Comparison of Congressional Districting Plans in Pennsylvania

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1 Assignment and qualifications

I am a Professor of Mathematics and a Senior Fellow in the Jonathan M. Tisch College of Civic Life at Tufts University. At Tisch College, I am the principal investigator of an interdisciplinary research lab focused on geometric and computational aspects of redistricting. I was recently awarded a major grant from the National Science Foundation to study *Network Science of Census Data*. My areas of research and teaching include the structure of census data, the design and implementation of randomized algorithms for generating districting plans, and the analysis of partisan fairness and of redistricting more broadly.

I was asked to evaluate several maps that have been proposed as alternatives for Congressional redistricting in Pennsylvania, and particularly to compare them in terms of traditional districting principles and partisan fairness.

I personally conducted all work in this report, supported by research assistants working under my direct supervision. A full copy of my CV is attached to this report.

1.1 Materials

- The largest single source of data is the U.S. Census Bureau. I principally use the Decennial Census release, together with supporting data products like the American Community Survey and the TIGER/Line geographical shapefiles. I have also made use of the datasets released by the Pennsylvania Legislative Reapportionment Commission at `redistricting.state.pa.us/maps/#census`.
- Language governing the guidelines for Congressional redistricting was drawn from the published principles of the Pennsylvania Redistricting Advisory Council [3].
- I extensively consulted the Court Order and the majority opinion from the 2018 case *LWV vs. Pennsylvania* [2, 1].
- I compared districting plans defined by block equivalency files. The Governor's plan is publicly posted at `portal.pennsylvania-mapping.org/plans`; the Citizens' Plan is posted at `drawthelinespa.org/pa-citizens-map`; and the data for `HB-2146` was provided to me by counsel.

2 Executive summary

In 2018, the Pennsylvania Supreme Court described four "neutral criteria" that collectively "provide a 'floor' of protection for an individual against the dilution of his or her vote": population balance, contiguity, compactness, and respect for political boundaries [1]. This gives initial points of comparison for the plans discussed in this report. The Congressional districting plan passed by the Pennsylvania House of Representatives (`HB-2146`) is population-balanced and contiguous, shows strong respect for political boundaries, and is reasonably compact. In this report, I compare the plan to two alternative plans called `GovPlan` and `CitizensPlan`. I find that these are also population-balanced and contiguous and have comparably strong respect for political boundaries but, crucially, each is markedly more compact than the House's proposed plan. In other words, I find that the Governor's Plan and the Citizens' Plan do a better job overall at accounting for the neutral criteria of redistricting.

In addition to the alternative plans outperforming the House Plan on neutral criteria, the maps differ significantly in their partisan fairness properties. `HB-2146` can be seen to systematically advantage the candidates of one major party over the other, when overlaid with a range of recent elections in Pennsylvania. In large part this is due to the "political geography" of Pennsylvania, in which the current patterns of concentration in electoral preferences create a landscape that is tilted towards Republicans. My analysis leads me to conclude that the Citizens' Plan, and especially the Governor's Plan, overcome this structural tilt to make fairer maps for the people of Pennsylvania—treating the parties even-handedly while still behaving responsively to shifts in voter preference—with no cost at all in the neutral criteria.

3 Introduction

The Commonwealth of Pennsylvania saw its population grow from 12,702,379 in the 2010 Decennial Census to 13,002,700 with the release of new numbers from 2020. Despite providing a boost from the 6th to the 5th largest state in the nation, the growth did not keep pace with the country as a whole, and Pennsylvania's congressional apportionment dropped from 18 districts to 17 for this cycle.

In the last ten-plus years, there has been a surge of citizen interest in redistricting around the nation, and many members of the public have tried their hands at drawing districts for the first time. One of those active citizens is Amanda Holt, who has been described in news reports as "a piano teacher from Upper Macungie" [7]. In its 2021-22 session, the Pennsylvania House of Representatives chose one of a collection of maps prepared by Holt and modified it to create the Congressional map that has now been passed as House Bill 2146.

In this report, I will be examining the design of Congressional districts in Pennsylvania. I will discuss the two enacted 18-district plans from the previous cycle (the legislative plan `2011-Enacted` from 2011 and the court's remedial plan `2018-Remedial` from 2018) alongside three proposed 17-district plans for the current cycle: the Governor's plan `GovPlan`, the public plan `CitizensPlan`, and the House's Holt-derived plan `HB-2146`.

I will use two main tools to study Pennsylvania Congressional redistricting. The first is a simple "overlay method" where districting plans are superimposed on actual recently observed voting patterns to record the plans' performance in a range of electoral conditions. The second is the "ensemble method" of generating large samples of legally valid redistricting plans that take the rules and criteria into account. I will use algorithmic ensembles to illustrate that partisan-blind redistricting in Pennsylvania does not tend to achieve partisan fairness. However, computational methods can also exhibit that there is a nearly inexhaustible supply of fairer maps that still obtain sterling scores on traditional criteria.

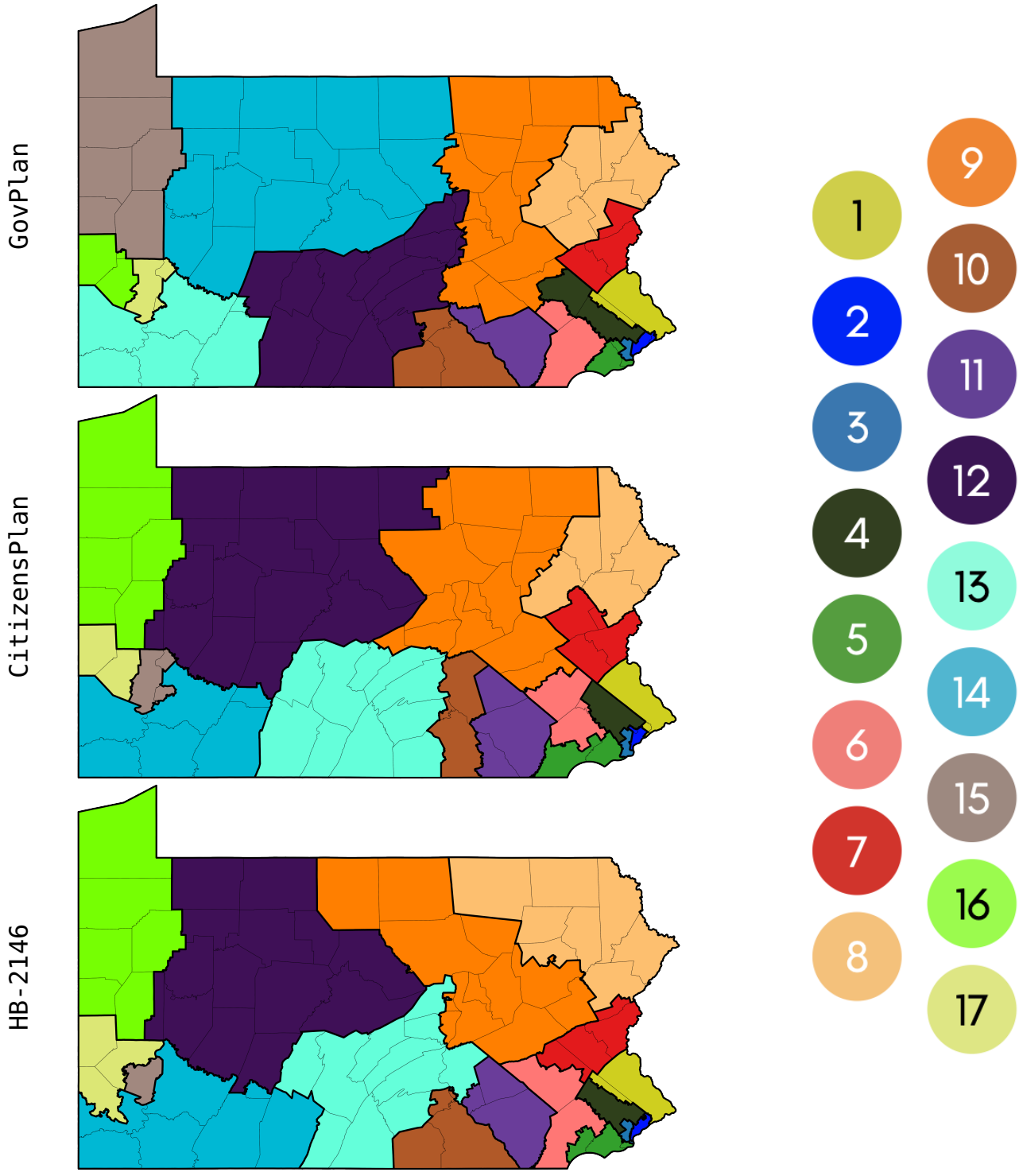


Figure 1: The three plans being compared in this report.

4 Review of redistricting criteria

Congressional redistricting for Pennsylvania is a matter of dividing up the 13,002,700 residents into 17 geographical subdivisions of the state. In doing so, we must balance a long and sometimes competing list of rules and priorities.

In 2018, the Pennsylvania Supreme Court struck down the congressional districts established in 2011 ("`2011-Enacted`") and ordered them to be replaced with a remedial plan drawn by a court-appointed expert ("`2018-Remedial`"). Justice Todd, writing for the majority in that decision, emphasized the roles of four major criteria for the design and adoption of a districting plan: population balance, compactness, contiguity, and respect for political boundaries. Quoting the opinion:

> Because these factors are deeply rooted in the organic law of our Commonwealth, and continue to be the foundational requirements which state legislative districts must meet under the Pennsylvania Constitution, we find these neutral benchmarks to be particularly suitable as a measure in assessing whether a congressional districting plan dilutes the potency of an individual's ability to select the congressional representative of his or her choice, and thereby violates the Free and Equal Elections Clause. [1]

These four considerations, as well as the federal requirement to safeguard electoral opportunity for minority groups, are echoed in the Redistricting Principles of the Governor's Advisory Council (henceforth, the "Principles"). Therefore these five criteria will be considered primary for this analysis.

4.1 Federal requirements

4.1.1 Population balance

Since the Reapportionment Revolution of the 1960s and 70s, courts have required serious attention to balancing the population across electoral districts in a plan, under a norm called *One Person, One Vote*. Over the decades, this has evolved to the tightest possible standard in practice: in most U.S. states, Congressional districts are fine-tuned so that their total population deviates by no more than one person from any district to any other.

Across the nation, the default dataset used to balance population is the Decennial Census release known as the PL94-171 data, named after the Public Law that mandated its publication. However, in Pennsylvania there is an alternative available: the Legislative Reapportionment Commission has released an adjusted block-level dataset known as LRC2, in which incarcerated people are geographically re-assigned to their communities of origin.[1] In the figures below, I will present the population balance of the plans with both the PL dataset and the LRC2 prison-adjusted alternative.

[1] The LRC also released LRC1, which corrects and updates some geographical definitions of precincts. The population figures reported here with respect to Census data were confirmed to be unchanged with the passage to the LRC1 dataset.

4.1.2 Minority opportunity to elect

Both the Voting Rights Act of 1965 and the U.S. Constitution protect against the denial, abridgement, or dilution of the vote for minority groups across the nation. For Congressional districting in Pennsylvania, this is of particular salience in Philadelphia, where people of color make up a majority of the voting age population and are collectively more numerous than the population of a district.[2]

In the previous cycle, the `2018-Remedial` map contained one majority-Black district (CD3 in Philadelphia) and a second majority-minority district. All three of the plans compared in this report retain the majority-Black character of CD3 and the majority-minority character of CD2. At the same time, the law clearly acknowledges that numerical majorities (50% plus one of voting age population) are neither necessary nor sufficient to provide effective opportunity to elect candidates of choice. Effectiveness of the comparison plans is discussed further in Section 6.

As a partial indicator of effective electoral opportunity, I considered recent at-large Philadelphia city council elections: the primary and general elections of 2015 and 2019. In 2015, Blondell Reynolds Brown and Derek S. Green were the candidates of choice for Black voters, according to an ecological inference analysis of voting polarization. In 2019, Green and Isaiah Thomas were the Black candidates of choice. Since all of these candidates ran city-wide, I can examine whether any district that intersects with Philadelphia had vote totals that supported these candidates.

4.2 Neutral criteria

4.2.1 Contiguity

Contiguity requires that, for each district, it is possible to transit from any part of the district to any other part, staying inside the district. That is, contiguity is the requirement that each district be composed of a single connected piece. In technical terms, for districts made from census blocks, the standard "rook-contiguity" definition holds that the connecting paths should pass through a sequence of census blocks that share boundary segments of positive length (and not through blocks that meet at corners).

4.2.2 Compactness

The two compactness metrics most commonly appearing in redistricting are the *Polsby-Popper score* and the *Reock score*. Polsby-Popper is a recent name for a metric from ancient mathematics: the isoperimetric ratio comparing a region's area to its perimeter via the formula $4\pi A/P^2$. Higher scores are considered more compact, with circles uniquely achieving the optimum score of 1. Reock is a different measurement of how much a shape differs from a circle: it is computed as the ratio of a region's area to that of its circumcircle, defined as the smallest circle in which the region can be circumscribed. From this definition, it is clear that it too is optimized at a value of 1, which is achieved only by circles. In addition, the 2018 Court Order specified three more metrics—*Schwartzberg*, *Convex Hull*, and *Population Polygon*—that should be reported for every plan.[3]

[2] Philadelphia White non-Hispanic VAP: 37.8%, Black VAP: 39.8%, Hispanic VAP: 13.1%, Asian VAP: 9.4%. Lehigh and Monroe counties have people of color making up 30-40% of voting age population, while the range is 20-30% in many other counties (namely, Allegheny, Berks, Chester, Forest, Montgomery, and Northampton).

[3] Schwartzberg is $P/2\sqrt{\pi A}$. Convex Hull is the ratio of the district's area to that of its convex hull, or "rubber-band enclosure." And Population Polygon is the ratio of the district's population to the state's population within the convex hull. All parties submitting maps to the Court were required to report these five scores for each district in the plan, but the Court did not specify how these numbers would be compared across plans.

All five of these scores depend on the contours of a district and have been criticized as being too dependent on map projections or on cartographic resolution [4, 5]. Recently, mathematicians have argued for using discrete compactness scores, taking into account the units of Census geography from which the district is built. The most commonly cited discrete score for districts is the *cut edges score*, which counts how many adjacent pairs of geographical units receive different district assignments. In other words, cut edges measures the "scissors complexity" of the districting plan: how much work would have to be done to separate the districts from each other? Plans with a very intricate boundary would require many separations. This score improves on the contour-based scores by better controlling for factors like coastline and other natural boundaries, and by focusing on the units actually available to redistricters rather than treating districts like free-form Rorschach blots.

4.2.3 Respect for political boundaries

One of the most common redistricting principles active in laws and guidelines for redistricting is the respect for political subdivisions: counties, cities, and other relevant political and administrative geographies should be kept intact in districts as much as practicable.

In Pennsylvania, there are 67 counties, further subdivided into 2572 municipalities.[4]

4.3 Other traditional principles

The LWV opinion from 2018 continues by identifying three more that can reasonably be considered once the fundamental principles are in place.

> We recognize that other factors have historically played a role in the drawing of legislative districts, such as the preservation of **prior district lines**, protection of **incumbents**, or the maintenance of the **political balance** which existed after the prior reapportionment. See, e.g., Holt I, 38 A.3d at 1235. However, we view these factors to be wholly subordinate to the neutral criteria of compactness, contiguity, minimization of the division of political subdivisions, and maintenance of population equality among congressional districts. These neutral criteria provide a “floor” of protection for an individual against the dilution of his or her vote in the creation of such districts. [1, emph. added]

The Principles of the Governor’s council spell out a version of political balance in their reference to "partisan fairness and proportionality" as well as "responsiveness and competitiveness." They also cite the traditional principle of respect for **communities of interest**. I will defer the political balance considerations to Section 7 but will briefly outline the other criteria here.

[4] The Census Bureau publishes these in its COUSUB file; Pennyslvania is one of the states in which county subdivisions are equivalent to minor civil divisions in the Census nomenclature. These are further classified as cities, towns, townships, and boroughs. As a technical note, 12 of the COUSUBs are split across counties, so 2572 is the number after dividing them to nest inside counties.

4.3.1 Least change

In 2018, the Pennsylvania Supreme Court ordered that the Congressional districts enacted in 2011 be replaced with a map that was deemed to better uphold traditional principles as well as the Free and Equal Elections Clause in the state constitution. This 18-district remedial plan, drawn by a court-appointed expert, has now been in place for two Congressional elections, those of 2018 and 2020. As the Court's opinion makes clear, it would be reasonable to prefer a plan that is least disruptive to the `2018-Remedial` plan. The identification of a least-change plan is made somewhat challenging in Pennsylvania by the loss of a district; still, it is possible, for each district in a new plan, to see which `2018-Remedial` district contains the largest share of its population and add up the number of people who are *not* assigned to that target district. For example, all three plans under discussion (`GovPlan`, `CitizensPlan`, and `HB-2146`) have in common that CD 3 in the new plan has its largest overlap with the one labeled CD 3 in the previous plan; that district is currently represented by Dwight Evans. That means the displacement score for the new plans will count the number of people who are now assigned to District 3 but were not previously represented by Dwight Evans. It is reasonable to prefer plans with lower displacement from the remedial plan, given that it was put in place by the Court as a model of fair districting.

4.3.2 Incumbency

Relatedly, we can compare the plans' consideration of incumbency by considering whether new districts are drawn so as to force current incumbents to compete—this usually goes by the name of "double-bunking." Some states encourage line-drawers to minimize double-bunking, while other states require that incumbent addresses not be considered. I will report double-bunking statistics below, but make no assumption that less double-bunking is necessarily better.

4.3.3 Communities of interest

Finally, a conceptually important traditional principle that has often been hard to measure is respect for *communities of interest*, or "COIs." In past census cycles, though line-drawing bodies have often solicited public comment at hearings and in writing, the redistricting community has generally lacked a systematic mechanism for connecting public testimony to mapping format. In this cycle, free web tools have emerged that have made it possible for community input to be visible in the line-drawing process. COIs are discussed further in Section 6.

5 Comparison of metrics for proposed Congressional plans

In this section, I review some quantitative comparisons to establish the conformance of the plans under consideration to the neutral criteria identified as being of primary importance. First, all three plans attain *de minimis* population deviation with respect to the official Census data.[5]

With respect to the prisoner-adjusted allocations found in LRC2, the plans have slightly higher levels of observed deviation, with the Governor's plan slightly tighter than the other two.

Table 1: Comparison of the population deviation across plans.

Population deviation – Census

	max positive deviation	max negative deviation	top-to-bottom deviation
GovPlan	–	−1	1
CitizensPlan	–	−1	1
HB-2146	–	−1	1

Population deviation – Prisoner-adjusted

	max positive deviation	max negative deviation	top-to-bottom deviation
GovPlan	3686	−4863	8549
CitizensPlan	3875	−5021	8896
HB-2146	3933	−4932	8865

Next, I enumerate the number of counties that are split across multiple districts in the respective plans. When a county is split, I record its number of pieces (the number of districts that it touches). All three plans have strong respect for political boundaries, splitting 14-16 of the state's 67 counties and only 16-18 of over 2500 municipalities.

Table 2: Comparing the plans' conformance to political boundaries.

Political boundaries

	county splits (out of 67)	county pieces	muni splits (out of 2572)	muni pieces
GovPlan	16	35	18	37
CitizensPlan	14	30	16	33
HB-2146	15	33	16	34

[5] The same one-person deviation is maintained if the dataset shifts to the adjusted LRC1 data referenced above.

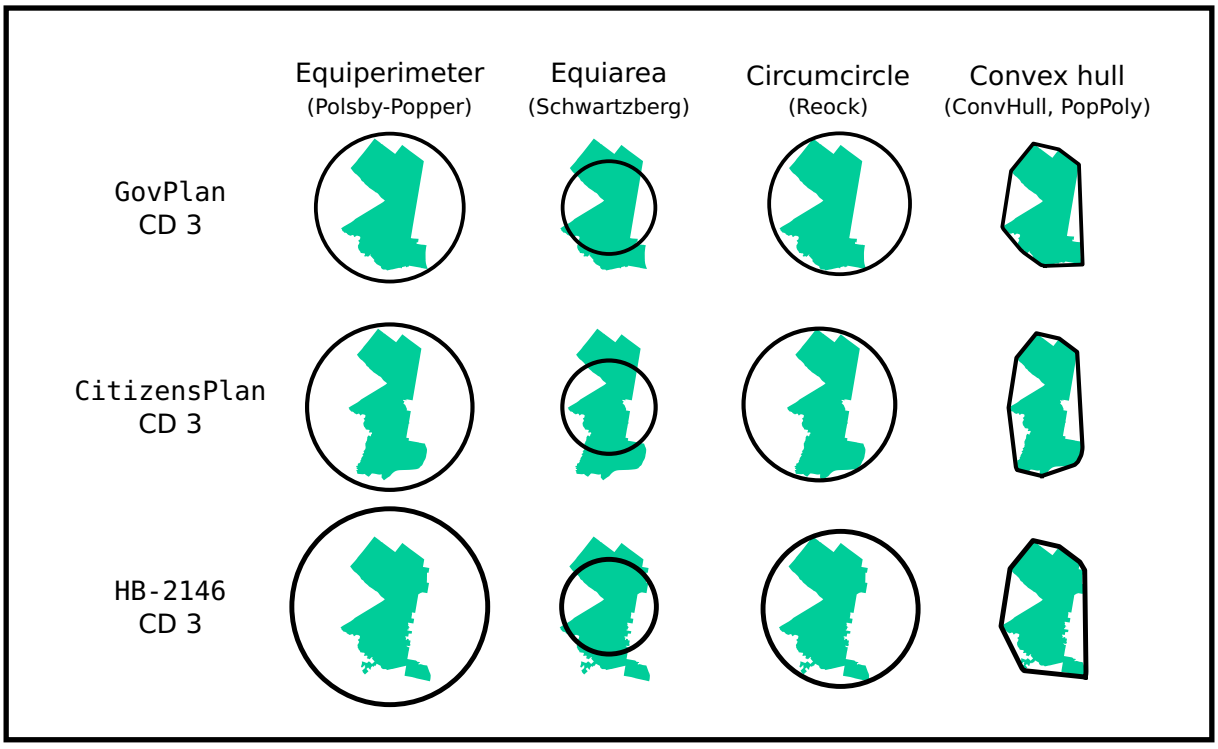
Another fundamental redistricting principle is compactness, which can be measured by a huge variety of metrics. Here, I provide six different ways of scoring a plan, defined in the previous section. The Governor's Plan rates most compact in five of these six metrics, with the Citizens' Plan slightly more compact on Reock. HB-2146 is the least compact across the board, often by a significant margin.

Table 3: Comparing compactness scores via one discrete and five contour-based metrics. Each contour-based metric works by comparing the shape to an associated contour. The comparison is illustrated on CD 3 from each of the plans under discussion.

Compactness

	block cut edges (lower is better)	average Polsby-Popper (higher is better)	average Reock (higher is better)
GovPlan	5185	0.381	0.431
CitizensPlan	5266	0.376	0.451
HB-2146	5907	0.321	0.409

	average Schwartzberg (higher is better)	average convex hull (higher is better)	average pop. polygon (higher is better)
GovPlan	1.653	0.826	0.783
CitizensPlan	1.669	0.812	0.772
HB-2146	1.820	0.799	0.752



Using the least-change metric described in the last section, we can see that GovPlan keeps the districts intact to the greatest extent of these three alternatives.

Table 4: In this table, maps are compared by finding a matching (i.e., a correspondence) from the new districts to their best fit in the previous map. The displacement score is then computed by adding up the people who don't share that previous district assignment. Under this metric, the Governor's Plan most closely resembles the court's remedial map.

Least change

	relabeling	displacement
GovPlan	(1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16, 17, 18)	2,438,850
CitizensPlan	(1, 2, 3, 4, 5, 6, 7, 8, 12, 10, 11, 15, 13, 14, 18, 16, 17)	2,755,864
HB-2146	(1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 15, 13, 14, 18, 16, 17)	2,797,612

Finally, I describe the division of incumbent addresses among the districts in the three plans under discussion, using the most accurate addresses I have been able to obtain. Given that an 18-district plan is contracting to just 17 districts, it is inevitable that some incumbents be paired. Each of the three plans under discussion has the same level of incumbent pairing.

Table 5: Each of the three plans has two districts that pair incumbents and one district with no incumbent.

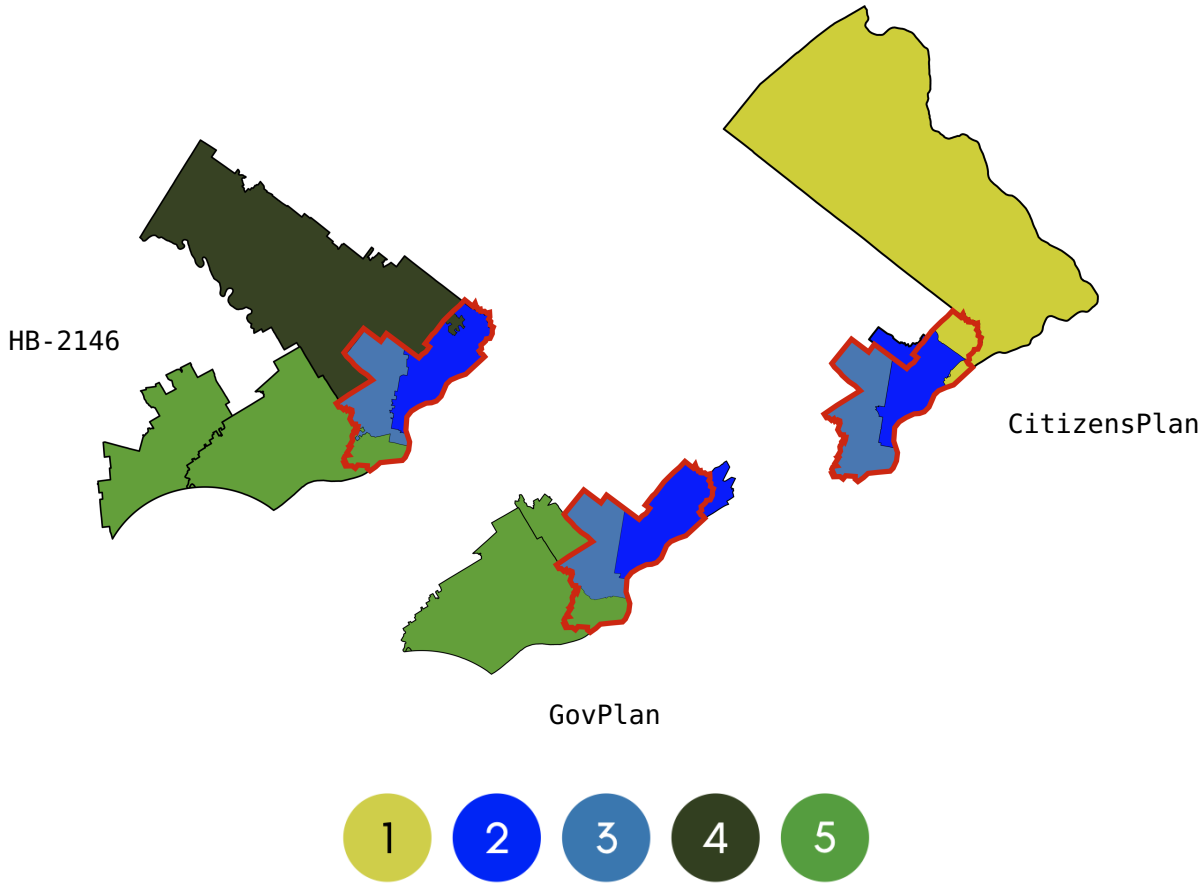
Incumbents by district

CD	GovPlan	CitizensPlan	HB-2146
1	Fitzpatrick	Fitzpatrick, Boyle	Fitzpatrick
2	Boyle	—	Boyle
3	Evans	Evans	Evans
4	—	Dean	Dean
5	Dean,Scanlon	Scanlon	Scanlon
6	Houlahan	Houlahan	Houlahan
7	Wild	Wild	Wild
8	Cartwright	Cartwright	Meuser, Cartwright
9	Meuser	Meuser, Keller	Keller
10	Perry	Perry	Perry
11	Smucker	Smucker	Smucker
12	Joyce, Keller	Thompson	Thompson
13	Reschenthaler	Joyce	Joyce
14	Thompson	Reschenthaler	Reschenthaler
15	Kelly	Doyle	Lamb, Doyle
16	Lamb	Kelly	Kelly
17	Doyle	Lamb	—

6 Communities of interest and minority opportunity to elect

Both GovPlan and CitizensPlan were drawn after a robust public input process and in view of hundreds of collected comments and suggestions. By contrast, my understanding is that the Holt map was based on a metric-centered process that began with a single person working in isolation. To illustrate some of the differences that these origin stories suggest, I will focus on Philadelphia, which was both the location of the densest public commentary (see Figure 3) and is the city most salient for VRA consideration—for Black voters in particular, who are the plurality racial group—in the context of Congressional redistricting.

Figure 2: Comparing the districts that touch Philadelphia (red outline) in the three plans. Other county lines are also shown.



Philadelphia has enough total population for roughly 2.1 Congressional districts, and its residents share a set of broad interests in addition to exhibiting great diversity. This suggests that the city should contain all or most of two districts and a small portion of a third, if the criteria of political boundaries and COIs are paramount. In the plans under consideration, GovPlan has three districts (CD 2, 3, 5) touching Philadelphia, and CitizensPlan has three (CD 1, 2, and 3). The House's Holt-derived plan HB-2146 has four districts that touch the city (CD 2, 3, 4, 5)—with district 4 taking a trident-shaped scoop out of North Philadelphia and district 5 weaving across city lines in two different places in the Southwest.

One way to measure whether the Philadelphia districts effectively secure electoral opportu-

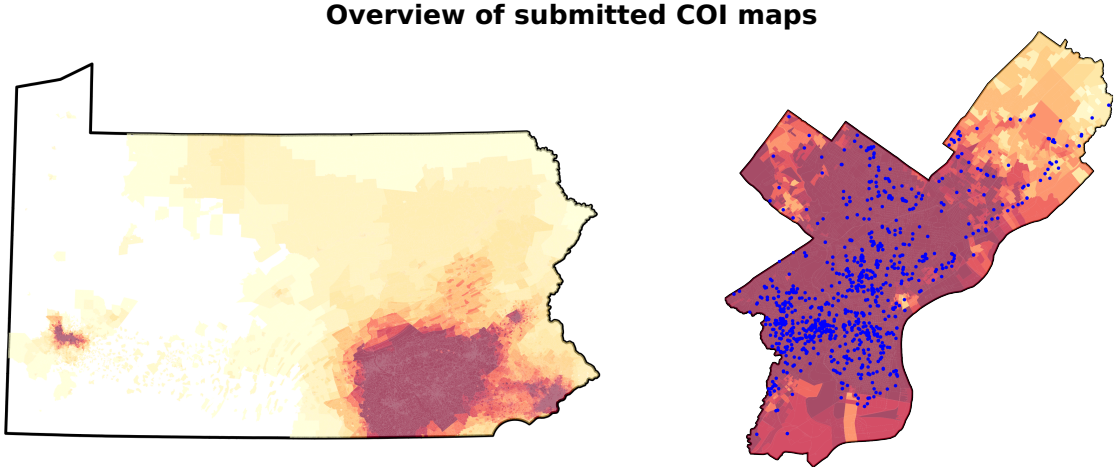
nity is to examine the vote totals from the at-large City Council elections of 2015 (where Black candidates of choice were B.Brown and D.Green) and 2019 (where Black candidates of choice were D.Green and I.Thomas). In these elections, voters could select up to five candidates, and five were ultimately elected.

With respect to the 2015 elections, GovPlan has D.Green as a top-two finisher in all three of its Philadelphia districts, with B.Brown essentially tied in CD 3. CitizensPlan has very strong outcomes for both Brown and Green in its CD 3, but districts 1 and 2 do not have either one in the top two finishers. In HB-2146 as well, only CD 3 has Brown and Green as the top two, while White-preferred candidates do better in districts 2 and 4, and district 5 has a mixed outcome.

In the 2019 outcomes, the GovPlan districts in Philadelphia all have strong showings for Green and Thomas as well as for city-wide progressive favorite Helen Gym. This is true in two out of three CitizensPlan districts that touch the city, while the story is more mixed in HB-2146, where in particular district 4 is way out of line with the city as a whole.

A possible explanation for these indications of more effective opportunity districts in GovPlan is a robust process for collecting public input in the lead-up to line-drawing. The Governor's office set up a website (portal.pennsylvania-mapping.org) to accept comments and maps from the public. One option for submitters was to include a map paired with narrative comments describing their communities of interest. Active from September to December of 2021, the portal received 126 COI submissions. In addition, grassroots organizations like Pennsylvania Voice (pennsylvaniavoice.org) collected hundreds of additional submissions through the same online mapping platform, called Districtr.

Figure 3: This heatmap shows 962 areas mapped by public commenters through the Districtr tool to show their communities of interest. Redder areas received more coverage, with the darkest areas in the heatmap indicating that ≥ 20 submitters described overlapping neighborhood and community areas in that location. The Philadelphia inset also shows (with blue dots) the locations of hundreds of landmarks, or points of interest, placed by those commenters as locations that anchor their communities.



By drawing lines in view of public testimony and the local definitions of community, GovPlan is able to create three Philadelphia-heavy districts (two that are over 90% city districts and a third with over 100,000 Philadelphians) where voting behavior comports with the city overall, better amplifying the voices of city residents. The fact that these districts are better aligned with local preferences of Black voters than in HB-2146, despite having similar shares of Black voting age population, shows that electoral opportunity is a matter of aligning community and not just targeting demographic metrics.

7 Partisan fairness

7.1 Theories of partisan fairness

There are numerous notions of partisan fairness that can be found in the scholarly literature and in redistricting practitioner guides and software. Many of them are numerical, in the sense that they address *how a certain quantitative share of the vote should be translated to a quantitative share of the seats* in a state legislature or Congressional delegation. Others are symmetry-based and deal with ideas of role-reversal between the parties.

The numerical notions and the symmetry notions of partisan fairness all tend to agree on one central point: an electoral climate with a roughly 50-50 split in partisan preference should produce a roughly 50-50 representational split. I will call this the *Close-Votes-Close-Seats* principle. Recent Pennsylvania statewide elections often have voting that is close to even between the two major parties, but the HB-2146 plan approved by the House of Representatives can be seen to systematically convert even voting patterns to a significant Republican advantage in the Congressional delegation.

Importantly, Close-Votes-Close-Seats is not tantamount to a requirement for proportionality. Rather, it is closely related to the principle of *Majority Rule*: a party or group with more than half of the votes should be able to secure more than half of the seats. In fact, Close-Votes-Close-Seats is essentially a corollary (or byproduct) of Majority Rule, making it a centrally important small-d democratic principle. It is not practicable to design a map that *always* attains these properties, but by contrast a map that *consistently thwarts* them should be closely scrutinized and usually rejected.

Unlike proportionality, neither Close-Votes-Close-Seats nor Majority Rule has any bearing on the preferred representational outcome when one party has a significant voting advantage: these principles are silent about whether 70% vote share should secure 70% of the seats, as proportionality would dictate, or 90% of the seats, as supporters of the efficiency gap would prefer. The size of the "winner's bonus" is not at all prescribed by a Close-Votes-Close-Seats norm.

7.2 The limitations of political geography

Some scholars have argued that all numerical ideals, including Close-Votes-Close-Seats, ignore the crucial *political geography*—this school of thought reminds us that the location of votes for each party, and not just the aggregate preferences, has a major impact on redistricting outcomes. In [6], my co-authors and I gave a vivid demonstration of the impacts of political geography in Massachusetts: we showed that for a ten-year span of observed voting patterns, even though Republicans tended to get over one-third of the statewide vote, it was impossible to draw a single Congressional district with a Republican majority. That is, the geography of Massachusetts Republicans locked them out of Congressional representation. It is therefore not reasonable to charge the Massachusetts legislature with gerrymandering for having produced maps which yielded all-Democratic delegations; they could not have done otherwise.

In Pennsylvania, this is not the case. The alternative plans demonstrate that it is possible to produce maps that give the two major parties a roughly equal opportunity to elect their candidates. These plans are just examples among many thousands of plausible maps that convert voter preferences to far more even representation by party. In Congressional redistricting, present-day Pennsylvania geography is easily conducive to a seat share squarely in line with the vote share.

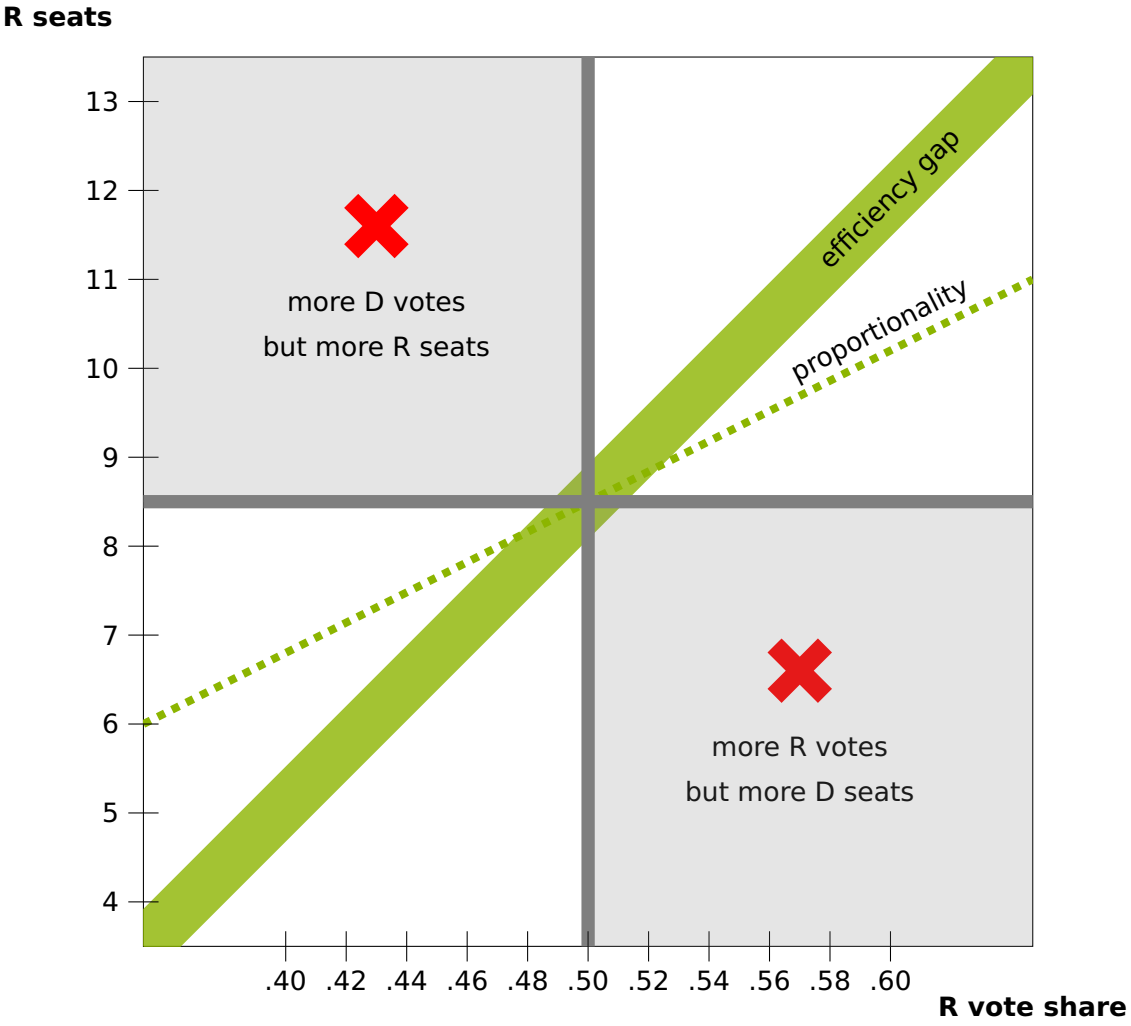
The clear conclusion is that the political geography of Pennsylvania today does not obstruct the selection of a map that treats Democratic and Republican voters fairly and even-handedly.

8 Votes versus seats

To illustrate Close-Votes-Close-Seats, Majority Rule, and other norms of partisan fairness, it is helpful to examine a plot that shows vote shares on one axis and seat outcomes on the other. A plan can be overlaid with a vote pattern to see how the seat share relates to the vote share for that election. Repeating this across a range of different kinds of elections provides a robust view of the performance of the plan.

Majority Rule, then, translates to the idea that the Southeast and Northwest quadrants should be avoided. Close-Votes-Close-Seats now says that if an election is near even placing it horizontally near the center of the plot, then the vertical position should be aimed at the bulls-eye in the middle of the plot rather than falling consistently above or below the target. And many other ideals of fairness, like proportionality and the efficiency gap, can be realized as lines or zones in the plot. This is summarized in Figure 4.

Figure 4: A seats-versus-votes plot. Below, we will plot the results from overlaying a districting plan on a series of elections. The x-coordinate is the vote share for Republicans in that election. The y-coordinate is the number of Republican seats. The figure is set up to show the 50-50 mark as a "bulls-eye" target in the center, meaning that a close vote produced even representation.



8.1 Overlaying the plans on recent elections

To see how a map performs, we can overlay the elections in our dataset and observe how the points fill out the seats-votes plot.

Figure 5: In this figure, the top row shows the outcomes when `2011-Enacted` and `2018-Remedial` are serially overlaid on recent Pennsylvania elections. We see that the overturned plan consistently converts close voting to a Republican representational advantage, while the court's remedial plan maintains electoral responsiveness while upholding Close-Votes-Close-Seats.

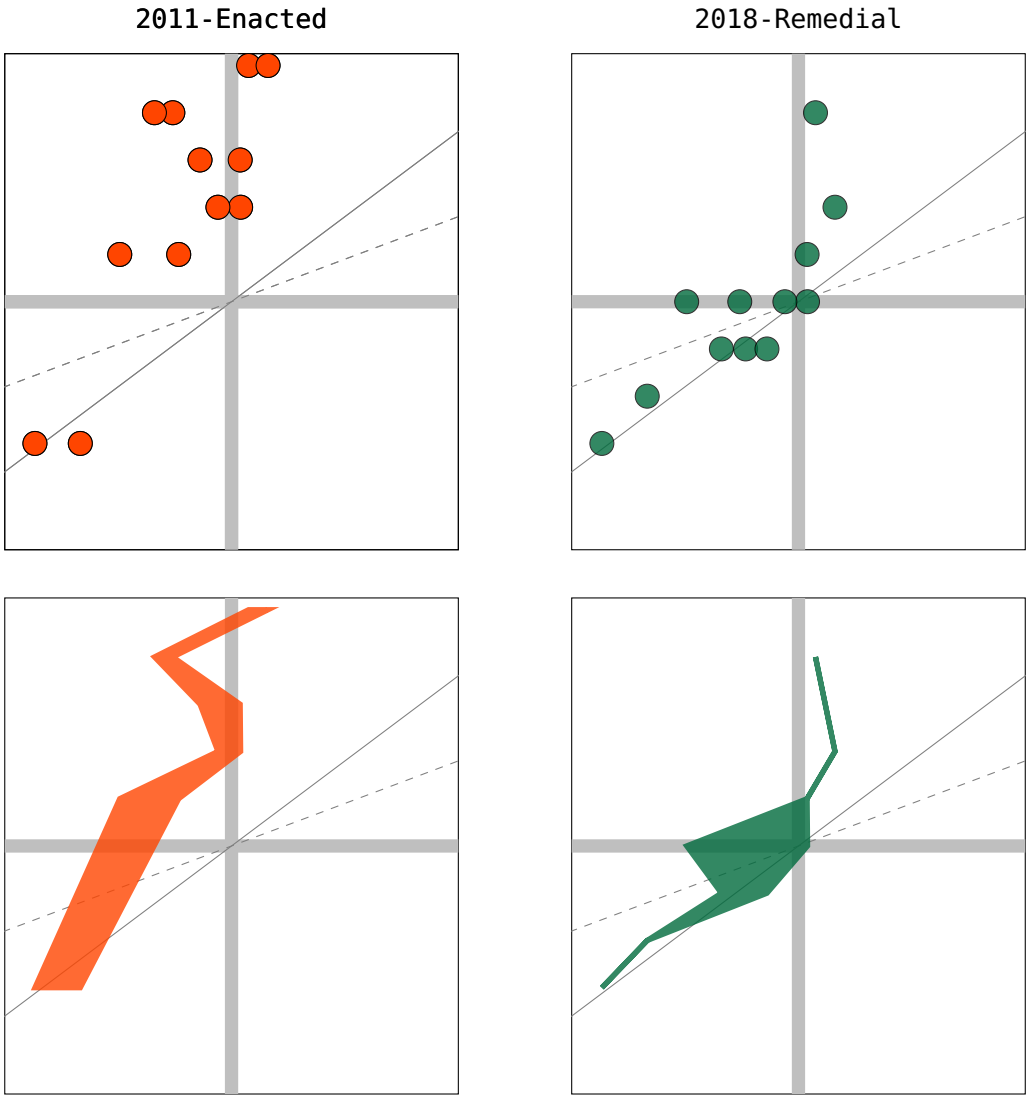
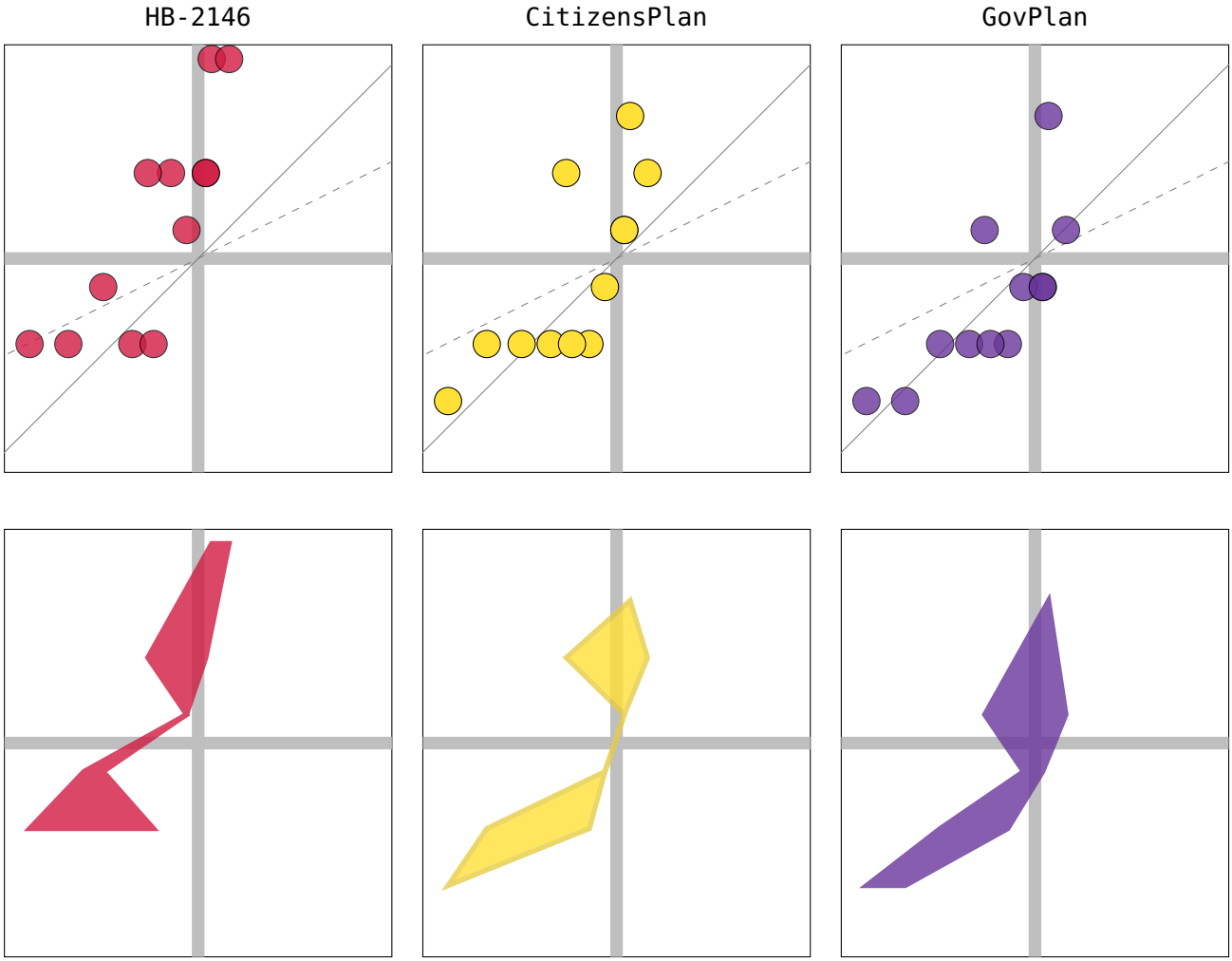


Figure 6: This time, the three new proposed plans are overlaid on the same elections. HB-2146 entrenches a Republican advantage, while CitizensPlan and especially GovPlan are far superior at leveling the partisan playing field.



Just as in 2018, there is no need to accept a plan that provides for a marked partisan tilt; options are available to the court that maintain excellent adherence to the traditional districting principles while treating the parties equally and even-handedly in terms of electoral opportunity. The 2018 remedial plan corrected the bias in its predecessor, and that same pattern is visible in the maps being compared today.

8.2 Partisan fairness metrics

In this section, I present a series of images that reinforce the theme elaborated above: the political geography of Pennsylvania creates a districting landscape that is tilted toward Republican advantage. Thus, blindly drawn Pennsylvania Congressional plans are not conducive to partisan fairness under any partisan metric that I have examined.

However, it is possible to level out this tilted playing field and produce a plan that is far more fair while still upholding the traditional principles. This is illustrated by both `GovPlan` and `CitizensPlan`, in contrast to `HB-2146`.

The metrics seen here can be briefly defined as follows. Without endorsing any of these as normatively correct, we will see that they all report consistent findings about the performance of the three plans considered here.

- *Efficiency gap* is based on the idea of wasted votes, defined as any winning votes in excess of 50%, or any losing votes at all. The EG score is computed by taking total Republican wasted votes minus total Democratic wasted votes, divided by total votes. If the EG score has a magnitude of greater than 8 percentage points, that flags a presumptive gerrymander [8].
- Eguia's artificial partisan advantage [9] compares the outcomes under districted plurality elections to the outcomes under ostensibly neutral political subdivisions, such as counties. It is calculated here by taking counties as the fundamental territorial subdivision of the state: the baseline for political performance for Democrats is the share of the population that lives in counties won by Democrats in a particular election. If the Democratic seat share outperforms that baseline, the metric is positive; otherwise, it is negative.
- The mean-median score is calculated by taking the mean Republican vote share in a district minus the median [10]. It is described as indicating how much of the vote in a state is needed to capture half of the representation.
- The partisan bias score calculates how much of the representation would be captured by each party if the election underwent a uniform partisan swing to a 50-50 share [10]. This is meant to approximate the counterfactual of exactly even voting, and is measured against the presumption that even voting should secure even representation.

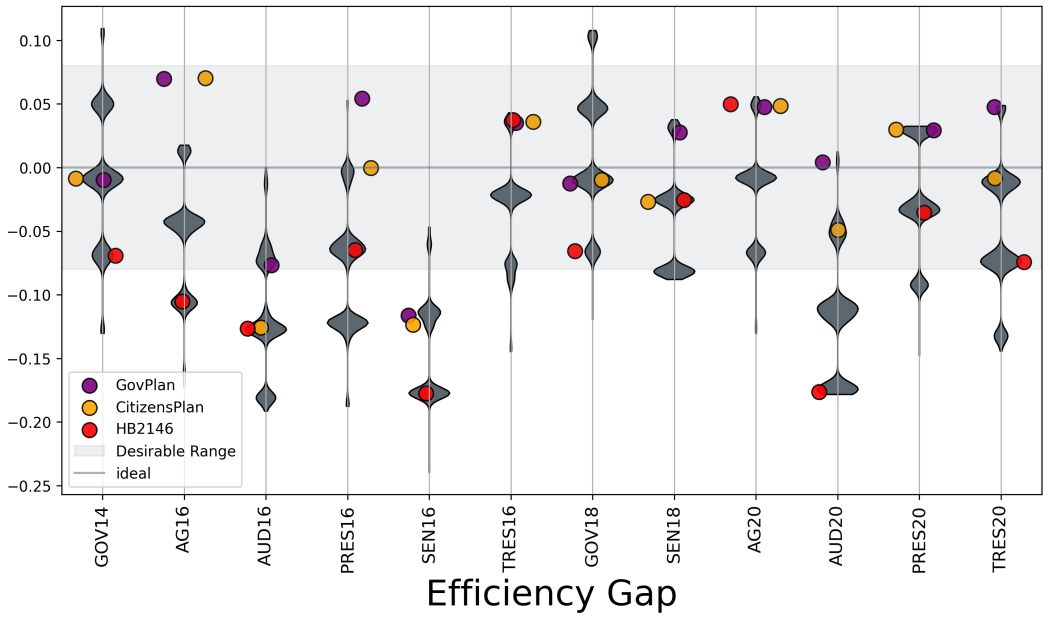
Each of the four metrics presented here is signed, and in each of the three plots, the positive direction indicates Democratic advantage and the negative direction indicates Republican advantage. Therefore it can be useful to sum the metrics over all twelve elections in this dataset; this way, it is easy to distinguish overall whether the advantage always tends to favor the same party.

Table 6: Summary of partisan metrics, summed over the twelve elections in the dataset. In each case, zero is ideal, positive scores indicate overall Democratic advantage, and negative scores indicate overall Republican advantage.

	total efficiency gap	total Eguia metric	total mean-median	total partisan bias
`GovPlan`	+0.10	−0.05	−0.01	−0.18
`CitizensPlan`	−0.17	−0.34	−0.10	−0.65
`HB-2146`	−0.83	−0.99	−0.29	−1.23

The playing field itself is illustrated by the violin plots in Figures 7-8, which show in gray the values achieved by the plans in the ensemble. The colored dots show the plan performance for each of the three proposed plans against the voting pattern in the indicated elections.

Figure 7: Here, an ensemble of 100,000 randomly drawn districting plans (shown in gray) is scored on the *efficiency gap* metric and on Eguia's county-based metric of *artificial partisan advantage*. Random plans tend to exhibit pronounced advantage to Republicans across this full suite of recent elections. `GovPlan` and `CitizensPlan` are seen to correct this tendency.



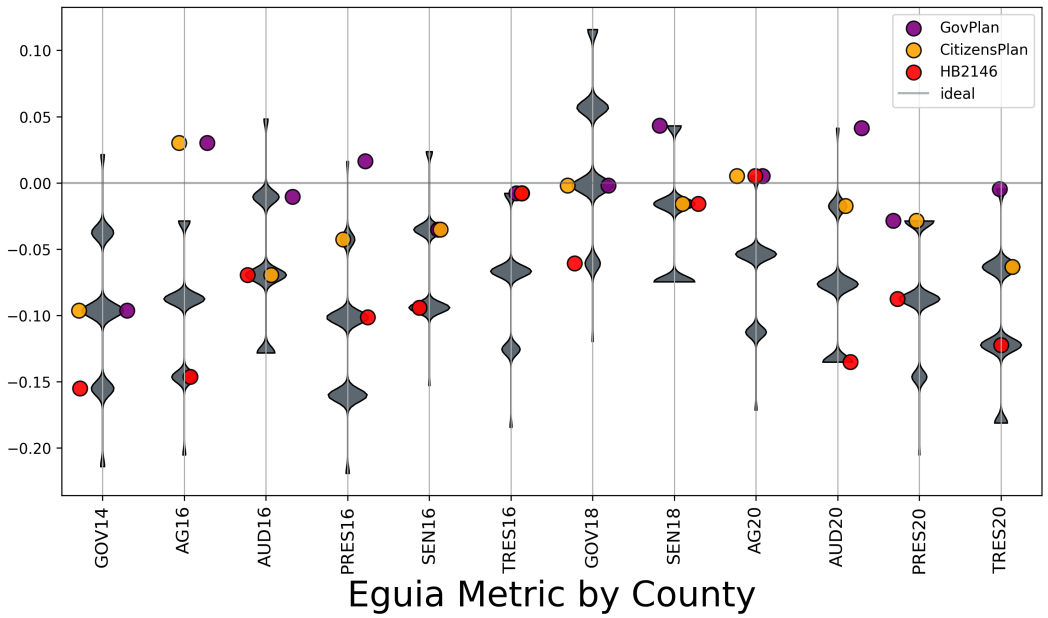
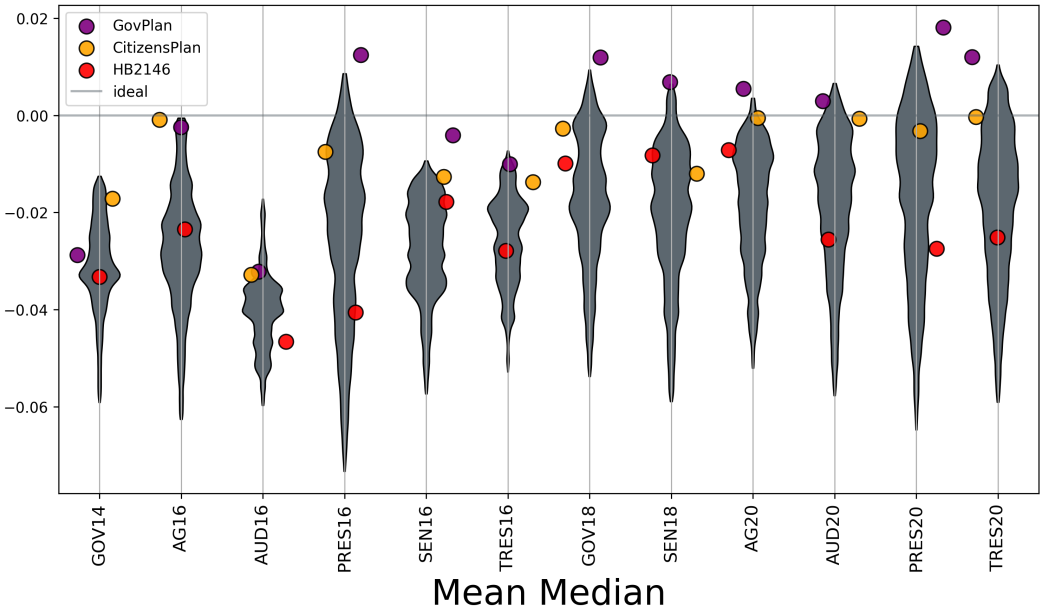
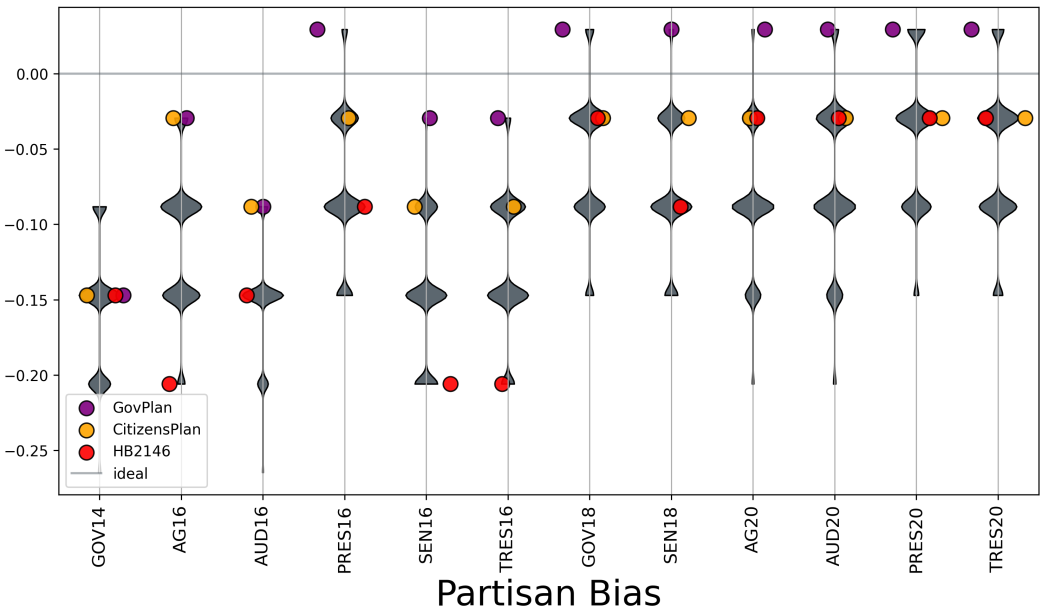


Figure 8: This time, the metrics are from the *partisan symmetry* family, namely the *mean-median score* and the *partisan bias* score. Once again, random plans favor Republicans, while `GovPlan` and `CitizensPlan` temper that tendency.





9 Conclusion

To summarize my findings, I will first return to the majority opinion of the Pennsylvania Supreme Court from 2018 as a touchstone. Justice Todd, having described the potential of computational redistricting to gerrymander, then strikes a more optimistic note.

> We are confident, however, that, technology can also be employed to aid in the expeditious development of districting maps, the boundaries of which are drawn to scrupulously adhere to neutral criteria. Indeed, as this Court highlighted in Holt I, "the development of computer technology appears to have substantially allayed the initial, extraordinary difficulties in" meeting such criteria. Holt I, 38 A.3d at 760; see also id. At 750 (noting that, since 1991, technology has provided tools allowing mapmakers to "achieve increasingly 'ideal' districts") (citing Gormley, Legislative Reapportionment, at 26–27, 45–47); see also Larios v. Cox, 305 F.Supp.2d. 1335, 1342 (N.D. Ga. 2004) ("given recent advances in computer technology, constitutional plans can be crafted in as short a period as one day"). As this Court views the record in this case, in the context of the computer technology of 2018, this thesis has clearly been proven.

These words ring true in 2022. Indeed, the science of computational redistricting has made great strides even in the last four years, and it is now possible to use algorithmic assistance not only to understand the universe of possibility created by the rules and priorities of redistricting, but to find novel combinations and configurations of geography that would have been very difficult to discover in previous census cycles. However, we do not need to outsource our line-drawing to the machines. Plans made with careful consideration of public input, like the Citizens' Plan and the Governor's Plan, can make good on the promise of computational redistricting while centering human geography and shared community interests. These plans reflect the voices of people across the state, secure excellent foundational scores on traditional criteria, and neutralize the tendency for blindly drawn plans to exhibit significant partisan bias. Thus, while protecting all of the good-government principles at play, we can secure a map that treats the parties even-handedly and safeguards the accountability of the representatives to the voters.

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