causal Effect Estimates: Time-to-Degree and Field of Study

	$MTE_2$ Net effect	=	$\omega$ Democratiz- ation share	+	$MTE_{2\leftarrow 0}$ Democratiz- ation effect	+	$(1 - \omega)$ Diversion share	$MTE_{2\leftarrow 4}$ Diversion effect
BA completion within:								
4 years	.046 (.020)		.653 (.050)		.038 (.012)		.347 (.050)	.060 (.056)
5 years	.057 (.033)		.653 (.050)		.096 (.022)		.347 (.050)	-.014 (.078)
6 years	.065 (.037)		.653 (.050)		.148 (.026)		.347 (.050)	-.092 (.079)
7 years	.085 (.040)		.653 (.050)		.200 (.030)		.347 (.050)	-.131 (.083)
8 years	.089 (.042)		.653 (.050)		.212 (.033)		.347 (.050)	-.141 (.083)
9 years	.090 (.043)		.653 (.050)		.227 (.034)		.347 (.050)	-.167 (.084)
10 years	.104 (.044)		.653 (.050)		.257 (.035)		.347 (.050)	-.184 (.084)
10-year BA completion in:								
STEM major	.004 (.011)		.653 (.050)		.015 (.011)		.347 (.050)	-.016 (.027)
Non-STEM major	.100 (.040)		.653 (.050)		.243 (.033)		.347 (.050)	-.168 (.077)

Notes: Locally weighted observations: 556,719. All estimates are evaluated at the mean values of the instruments. Standard errors in parentheses are block bootstrapped at the high school campus by cohort level. Complier shares are the same across outcomes due to common first stage equations.