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# Precinct resources and voter wait times<sup>☆</sup>

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## ABSTRACT

The amount of time that voters wait in line while casting their ballots has been a matter of consternation in electorates across the world and a subject of ongoing academic research in the field of election administration. With this as context, we offer here a study of voting lines that combines observed voter arrival times and measures of precinct processes with simulation results. Empirically, we focus on the town of Hanover, New Hampshire, during the 2014 United States General Election. Voters in Hanover initially authenticate themselves to election officials, mark their ballots in secret, and finally insert said ballots into optical scan tabulating machines. These steps are reasonably generic, and thus the way we study Hanover voters is generalizable to the study of voters in democracies across the world. Our simulations show that line voting evolution can be studied after a simple data-collection plan is implemented, and we show how scholars and election officials can evaluate the effects of changing precinct resources, like the numbers of voter authentication stations and voting booths, on the formation and duration of voting lines.

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## 1. Introduction

The amount of time that voters wait in line while casting their ballots has been a matter of consternation in electorates across the world. For example, the 2010 General Election in the United Kingdom witnessed a surge of voters that overwhelmed numerous

polling stations, leaving “hundreds of voters...unable to vote...despite [having queued] for hours.”<sup>1</sup> During the 2012 General Election in the United States, there were extensive reports of long Election Day and early voting lines across Florida and other key states; long voting lines were reported in the city of Baltimore; and, some voters in Sandoval County, New Mexico, had to wait as long as five hours to vote, an occurrence attributed to a dearth of adequate voting machines in the county's voting centers.<sup>2</sup> Finally, Canada suffered from similar problems in its 2015 General Election; long

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<sup>1</sup> See “General election 2010: Polling queues leave hundreds unable to cast vote,” Guardian US, May 5, 2010, available at <http://www.theguardian.com/politics/2010/may/07/polling-queues-hundreds-unable-vote> (last accessed December 25, 2015).

<sup>2</sup> On the prevalence of lines in a variety of states, see “Complaints about voter IDs, ballots, long lines in election,” Reuters, November 6, 2012, available at <http://www.reuters.com/article/2012/11/06/us-usa-campaign-irregularities-idUSBRE8A51E720121106> (last accessed May 31, 2015). Regarding Baltimore in particular, see “Officials investigate long lines at polls,” The Baltimore Sun, November 7, 2012, available at <http://www.baltimoresun.com/news/maryland/politics/bs-md-poll-complaints-investigated-20121107-story.html> (last accessed May 31, 2015). The experiences of Sandoval County, New Mexico, are described at “County takes responsibility for election flub,” KRQE News 13, August 26, 2014, available at <http://krqe.com/2014/08/26/county-takes-responsibility-for-election-flub/> (last accessed June 9, 2015) and “Lawsuit alleging long Election Day lines in Sandoval County will move forward,” KOB 4, August 26, 2014, available at <http://www.kob.com/article/stories/s3543532.shtml#.VXcPtWD5i-Q> (last accessed June 9, 2015).

lines were reported during “advanced voting” in the run-up to this election and also on Election Day, leading the *The Globe and Mail* to editorialize that “Canada needs to bring the voting process into the 21st century.”<sup>3</sup> These three examples span countries and continents, and they illustrate the complications that extensive lines can cause for voting and, ultimately, perceived electoral legitimacy.

The vernacular of voting in democratic countries differs based on geography. For example, an American “precinct” is roughly equivalent to a “polling station” in the United Kingdom and a “Wahllokal” in Germany. Nonetheless, the basics of voting processes are comparable worldwide (Massicotte et al., 2004). In particular, all voting locations—whether supporting in-person, Election Day voting or early/advanced voting and whether they are precincts with defined and limited jurisdictions or more broadly defined centers with disparate jurisdictions—typically require voters to carry out a sequence of steps consisting of authentication, ballot marking, and ballot insertion into a tabulator or placement in a generic collection device. The exact steps required of an in-person voter in any given voting location will vary depending on applicable voting technology, and the same is true regarding permitted forms of voter identification, but the basic steps taken by in-person voters across the world are roughly similar.<sup>4</sup>

Each of the voting steps noted above—authentication, ballot marking, and ballot insertion—can involve delays and lines. Thus, the study of voting lines writ large and what causes lines to form must treat each distinct step separately. We should not, that is, “black box” the voting process in a way that ignores the fact that voting involves multiple steps, all of which can affect a voter’s overall voting experience and, notably, the amount of time that a voter spends in line.

With this point in mind, we contribute to the literature on voting and waiting in line a study of voting processes in Hanover, New Hampshire. Hanover is a town in the East Coast of the United States, and in-person Hanover voters are required to complete three steps in their overall voting processes. Consistent with our aforementioned arguments about the analysis of voting lines, we treat these steps separately, and our objective is to study line formation in Hanover.<sup>5</sup>

Our approach to this objective is twofold: first, we gathered data on voter processes in Hanover during the 2014 General Election

and, second, we used a simulation to explore these data. Our study is thus illustrative of a hybrid research model, one that combines observed data with a simulation that is more theoretical in nature. The approach described here can be easily transferred to other electoral environments, and it can be used to study how lines might affect certain classes of voters. As will be clear shortly, we focus particular attention on the effect of precinct resources on voting lines, and suppose, for example, that one were concerned that certain voter classes—perhaps certain racial or ethnic groups—disproportionately used resource-poor precincts. Our research design could be used to investigate whether the experiences of these particular voters would have been different under an alternative allocation of resources.

Insofar as our conclusions draw on results from a single voting location, one might be concerned that Hanover may not be representative of precincts across the United States. Indeed, Hanover is a rather small New England town (8636 residents according to the 2010 Census) and is relatively racially/ethnically homogeneous (77.5 percent white, 12.4 percent Asian, and 4.3 percent black) and wealthy (median household income of \$82,875).<sup>6</sup> Nonetheless, from the perspective of studying precinct processes and the factors that lead to voting line formation, Hanover is in fact quite typical, and see Massicotte et al. (2004, pp. 102–141) for a discussion of the broad similarities across democracies in the way that people vote. As in many thousands of voting locations across the United States and the world, voters in Hanover follow a three-step voting process (authentication, ballot marking, ballot insertion). The voting steps in Hanover are generic, and thus the way we study voters in this location—in particular, how our data on in-precinct, voting processes inform our simulation analysis—is easily generalized to the study of voters in democracies broadly defined.<sup>7</sup>

In what follows we describe how we gathered data on 2014 General Election voting processes in Hanover. The technical requirements inherent in our approach are minimal albeit not completely inconsequential; our data-gathering approach relies on labor and access to an Internet-based server. Among other things, our data on Hanover characterize the arrival times of voters and what we call the *voting-step times* for each of the three steps that all in-person Hanover voters faced in their overall voting processes. Based on our voting data from Hanover—arrivals plus voting-step times—we construct a simulation that allows us to model the formation of lines as a function of precinct resources. By resources we mean here authentication stations, voting booths, and optical scan machines. With our simulations we consider both the resources that Hanover actually used in November, 2014, as well as counterfactuals such as, what would voting line evolution in Hanover have looked like if the town’s precinct had fewer optical scan machine available at its voting precinct? And, how would voting line evolution in Hanover been affected by a drastic reduction in voting booths? Our simulation approach to the study of lines is a general one that has nothing to do with Hanover *per se*. The software that we wrote for the simulation will be made publicly available, and

<sup>3</sup> See “Canada needs to bring the voting process into the 21st century,” *The Globe and Mail*, October 15, 2015, available at <http://www.theglobeandmail.com/globe-debate/editorials/canada-needs-to-bring-the-voting-process-into-the-21st-century/article26831411/> (last accessed December 1, 2015) and “‘You get fed up’: Long lines frustrate some voters,” *CTV News*, October 19, 2015, available at <http://www.ctvnews.ca/politics/election/you-get-fed-up-long-lines-frustrate-some-voters-1.2616408> (last accessed December 1, 2015).

<sup>4</sup> As for late 2015, some American states have no voter identification requirements, e.g., Illinois, and others require forms of identification like driver’s licenses, e.g., Arizona. On Illinois, see <http://www.chicagoelections.com/en/when-you-need-id-to-vote.html> (last accessed December 20, 2015), and on Arizona, <http://www.azsos.gov/elections/voting-election> (last accessed December 20, 2015). Variance in voter identification requirements across states is tracked by the National Conference of State Legislatures, and in particular see the report titled “VOTER IDENTIFICATION REQUIREMENTS — VOTER ID LAWS,” available at <http://www.ncsl.org/research/elections-and-campaigns/voter-id.aspx#Two> (last accessed December 20, 2015). See Schaffer and Wang (2009, pp. 400–401) for a discussion of variance in voter identification requirements across counties.

<sup>5</sup> Like many jurisdictions, Hanover also allows absentee voting. Absentee voters, who fill out their ballots in the homes, are not subject to lines in the way that in-person voters are. However, absentee voters face other administrative hurdles, i.e., ensuring that their completed ballots are received by relevant election officials, ensuring that they correctly authenticated said ballots, and so forth. Absentee voting is not part of our analysis, but a comprehensive depiction of the election administrative issues that affect voting should consider absentee balloting. On this point, see Oliver (1996) and Alvarez et al. (2008), for example.

<sup>6</sup> For these statistics on Hanover, see census data at <http://quickfacts.census.gov/qfd/states/33/3333780.html> (last accessed June 5, 2015).

<sup>7</sup> As an aside, New Hampshire allows voters to register on Election Day; this is known as “Same Day Voter Registration.” On account of this, the authentication process for a Hanover voter can involve a registration step in addition to the steps noted in the body of the article. To keep things simple, our results ignore New Hampshire voters who registered on Election Day 2014; incorporating them into our analysis would be straightforward, however, and we discuss this matter in the conclusion. The National Conference of State Legislatures maintains list of states that offer Same Day Voter Registration, and this list can be found at <http://www.ncsl.org/research/elections-and-campaigns/same-day-registration.aspx> (last accessed May 31, 2015).

this will enable researchers and election officials to model line formation as a function of voter arrival processes and available resources.

Our simulations show, not surprisingly, that reducing precinct resources leads to longer lines and more waiting by voters. However, the motivation for our research is not to illustrate this somewhat obvious point. Rather, what we seek to do here is to show how scholars and election officials worldwide can evaluate the tradeoff that exists between election resources and voter waiting. Election administration jurisdictions—counties, cities, and towns in the United States, communes and arrondissements in Senegal, and *kommunes* in Denmark, for example—need to consider how they allocate resources for election work and, in a jurisdiction that contains multiple precincts, how to allocate resources across precincts. An optimal allocation of resources depends on knowing the marginal cost of, say, reducing one precinct's resources in favor of another's. The cost of such a reduction, as we show here, will be paid by voters forced to wait in line, and the precise amount of this cost depends on voter arrival process as well as on voting-step times. Our simulations make this point clear, and they show how changes in resources interact with arrivals and voting-step times to generate precinct lines.

In the next section of the article we discuss contemporary literature on voting lines. We then discuss how during the 2014 General Election we measured the voter arrival process in Hanover and how we assessed the three-step voting process inside of its polling station. The next section of the article presents simulation results that model the evolution of lines as function of precinct resources, and we conclude with a discussion of our main findings and directions for future research.

## 2. Election administration and voting lines in elections

The study of voting lines is one component within the field of election administration, an extensive field that crosses political science, public administration, and computer science. Scholars of election administration focus on the mechanics of voter registration and the rules that prescribe when voters are allowed to register (e.g., Hanmer, 2009; Herron and Smith, 2013; Alvarez and Hall, 2014; Burden, 2014); the forms of identification that voters need in order to cast their ballots (e.g., Barreto et al., 2007; Barreto et al., 2009; Erikson and Minnite, 2009; Hale and McNeal, 2010); where voters physically cast their ballots (e.g., Oliver, 1996; Stein, 1998; Dyck and Gimpel, 2005; Barreto et al., 2006; Brady and McNulty, 2011; Alvarez et al., 2012; Stein and Vonnahme, 2014; Biggers and Hanmer, 2015); the types of technology that voters use when registering their preferences over candidates and ballot measures (e.g., Knack and Kropf, 2002; Tomz and van Houweling, 2003; Alvarez and Hall, 2010; Stewart III, 2014); the formats of voting interfaces (e.g., Wand et al., 2001; Kimball and Kropf, 2005; Herrnson et al., 2006; Frisina et al., 2008; Kropf, 2014); when voters are allowed to vote (e.g., Neeley and Richardson, 2001; Herron and Smith, 2012, 2014); and the poll workers who manage elections at the local level (e.g., Kimball and Kropf, 2006; Hall et al., 2007; Hale and Slaton, 2008; Hall and Moore, 2014).

The study of voting lines can be thought of as a public administration matter as opposed to a matter purely of election law (Montjoy, 2008). Electoral statutes specify many features of election conduct—e.g., ballot access laws for candidates, requirements for voting, types of permissible technology—but lines fall outside of the types of issues typically engaged in legal election disputes. Given the lack of a legal framework that surrounds lines, perhaps it is not surprising that, compared to the varied subjects noted above, the state of knowledge on voting lines remains limited and the policy responses to perceived line issues uneven.

In her global assessment of “why elections fail,” Norris (2015, p. 3) observed that “[n]umerous types of flaws and failures undermine elections,” including inaccessible polling stations, poorly trained poll workers, long lines, inadequate voting supplies, incorrect voter registers, and jammed voting machines. These factors and a plethora of others may jeopardize the integrity and legitimacy of an election, be they the result of “accidental maladministration,” “official incompetence,” or “intentional acts of partisan fraud and manipulation” (p. 133). Images of voters queuing in seemingly interminable lines can be seen around the globe, from developing countries such as Kenya (Long et al., 2013) and Venezuela (Kornblith and Jawahar, 2005), to developed ones, such as the United Kingdom (James, 2014). In the United States, prominent voting line issues during the 2008 General Election were not ameliorated in 2012; “[Since 2008] policy changes in many states have increased, not reduced, the stress on Election Day polling operations” (Levitt, 2013, p. 466). Long wait times in 2012 and overall voter experiences helped spur United States President Barack Obama to form the Presidential Commission on Election Administration, whose final report recommended that, “[A]s a general rule, no voter should have to wait more than half an hour in order to have an opportunity to vote” (p. 14).<sup>8</sup>

Notwithstanding historical problems with lines, compared to other democracies the United States may be advantaged in the realm of voting lines. Many voters in American General Elections now cast early or absentee ballots (Gronke, 2012), thus avoiding crowds on Election Day; in the 2014 Midterm Elections, for example, only approximately 60% of voters cast in-person, Election Day ballots.<sup>9</sup> Nonetheless, the majority of voters around the world cast still vote on a single Election Day at a local precinct.<sup>10</sup> As such, the likelihood of an electoral meltdown due to excessive wait times at the polls has even greater import in the comparative context (Birch, 2011; Hyde, 2011).<sup>11</sup>

Broadly speaking, within the scholarly literature on election administration there are two approaches to the study of voting lines and their consequences. In one approach, scholars draw on observational data at the individual or precinct level and seek to understand whether there are differential patterns of voter wait times across jurisdictions and across voter demographic profiles. Some studies in this vein also seek to determine whether limitations in voting jurisdiction resources are associated with long lines. The second approach to the study of voting lines relies on queuing theory and in some cases on simulations.

An archetype of the first approach to voting line research is Stewart III (2013). Based on the Survey of the Performance of American Elections (SPA), Stewart III analyzes the 2012 General Election and highlights the tremendous variance in wait times across voting precincts in the United States. Stewart III's survey evidence on wait times covers many jurisdictions across the country and shows that, in November, 2012, Floridians waited on average longer to vote than the residents of any other state. Stewart III also draws attention to an urban/rural split in wait times insofar

<sup>8</sup> The Commission's website and final report are available at <http://www.supportthevoter.gov> (last accessed May 26, 2015).

<sup>9</sup> See “The 2014 EAC Election Administration and Voting Survey Comprehensive Report,” available at [http://www.eac.gov/assets/1/1/2014\\_EAC\\_EAVS\\_Comprehensive\\_Report\\_508\\_Compliant.pdf](http://www.eac.gov/assets/1/1/2014_EAC_EAVS_Comprehensive_Report_508_Compliant.pdf) (last accessed December 20, 2015).

<sup>10</sup> As of 2004, in more than 90 percent of democracies voters in legislative elections cast ballots on a single day (Massicotte et al., 2004, p. 116).

<sup>11</sup> The lack of a single Election Day might help with line prevention, but there could be other, downstream consequences of the trend, at least in the United States, toward early and absentee voting. Early voters, for example, register their preferences over candidates before campaigning is over, and hence they cannot respond to late-breaking campaign news in the way that Election Day voters can.

as urban voters tend to have longer waits than their rural counterparts. Kimball (2013), also drawing on the SPAE, has similar findings in terms of voting lines in urban locations. In a national survey of voter wait times in the 2008 General Election, Alvarez et al. (2009) find that “20% of African American voters waited more than half an hour to vote, compared to 14% of Whites and 15% of Hispanics” (p. 2).

Drawing on observational data and the premise that congested precincts will tend to close late, *ceteris paribus*, Herron and Smith (2015) consider precinct closing times in Florida in the 2012 General Election. They identify racial patterns in late-closing precincts in Florida and in particular show that Hispanic Election Day voters in the state disproportionately used late-closing precincts in 2012. In another study, Herron et al. (2015) consider voter wait times in Miami-Dade County, Florida, in the 2014 General Election, and they show that voters forced to wait a long time to vote had disproportionately low levels of confidence in electoral processes, *ceteris paribus*. Such a confidence cost compounds the time tax that waiting at the polls imposes on voters (e.g., Mukherjee, 2009).

In one of the most detailed studies of the correlates of voting lines, Spencer and Markovits (2010) examine voting times in 30 California precincts during the state's 2008 Presidential Primary. Among other things, Spencer and Markovits show that voters using electronic voting machines take disproportionately long to vote and that voting lines are longest during peak voting hours. Spencer and Markovits is the only study we know of that tries to estimate the deterrent effects of long voting lines, and it concludes that approximately 1.89 percent of voters who were in one of their 30 monitored voting lines departed before actually voting. Another study of the cause of long lines is Highton (2006), who uses precinct-level data from the 2002 gubernatorial election and the 2004 presidential election in Ohio to assess whether there was a “causal relationship between the number of registrants per available voting machine (RPM) and turnout” in the state's Franklin County. Highton argues that “machine scarcity was a cause of lower turnout” and estimates that, in the 2004 presidential election, 21,786 more people would have voted in Franklin County if there had been lower RPMs.

The second approach to the study of voting lines relies explicitly on queuing theory and simulation. For example, Allen and Bernshteyn (2006) study Franklin County in the 2004 presidential election. Similar to Highton (2006), their focus was voting equipment—namely, Franklin County's use of direct-recording electronic (DRE) machines—but Allen and Bernshteyn also consider ballot length as a factor that might affect voter wait times. They predict that 23,445 more people would have voted in the 2004 presidential election in Franklin County if all the precincts there had been able to process voters in a timely fashion. Allen and Bernshteyn claim that this would have been possible had election administrators used their algorithm to determine how many machines and poll workers were needed throughout the day to minimize wait time and maximize efficiency.

Another simulation-based study of voting lines is Yang et al. (2013), who are interested in how to allocate voting resources across precincts in a way that is fair to all voters; this objective parallels Allen and Bernshteyn's discussion of malapportionment of resources in Franklin County. Yang et al. argue that algorithms for allocating machines to jurisdictions should be based on voter equity in wait times as opposed to voter access to machines. And, they argue via simulation that an algorithm they developed is better for voters than an algorithm that defines voter equity based on voting machine utilization. Another simulation study of voting lines is Edelstein and Edelstein (2008), who posit that the use of electronic voting machines causes long lines. A precinct would need many more electronic machines than optical scan machines to achieve a

similar level of performance, and this is problematic, according to Edelstein and Edelstein, given the relatively high costs of the former.

We contribute to the literature on voter wait times and election administration more broadly with a simulation-based study of lines in Hanover, New Hampshire. Our study is a hybrid of the two approaches to voting line research we noted earlier: its results draw on both observational data and the results of simulation. Although, demographically speaking, Hanover is not necessarily representative of voting jurisdictions across the United States, with respect to voting processes Hanover voters are typical voters. Here, our use of the word “typical” refers to democratic voters across the world. Hanover voters face a three-step voting process, and two things determine the rate of progress that a given Hanover voter makes through the voting process: the time required for said voter to complete each voting step and the number of stations or slots in the Hanover precinct dedicated to each step. Our data collection exercise is similar to that in Spencer and Markovits (2010) insofar as its results are based on observed times per voting step for a large set of Hanover voters. As such, our study is observational in nature and also simulation-based as it uses observed voting-step times to study the effect of resource changes on voting lines.

We argue below that our hybrid mode of data collection in conjunction with simulation exemplifies the type of overall analytical approach that scholars and election officials alike can employ when they want to study the evolution of voter lines. Indeed, this is the ultimate objective of our research. One perspective of our results is that they constitute a proof of concept for our data collection exercise combined with a simulation. As we will see shortly, voting lines in Hanover were not problematic in any sense during the 2014 General Election, and our simulations reveal that this is because the Hanover voting precinct is so heavily endowed with voting resources. They show as well that voting lines in Hanover would indeed be a problem if this resource situation were to change.

### 3. Collecting data in Hanover, New Hampshire

On November 4, 2014, we collected individual-level data on voter arrivals and within-precinct processes in Hanover High School, the location of the Hanover voting precinct. For the purposes of our study, it is not enough for us to determine whether, say, voter authentication takes on average 40 s or 50 s; rather, for each step in the Hanover voting process, we need to know the full distribution of authentication times across a set of voters. Among other things, this means that we had to study the three separate steps in the Hanover voting process: authentication, ballot marking, and ballot insertion. In the introduction we argued that these steps are plausibly generic, and here we justify this claim.

#### 3.1. Authentication

New Hampshire state law imposes a voter identification requirement, and this means that the authentication step in Hanover required each voter to proffer a form of identification before receiving a ballot. In the absence of a formal identification requirement, there would still be an authentication step in the Hanover voting process although we might call said step a voter check-in step.<sup>12</sup> According to the National Conference of State

<sup>12</sup> Prior to the implementation of New Hampshire's voter identification law, a newly-arriving voter at the Hanover precinct would give his or new name to an election official. The official would locate this name on a list of voters, and then would give a ballot (or possibly ballots) to the voter.



Legislatures, 31 of 50 states as of mid-2015 require voters to provide a form of identification prior to voting.<sup>13</sup> Many countries have identification laws as well (Massicotte et al., 2004; Schaffer and Wang, 2009).

### 3.2. Ballot marking

In Hanover, what we call ballot marking—the second step of the voting process—is the physical step of making a paper ballot with a black pen. This step is generic even though the act of ballot marking might involve different physical behaviors depending on a jurisdiction's voting technology. For example, in jurisdictions that rely on electronic voting machines, there are no formal ballots; in these jurisdictions, ballot marking and ballot insertion are not distinct steps (e.g., Alvarez and Hall, 2010).

### 3.3. Ballot insertion

We have already noted that Hanover uses optical scan voting machines in its precinct. Moreover, Hanover is what is called a “precinct count” jurisdiction, meaning that ballots are counted at the precinct after voters insert them in optical scan tabulators. In contrast, some optical scan precincts in the United States are “central count.” These precincts collect optical scan ballots which are then counted in a central location after voting has concluded. Optical scan precincts that are central-count do not technically have a ballot insertion step. However, these precincts must collect their voters' ballots, and in terms of individual voter behaviors the step of collecting ballots is analogous to what we call here the ballot insertion step. In Germany, for example, completed ballots are placed in an urn where they are later counted by hand.<sup>14</sup> Regardless, the final step of a voting process that uses a paper ballot is one in which a voter places his or her ballot in some device or container.

Like others before us we conceptualize of precincts as queues which involve multiple steps. Each step in the vote-casting process has an associated distribution of what we previously called voting-step times, and these times describe how long a voter takes to complete various required voting steps.<sup>15</sup> A step can have a line preceding it if there are more voters demanding positions in a given voting step than there are available slots. Preceding the first voting step is the voter arrival process, which describes the rates at which voters come to the precinct.

Queuing processes are subject to both balking and reneging. In the context of a voting precinct, a voter is said to balk if, upon arriving and observing a long line, she declines to join a queue. Similarly, a voter is said to renege if, after joining a queue, she departs before completing it. The results that follow assume that balking and reneging rates are zero. This means that we assume that voters who want to vote are not deterred by long lines nor, conditional on joining it, do they leave a line before voting.

To characterize the operations of the Hanover precinct we contracted with a set of 14 research assistants who were stationed at the entrance of Hanover High School and also within the school. There were at least two research assistants on the premises of the school at all times. Each assistant wore a bright orange shirt that

identified him or her as a researcher gathering data on precinct processes, and officials in Hanover gave our research assistants permission to be on site. Our research assistants did not themselves vote while gathering data for the project described here, and they were instructed to be as unobtrusive as possible during their shifts. The assistants were allowed to stand right next to the precinct entrance within the high school; this is important because it means that our data are not contaminated by passers-by who were visiting Hanover High School for reasons unrelated to the 2014 General Election.

The Hanover High School gymnasium was used solely for voting on November 4, 2014, and it is pictured in Fig. 1. The figure's hand-drawn map is a copy of the actual diagram used by precinct officials to set up the Hanover precinct. One can see at the top of the map where voters enter (“Registered Voters”); where they authenticate (“Ballot Check-In Tables”); where they mark their ballots (“Curtailed Voting Booths,” “Fold-up Voting Booths,” and “Card-board Voting Booths”); and, finally, where they insert completed ballots into optical scanning machines (“Ballot Box #1” and “Ballot Box #2”). While Fig. 1 is not entirely to scale, e.g., Hanover has 76 ballot marking stations, it nonetheless shows how the flow of voters is intended to move through the Hanover High School gymnasium. The figure also shows where voters who plan to register on Election Day enter the gymnasium (“Same Day Registrations”) and where other election-related activities take place (e.g., “Absentee Ballot Processing”).

## 4. Voter arrivals

The Hanover precinct opens at 7:00 am on Election Day, and barring unusual circumstances no voter is allowed to join a line to vote after 7:00 pm. We mention such a caveat here because a fire alarm went off at Hanover High School a bit after 6:00 pm on November 4, 2014, and a small number of voters (eight) was allowed to cast their ballots after polls would have ordinarily closed. A New Hampshire state judge later ruled that these ballots could be counted.<sup>16</sup> We explain shortly how we deal with the fire alarm issue.

To measure the time that each Hanover voter arrived at Hanover High School, a research assistant stationed directly in front of the gymnasium's entrance used a mobile web application. The application displayed a screen which was accessible via a smartphone (all of our research assistants had smartphones). The so-called arrival tracking screen, which is shown in Fig. 2, displayed a set of 15 buttons. When an assistant pushed one of the pictured buttons, the application recorded a timestamp on an offsite server and recorded as well the type of button pressed.<sup>17</sup> As Fig. 2 makes clear, the buttons available to our research assistants corresponded to voter gender and race/ethnicity, and we allowed for two genders (male and female) and four races/ethnicities (white, Hispanic, black, and Asian). The web application also had buttons without race/ethnicity, and these buttons were labeled “Male” and “Female.” Lastly, there was one button labeled “Someone,” and this button recorded a voter's arrival time without respect to any voter characteristics.

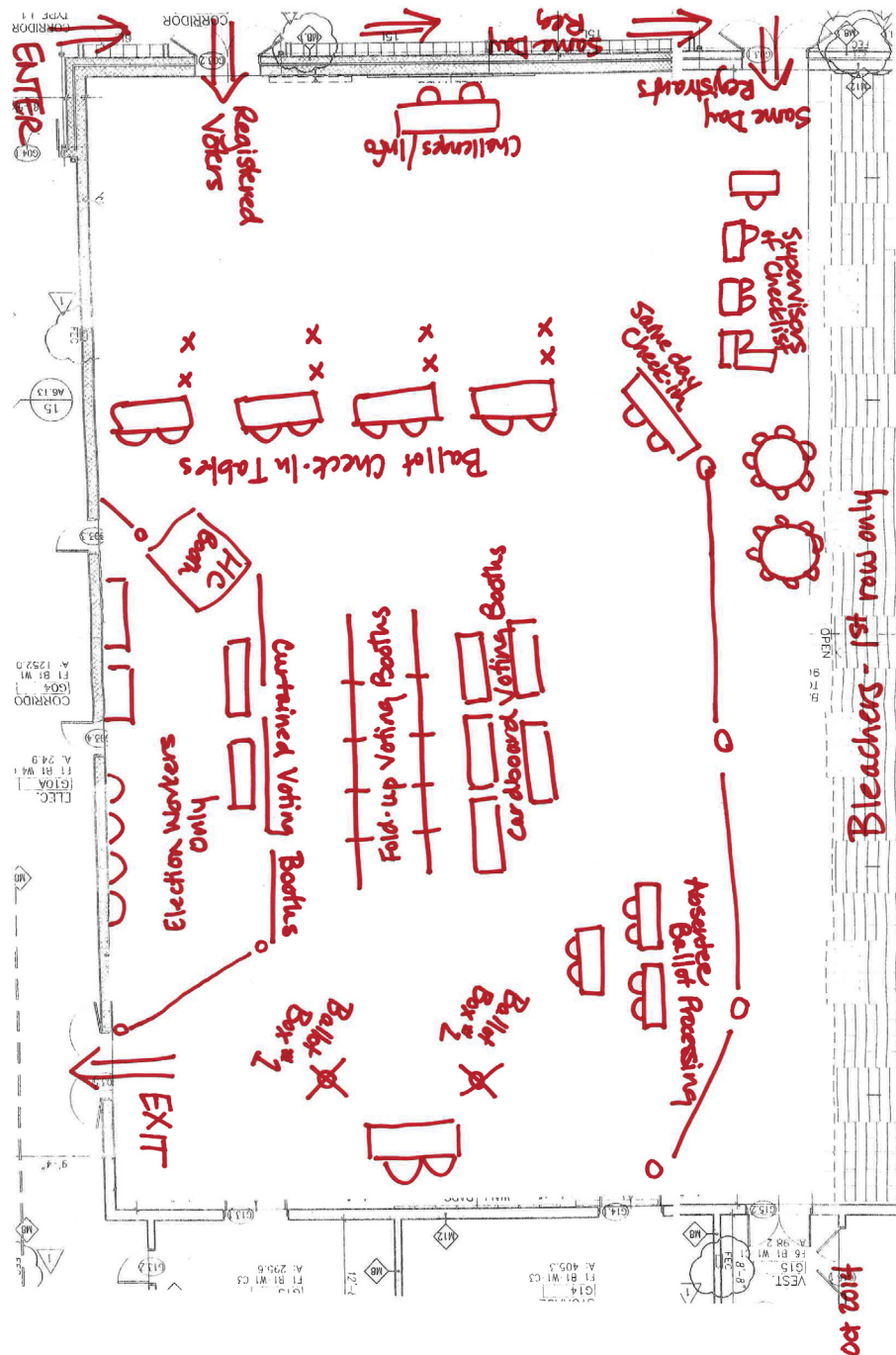
<sup>13</sup> See Table 1 of “VOTER IDENTIFICATION REQUIREMENTS — VOTER ID LAWS,” as described in fn.7.

<sup>14</sup> For details on German election law, see <https://www.bundeswahlleiter.de/de/bundestagswahlen/downloads/rechtsgrundlagen/bundeswahlordnung.pdf> (last accessed January 12, 2016).

<sup>15</sup> In queuing literature, one would see the term *service time* as opposed to voting-step time. Here we use the latter because we feel that it better captures the idea that voters are active agents in voting processes as opposed to individuals who are served.

<sup>16</sup> See “Fire Alarm Postpones Hanover Vote 20 Minutes,” *Valley News*, November 5, 2014, available at <http://www.vnews.com/news/14215284-95/fire-alarm-postpones-hanover-vote-20-minutes> (last accessed May 28, 2015) and “Fire alarm sounds at polling place in Hanover,” *WMUR.com*, November 4, 2014, available at <http://www.wmur.com/politics/fire-alarm-sounds-at-polling-place-in-hanover/29532968> (last accessed May 28, 2015).

<sup>17</sup> There was in principle a small amount of latency between button-pushing on site at Hanover High School and receipt of signal on a server. We treat this latency as negligible.



**Fig. 1.** Hanover High School Gymnasium.

We instructed our research assistants not to engage voters who were approaching the precinct entrance inside Hanover High School, and thus they were not able to verify the genders and races/ethnicities of the individuals whose arrivals they tracked. Consequently, the assistants had to use their judgment when deciding which button on the arrival screen to press upon seeing a new voter. We instructed the assistants that pressing a button for each voter who arrived was more important than determining, say, the race/ethnicity of a particular voter.

Given Hanover's relative racial/ethnic homogeneity, we did not anticipate when planning our research project that we would be able to characterize the white voter arrival process as distinct from,

say, a Hispanic voter arrival process. However, we do anticipate using our voter-tracking web application in environments outside of New Hampshire, and hence we designed it so that it includes various race/ethnicity buttons. This set of buttons could be expanded should we want to keep track of other voter characteristics in the future.

After the aforementioned fire alarm went off in Hanover High School, our research assistant then tracking voter arrivals had to leave the entrance to the school gymnasium. This assistant, however, attempted to keep track of new voter arrivals outside of the school to the extent that this was possible. When the fire alarm situation was resolved (there was no fire to begin with), this

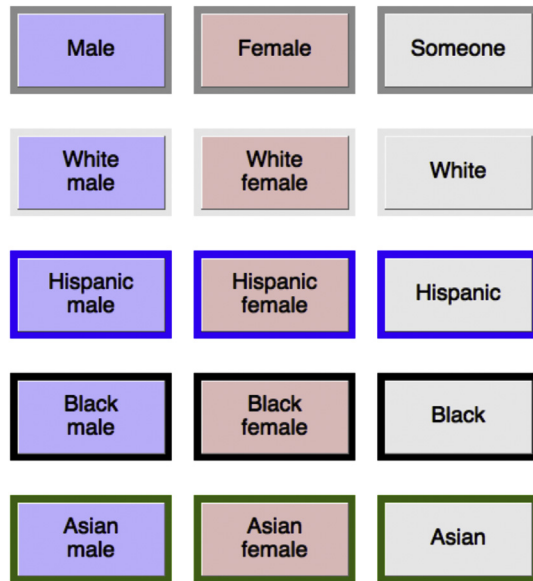


Fig. 2. View of arrival tracker web page.

assistant returned to the entrance of the high school gymnasium.

On November 4, 2014, our research assistants recorded 4229 total voters at Hanover High School. According to the New Hampshire Secretary of State, Hanover had 4270 in-person votes cast on Election Day.<sup>18</sup> These two numbers are not identical, but are nonetheless quite close. Given the confusion caused by the fire alarm, we are very pleased that the number of voters whose arrivals we tracked is so close to the number of voters who cast in-person ballots.

Fig. 3 describes the recorded arrival times of Hanover voters, and the figure pools arrivals by minute. It also disaggregates arrivals by gender. Actual arrivals—depicted in the figure's background in light gray—are somewhat noisy, but a superimposed loess smoother—shown in black—provides useful structure to the observed arrivals. Smoothed male and female arrival processes are shown in dashed and dotted curves, respectively. For obvious reasons we have somewhat less confidence in the voter arrivals that are to the right of the vertical line in Fig. 3; this line denotes the approximate time of the fire alarm.

Looking at the smoothed black curve that describes total voter arrivals, Fig. 3 suggests that approximately five voters arrived per minute during the initial two hours of Election Day 2014; that this arrival rate increased to around six voters/minute around 10:00 am; and, that the arrival rate of voters per minute fluctuated between five and seven throughout the day. The arrival rate dropped precipitously after 6:00 pm, but we cannot know if this is a regular facet of the voter arrival process in Hanover or a reflection of the fire alarm that disrupted voting.

In terms of gender, it appears from Fig. 3 that male and female voters in Hanover had somewhat different arrival patterns. Compared to the female voter arrival rate, the male arrival rate was relatively constant—approximately 2.5 voters per minute—throughout the day. The female arrival rate initially was approximately two voters per minute, and this rate then increased to around three voters per minute by 10:00 am. The female arrival

rate had two local peaks during the afternoon of November 4, 2014, and these peaks occurred around 2:45 pm and 4:15 pm.

It is natural to wonder whether the gender differences in arrival rates and whether the overall patterns we observe in Fig. 3 hold in general. To this end, Spencer and Markovits (2010) describe voter arrival processes in 30 precincts across three counties in California during the 2008 Presidential Primary in that state. Roughly speaking, Spencer and Markovits find that arrivals are moderately high in the morning, drop around noon, and then surge in the evening. This pattern is similar but certainly not identical to what we see in Fig. 3; in the latter we observe a late afternoon surge but not a strong drop-off in the middle of the day.

To the best of our knowledge, the factors that drive temporal variability of voter arrival rates are not well-known within the election administration research community. Our Hanover arrivals in Fig. 3 may be confounded by the particular demographics of Hanover; by the fact that the 2014 General Election is a mid-term election; and, by factors idiosyncratic to voters in New Hampshire. Similarly, Spencer and Markovits's findings on arrivals during the 2008 Presidential Primary in California may be confounded by the fact that primary voters have different voting habits than general election voters. Until voter arrivals processes are tracked at many different types of precincts across the United States and across different types of elections, our knowledge of these processes will remain largely anecdotal.

Finally, we are not aware of any voters who reneged once they joined the line to vote. Notwithstanding the momentary confusion caused by the fire alarm in Hanover High School, voting on November 4, 2014, proceeded smoothly throughout the entire day. However, one might be concerned about a Hawthorne Effect, induced by our research assistants, on voter reneging (e.g., Kraut and McConahay, 1973). Namely, the presence of orange-shirted observers with smartphones may have encouraged voters to stay in line when they otherwise might not have wanted to do so. While we cannot be completely sure that voters did not behave this way, conversations with a number of Hanover voters in the days after the 2014 General Election suggest that a Hawthorne effect on reneging was unlikely. Namely, the vast majority of Hanover voters with whom we discussed voting processes in the then-recent 2014 General Election professed to be completely unaware that anyone was tracking them. It is also notable that there are various precinct officials scattered throughout the Hanover High School gymnasium, and our research assistants might easily have been confused for such officials. Thus, if there were a Hawthorne Effect that depressed voter reneging rates, it almost certainly would not have been any more meaningful than the comparable effect induced by the presence of town officers or the occasional member of the local press reporting on activities in the Hanover precinct. The matter of reneging and how to study it is certainly worthy of future study.

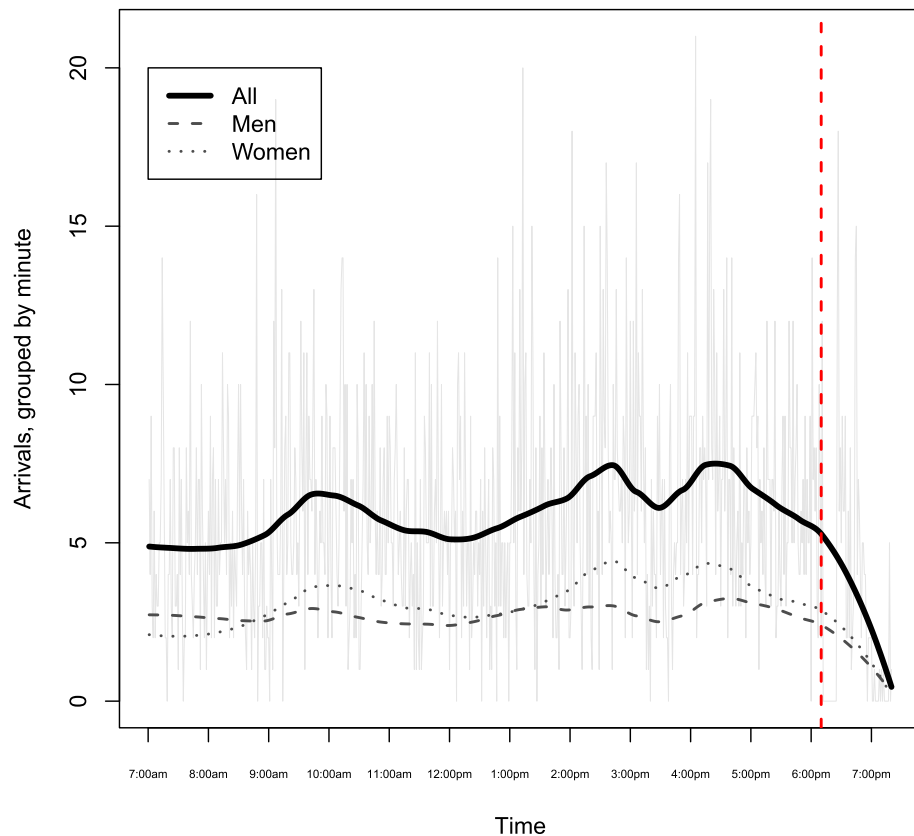
## 5. Measuring voting steps

Beyond keeping track of voter arrivals, our research assistants tracked voters inside of the Hanover precinct. To do this they used a different web application, one that allowed them to indicate when a voter started a particular step—authentication, ballot marking, or ballot insertion in an optical scan machine—in the voting process and when she finished said step. Each step in the voting process is thus associated with a distribution of durations, and the step times tracked by our research assistants are displayed in Fig. 4.

The three histograms in Fig. 4 are right skewed, which is not surprising given that voting-step times are bounded below by zero. There is a fair amount of variance in how long voters took to complete their three steps, and we see that ballot insertion was a relatively fast step. Table 1 describes some basic statistics across the

<sup>18</sup> The Secretary of State provides an Excel file that breaks down voter turnout in the 2014 General Election by county and town. This file is titled "BallotsCast2014-general.xls" and is available at <http://sos.nh.gov/WorkArea/DownloadAsset.aspx?id=8589942364> (last accessed May 28, 2015).





*Note: shows actual arrivals in grey; smoothed arrivals in solid black; and arrivals broken down by gender in dashed (male) and dotted (female) grey. The dashed vertical line in red indicates the approximate time of a fire alarm in Hanover High School.*

**Fig. 3.** Arrival times of Hanover voters.

three voting-step times that we tracked. On average, the data in the table confirm that ballot marking was on average the longest voting step, that this step had significant variance, and that some Hanover voters took up to five minutes to fill out their ballots. In contrast, Table 1 shows that ballot insertion was relatively quick, with some voters finishing this step in approximately one second.

It is natural to inquire as to whether the voting-step times shown in Fig. 4 can be modeled with Poisson distributions. The sample statistics in Table 1 suggest, however, that there is excessive variance or what is called overdispersion in the step times compared to what one would expect under a standard Poisson model; if voting-step times were Poisson, the mean of the distribution of, say, the authentication time would equal its variance. Thus, when our upcoming simulation samples from observed voting-step times, it samples from the actual empirical distributions of these times as opposed to Poisson approximations of them.

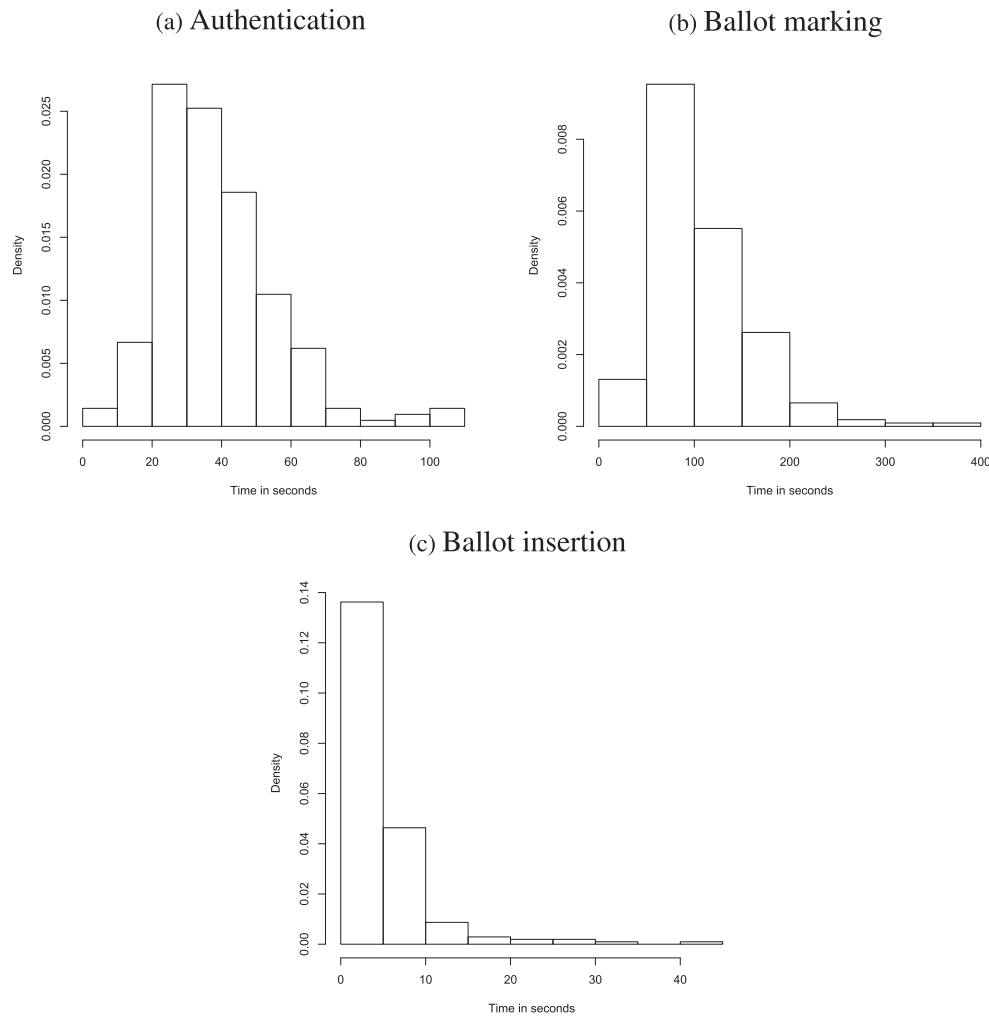
We—and presumably other scholars of election administration—care about voting lines and voting step times because waiting in line is a time tax as well as the potential that extended voting processes could lead to dissatisfied voters and a lack of legitimacy in election outcomes. With this in mind, it is worth asking if any of the steps described in Table 1 seems problematic. In our opinion, the answer is no. What is conceivably the most problematic step in the voting process is the first step, authentication. This step has the potential for conflicts about voter identification, whether a voter is who she says she is, and so forth. Table 1 shows that the average Hanover voter was authenticated in approximately 40 s, and the longest authentication time was a bit

under two minutes. We do not have access to survey data on how long an argument about authentication would have to be before it became problematic. However, it is nonetheless hard to imagine that even 110 s, which as shown in Fig. 4a is not at all representative, is particularly long. Given that authentication in New Hampshire requires a voter to offer a form of identification and then an election clerk to find the voter in a multi-page, paper list and cross off her name, the authentication times described in Table 1 seem quite quick.

When a Hanover voter finishes with a step in her voting process, she must either transition directly to the following step or join a line preceding said step. In principle, moving between voting steps this can take a few seconds given the distribution of equipment in the Hanover precinct; the earlier Fig. 1 makes the necessity of moving clear. We assume here that transition times from one voting step to another are negligible and are not a function of the existence of lines. To some extent this assumption may be problematic as one could envision that an excessively long line could lead to congestion which might cause problems for voters in the gym who are trying to navigate from one step of the voting process to another. However, to the extent that this is true and ignored in our analysis, our estimates of the consequences of long lines will be conservative.

## 6. Simulation design

Having described how we gathered arrival and voting step times in Hanover, New Hampshire, during the 2014 General Election, we



*Note: voting-step times are in seconds. Note that the scales of the horizontal and vertical axes in the three histograms are not identical.*

**Fig. 4.** Distributions of Hanover voting-step times.

**Table 1**  
Summary of Hanover voting step times.

Step	Observations	Minimum	Maximum	Mean	Median	Variance
Authentication	210	3	110	39.4	36	314.7
Ballot marking	214	1	378	108.3	97	2884.0
Ballot insertion	207	1	43	5.5	4	30.0

Note: times are in seconds.

now describe our simulation, which is designed to model line evolution in the Hanover precinct. The combination of observed voter process data and a simulation are the crux of our hybrid research design, and our simulation operates as follows.

### 6.1. Voter arrival process

We model voter arrivals with a non-homogeneous Poisson process. In particular, we allow the rate parameter in our Poisson arrival process to vary by hour, and we consider two separate vectors of rate parameters. Our first vector, which we call Vector A, is based on actual Hanover arrivals depicted in Fig. 3; associated

Poisson rate parameters are as follows: 5, 5, 6, 7, 5, 5, 6, 7, 6, 7, 5, 4. We divide each rate parameter by 60 corresponding to Fig. 3's grouping of arrivals by minute. According to Vector A, voter arrivals in Hanover average five per minute for the first precinct hour, five per minute for the second, six per minute for the third, and so forth.

Beyond Vector A, our simulations consider a second set of Poisson rate parameters that we call Vector B. These parameters, prior to being divided by 60, are as follows: 4, 4, 6, 6, 5, 5, 6, 8, 7, 8, 5, 4. Note that the sum of Vector A's parameters equals the sum of Vector B's, and thus, over the course of a full day of voting, the expected number of voter arrivals is equal under both Vectors A and B. However, these two vectors differ with respect to a late afternoon

surge. Namely, in Vector A, the afternoon surge to the extent that it existed is captured by rate parameters of 6, 7, 6, 7, 6; in Vector B, the corresponding rate parameters are 6, 8, 7, 8, 5. The two sets of numbers imply that, when voter arrivals follow Vector B, they are relatively more concentrated in the later afternoon than in Vector A. We consider both Vectors A and B so that our simulation can address the effects of a larger afternoon surge of voter arrivals on line formation.

### 6.2. Service times

We model voting step times using the three empirical distributions described in Fig. 4. In particular, upon arrival a voter is assigned an initial time for authentication; this time is a random draw from Fig. 4a. Of course, such a voter may have to wait in line prior to authentication if there are no positions available for authentication when she arrives to vote. After the voter finishes authenticating, she either joins a line before ballot marking or immediately begins marking her ballot; the amount of time required for ballot marking is a random draw from Fig. 4b. Then, following ballot marking our hypothetical voter either waits in line prior to ballot insertion or immediately inserts her ballot into a machine; the time required for this step is a random draw from Fig. 4c.

### 6.3. Resources

The availability of slots in the three voting steps considered here depends on precinct resources. In Hanover during the 2014 General Election there were seven stations for voter authentication, 76 booths for ballot marking, and two optical scan voting machines. With respect to authentication, the stations were delineated by first letter of last name, e.g., A–B, C–F, and similarly through T–Z. Thus, two individuals with the same last names arriving together at Hanover High School is different than the simultaneous arrivals of one voter whose last name is “Smith” and another voter whose last name is “Abrams.” What this means formally is that the seven voter authentication stations used in November, 2014, in Hanover were equivalent to some number of stations that is strictly fewer than seven. The precise amount fewer than seven depends on the arrival rates of voters based on their last names and the extent to which, say, married couples with the same last name tend to vote together. The scholarly literature does not have much to say about the relationship between voter arrivals and last names, and, the above caveat notwithstanding, we treat Hanover’s seven authentication stations as seven independent stations.<sup>19</sup>

Our simulation operates as follows. Using a vector of 12 Poisson parameters, one per hour, we randomly generate a set of voter arrivals denominated by second. The number of arrivals for each simulation is itself a random variable, and the arrivals by second tells us, for example, if a simulated voter arrives at second 60 of election day; this is equivalent to 7:01 am. Once our simulation has characterized all voter arrivals times in seconds after 7:00 am, we then step through each second in an election day and move voters through the three-step voting process based on randomly drawn voting step times.

Suppose that the first voter were to arrive at second 20; this is equivalent to 20 s after 7:00 am. Since this voter is the first one to

vote, there is no line prior to authentication. Our simulation randomly draws an authentication time for this voter, and she spends some amount of time authenticating. When this voter is done authenticating, she either waits in line for a voting booth if all booths are full—in principle, this could happen if, while our first voter was busy authenticating, other voters arrived and leapfrogged our initial voter while she was authenticating—or she immediately enters a voting booth. Once in a booth, our simulation draws a random time that specifies how long the first voter takes to mark her ballot. Finally, after marking her ballot, our voter either waits in line to use an optical scan machine (if the machines are already being used) or immediately uses one. The amount of time that she spends with this machine is drawn from the distribution of tabulator usage times.

We repeat this process for all voters. Our simulation keeps track of when each voter arrived, how much time she spent voting, how much time she spent in line, and such.

It should be clear from this discussion that the term “voting line” is somewhat ambiguous. A voter can be said to wait in line before voting with the emphasis on *before*, that is, prior to authentication. However, the same voter can also wait in line while voting, i.e., after authentication but prior to ballot marking. With this in mind, we believe that the key waiting time variable is the total time that a voter spends in line. Insofar as waiting in line is a time tax, it should not matter whether a voter waits after or before authenticating with an election official, after or before ballot marking, and so forth.

## 7. Simulation results

We now presents results of simulating voting lines based on the voting step time distributions in Fig. 4 and the non-homogeneous Poisson arrival processes characterized by rate parameters in the aforementioned Vectors A and B. Recall that Vector A is intended to approximate the actual arrival process of voters in Hanover on November 4, 2014, while Vector B includes a sizable late afternoon surge. Our simulations adjust the resources in the Hanover precinct, and we have already noted that the resource vector in Hanover has three components: the number of stations available for voter authentication, the number of voting booths used for ballot marking, and the number of optical scan machines into which voters can insert their ballots. For a given set of precinct resources we simulate the overall Hanover voting process 20 times, and in each simulation we keep track of the total amount of time voters spent in line.

Table 2 contains basic statistics on the number of minutes voters spent in line during their simulated voting experiences. In particular, the table has average values (averages are taken over 20 simulations) for various quantiles of the distribution of overall time voters spent in line(s). Note that the simulations in Table 2 do not change the number of voting booths in the Hanover precinct; this number is set at 76 for all simulations, and one consequence of this is that across all simulations no lines before ballot marking.

Simulation 5A is equivalent to Hanover’s resource status quo and, by virtue of its using Vector A, is also consistent with a voter arrival process that is a close match as to what was observed on November 4, 2014. The row corresponding to this simulation shows that lines were not a problem in the 2014 General Election in Hanover. According to our simulation, the median time spent in line was zero seconds, and the third quartile of overall line time was zero seconds as well. This result is not very sensitive to a late afternoon surge in voter arrivals. To see this, consider Simulation 5B, which features a late afternoon surge and the same resource vector as Simulation 5A. Table 2 shows that lines were minimal even in this case. One implication of the 5A and 5B lines in Table 2 is that Hanover is well-endowed in voting resources.

<sup>19</sup> Had our arrival tracking research assistants queried voters as they approached the Hanover precinct, we could in principle have tracked Hanover voter arrivals based on last names. However, this would have been disruptive, and we wanted our precinct observers to be as unobtrusive as possible. Moreover, explicitly asking voters about their names would have confounded our study if, for example, the willingness of a voter to vote is correlated with her willingness to provide her name, or even a last initial, to an outside observer.

**Table 2**  
Voter line times with 76 voting booths.

Index	Auth. stations	Voting booths	Scanning machines	Min.	1Q	Median	3Q	Max.
1A	7	76	1	0	0	0.62	8.19	98.15
2A	6	76	1	0	0	1.6	10.5	103.2
3A	5	76	1	0	0	5.5	21.2	147.4
4A	4	76	1	0	10	71	254	654
5A	7	76	2	0	0	0	0	41
6A	6	76	2	0	0	0	0.2	59.1
7A	5	76	2	0	0	0	12	130
8A	4	76	2	0	7.1	76.8	260.5	641.1
1B	7	76	1	0	0	1.1	9.4	100.8
2B	6	76	1	0	0	2.1	13.1	121.8
3B	5	76	1	0	0	7.2	35.5	243.3
4B	4	76	1	0	12	104	1020	2062
5B	7	76	2	0	0	0	0	46
6B	6	76	2	0	0	0	1.6	80.2
7B	5	76	2	0	0	0.62	27.57	221
8B	4	76	2	0	8.5	96	1104	2122.3

Note: all times are in seconds, and 1Q and 3Q refer to first and third quartiles, respectively. The index of a given simulation describes whether it uses the voter arrival process parameters in Vector A or those in Vector B. All line statistics are based on averages of 20 simulations.

Voting lines are in principle nonetheless plausible in Hanover. Indeed, as soon as the number of authentication stations drops, lines start forming prior to authentication. To be precise, consider Simulations 1A–4A and 5A–8A. From 1A to 4A, the number of authentication stations drops and other voting resources are held fixed. The same applies to Simulations 5A–8A. The difference between the four simulations in 1A–4A versus 5A–8A is that the number of optical scanning machines is one in the former set versus two in the latter. In both the 1A–4A or 5A–8A cases, median overall voter wait times increase from approximately zero seconds to perhaps one and one-half minute when the number of authentication stations in the Hanover precinct drops from seven to four.

This effect of a drop in authentication stations is more pronounced in the Vector B simulations, when there is an afternoon surge in voter arrivals. For example, consider Simulations 1B–4B and, similarly, 5B–8B. In these simulations, median overall line times change from 1 s to around 100 s when the number of authentication stations drops from seven to four. Even with only four authentication stations, though, our simulations imply that Hanover's resources are easily sufficient according to the aforementioned wait time guidelines offered by the Presidential Commission on Election Administration, which call on jurisdictions to ensure that no voter wait more than half an hour to vote.

The quantiles of line times displayed in Table 2 do not describe line dynamics and in particular how our simulated lines evolved over time. For this we turn to Fig. 5, which for selected configurations (7A, 7B, 8A, and 8B) of precinct resources plots line lengths by time. The figure focuses on lines before authentication as these lines are perhaps the most notable and are consistent with the concept of “waiting to vote.” Lines before ballot marking are non-existent in the simulations described in Fig. 5 because Hanover has so many ballot booths and lines before ballot insertion do exist but are very short.

Fig. 5 consists of a matrix of four small figures, and voter arrival processes are constant within rows. Namely, the top row of Fig. 5 uses Vector A and the bottom row, Vector B with its late afternoon surge. The vertical axes in each figure are the number of people in line to vote.

Focusing first on the top row, the difference between Fig. 5a and b is that the simulation in the latter involves one fewer authentication stations; one can see this in Table 2's rows labeled “7A” and “8A.” The top row of Fig. 5 shows how the reduction of one authentication station leads to longer lines to vote and that the marginal cost of subtracting such a station varies across the time of

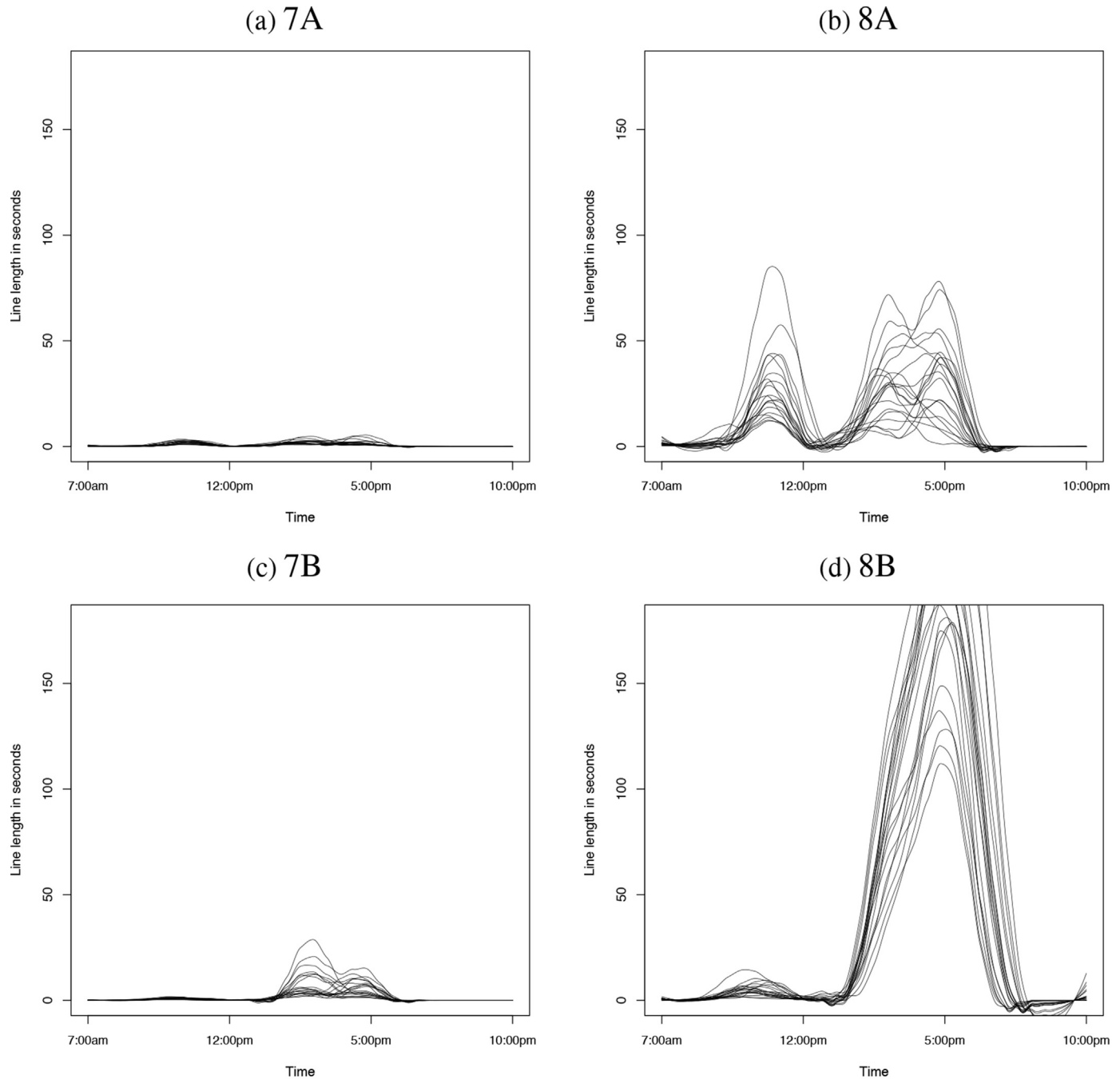
day. When there are few voter arrivals (early morning hours), having four authentication stations rather than five is of little consequence. Almost no one is in line regardless. However, when there is an uptick in arrivals, the consequences of a smaller number of authentication stations is clear. In particular, Fig. 5b shows that, when the number of authentication stations is small, there are up to 50 people waiting to vote in the late morning and during the afternoon. Moreover, when there is a pronounced late afternoon surge, as depicted in the bottom row of Fig. 5d, line lengths increase considerably and approach 200 voters at peak moments. In Simulation 8B, the average maximum overall time in line is around 35 min (this is close to 2062 s). This time is long, but even here the average median time in line is under two minutes (107 s).

One of the ways in which Hanover is heavily-resourced in the area of voting equipment is with respect to ballot marking stations. We have already noted that there were 76 such stations in Hanover High School in November, 2014, a testament to their relative inexpensiveness (some are made of cardboard) as well as to the fact that Hanover voting takes place in a large gymnasium. What, however, if Hanover had many fewer stations, say, only eight or ten? This question is addressed in Table 3, which describes overall voter wait times when the number of voting booths is much smaller than 76.

Table 3 is organized identically to the previous simulation table. Namely, it reports results from 16 sets of simulations, each of which is based on resource vector that prescribes authentication stations, voting booths, and optical scan machines. Some simulations use the observed Hanover voter arrival process (these are identified as “A”) and others use a voter arrival process that has a pronounced after surge (“B”). All of the simulations in Table 3 assume that Hanover has two optical scan voting machines, but this assumption is not extremely important because the times associated with ballot insertion tend to be short (see Table 1).

According to Table 3, if Hanover had only eight voting booths, then lines in Hanover High School would have been extensive. And, this conclusion holds with the regular voter arrival process characterized by Vector A and the afternoon surge characterized by Vector B. Consider Table 3's Simulation 9A, for example, with seven voter authentication stations, eight voting booths, and two optical scan machines. In this situation, the average median overall line time is a bit over 70 min, and the average third quartile line time is over two hours. In other words, 25 percent of voters in Simulation 9A waited in line more than two hours during their voting processes. These line lengths, which are similar in magnitude to other





*Note: each curve depicts line lengths, and there are 20 curves per plot, representing 20 simulations for a given set of precinct resources.*

**Fig. 5.** Authentication line evolution with many voting booths.

average medians and average third quartiles in the top four rows of Table 3, would place Hanover well beyond the recommended maximum wait times as promulgated by the Presidential Commission on Election Administration.

Contrast Simulations 11A–14A with 11B–14B; the difference between these two simulations is that the latter set is associated with an afternoon surge in voter arrivals. One can see from Table 3 that the afternoon surge is associated with lower average median

line times but higher average third quartile line times and higher maximum line times. What explains this is as follows. A surge is bad for those voters involved—they end up spending time in line because a surge causes congestion—but good for voters not so involved. Recall that Vectors A and B hold constant the expected total number of voter arrivals. So, when voter arrivals are relatively more concentrated in the late afternoon, as they are in Simulations 11B–14B, median line times drop. But, a set of voters is forced to

**Table 3**  
Voter line times with limited voting booths.

Index	Auth. stations	Voting booths	Scanning machines	Min.	1Q	Median	3Q	Max.
11A	7	8	2	0	1960	4353	7778	10,193
12A	6	8	2	0	1958	4350	7993	10,478
13A	5	8	2	0	1900	4137	7554	9866
14A	4	8	2	0	1960	4317	7690	10,101
15A	7	10	2	0	187	541	1070	1873
16A	6	10	2	0	184	598	1274	2171
17A	5	10	2	0	137	558	1098	1911
18A	4	10	2	0	111	473	1008	1879
11B	7	8	2	0	1478	3179	7845	10,771
12B	6	8	2	0	1652	3633	8328	11,321
13B	5	8	2	0	1508	3120	7725	10,544
14B	4	8	2	0	1665	3537	8066	10,965
15B	7	10	2	0	57	350	2296	3647
16B	6	10	2	0	64	381	2005	3410
17B	5	10	2	0	57	334	1997	3457
18B	4	10	2	0	73	366	2116	3472

Note: all times are in seconds, and 1Q and 3Q refer to first and third quartiles, respectively. The index of a given simulation describes whether it uses the voter arrival process parameters in Vector A or those in Vector B. The statistics for each set of parameter values are based on averages of 20 simulations.

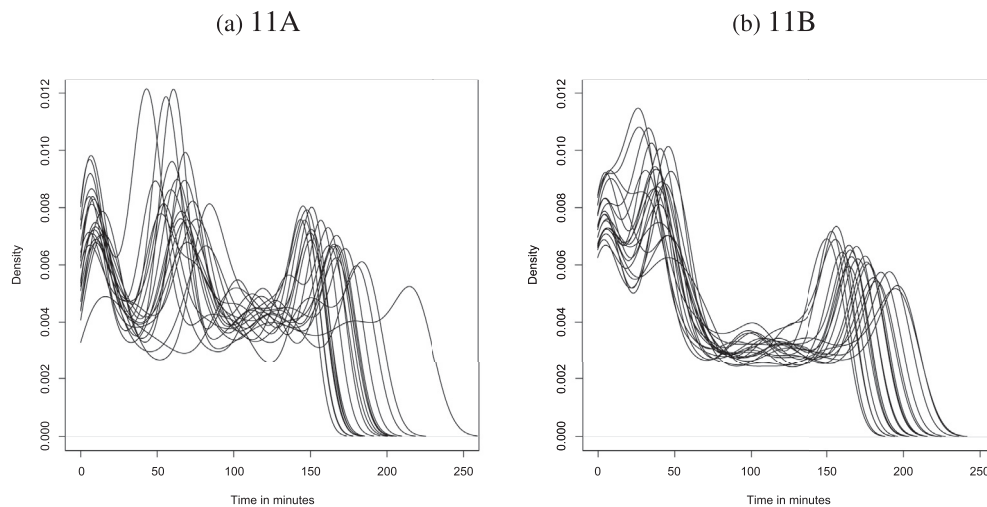
spend a lot of time in line, and this explains why the third quartiles of the 11B–14B line times increase even though medians do not.

This raises an important point. The typical (say, median) line time for a set of voters is one measure of time spent waiting to vote. However, the spread of line times is also important. The inter-quartile range (third quartile minus first) of the overall line times in Table 3 is greater when there is an afternoon surge (see “B” simulations) than when there is not (“A”).

Fig. 6 contains another perspective on this point. For Simulations 11A and 11B, this figure plots densities of overall time in line. There are 20 densities per plot, one for each simulation. There is a fair amount of randomness in the plots, but even with this the effects of the pronounced afternoon surge are evident. When there is a surge, as in Fig. 6b, line times are roughly bimodal, with many voters standing in line for a short time and a smaller number, for a long time. In contrast, when there is not a surge, the modes associated with short and long waits are not nearly as pronounced. This is because, in the absence of an afternoon surge, voter arrivals are more uniformly spread out than when there is a surge. Uniform arrivals decrease variance in line times, and this is apparent when

comparing the 11A and 11B densities in Fig. 6.

The line times in Simulations 11A–14A and 11B–14B are all long, certainly excessive compared to the 30-min recommendation we have discussed earlier. However, average overall median line times drop to around ten minutes as soon as the number of voting booths in the Hanover precinct is ten. To see this, consider simulations 15A–18A and 15B–18B. In these eight simulations, average median line times are between six and ten minutes, a far cry from the 70 min noted above. Our point here is straightforward. A dramatic drop in waiting time waiting can be achieved at a relatively low cost: two more voting booths. Obviously the extent of this drop depends on voter arrivals, and this is evident in Table 3 as well. But, the broader point is that the marginal value in Hanover of two voting booths is large. From Hanover’s perspective, the good news is that 76 voting booths are overwhelmingly sufficient to prevent lines from forming between voter authentication and ballot marking. If, for some reason Hanover voting had to relocate to a smaller physical space for an election or two, the results we have discussed can be used to tell Hanover officials how small a space they can tolerate given a willingness to impose a time tax on voters.



Note: each plot contains 20 densities, representing 20 simulations for a given set of precinct resources.

**Fig. 6.** Densities of overall line times.

If such officials were content with a ten minute wait, then ten ballot booths is sufficient given the voting step times we observed in November, 2014.

The observed voting data that support the simulations described above rely on a precinct that served over 4000 voters in the 2014 General Election. This large number is an artifact of the way that New England towns administer elections; namely, many towns in the region are not divided into precincts and instead have a single, large voting location. The implication here is that the scale of the numbers in our simulations is a function of the size of the Hanover precinct. The number of voting stations and booths, for example, are appropriate given the scale of the Hanover precinct. Were the precinct to handle, say 500 voters instead of 4,000, we might ask about the marginal difference on lines of one versus two authentication stations as opposed to the marginal difference of four versus five. Qualitatively our simulation would not change were the scale of Hanover to be smaller.<sup>20</sup>

## 8. Discussion

Voting lines are a subject of interest to voters—who must wait in them—to election officials—who presumably care about minimizing congestion at voting locations—and to scholars of election administration and voting rights attorneys—who care about line evolution and whether time spent in line is a tax uniformly distributed among all voters or disproportionately leveled on certain groups thereof. Despite the plethora of reasons to be interested in voting lines, the literature on this subject is nonetheless quite limited.

Our approach to the study of voting lines draws on the fact that voting takes several steps and that an overall voting process can be thought of as a special cases of a queue. The evolution of lines in a queue can be studied if one knows the distribution of arrival times and the distributions of voting-step times, and we have explained how we gathered data on these distributions in Hanover, New Hampshire, during the 2014 General Election. From our perspective, Hanover is a typical voting precinct, and we have supported this point by noting that Hanover in-person voters, like millions of in-person voters across the world, authenticate themselves to election officials, fill out ballots, and then insert or deposit ballots into collective devices. Subtleties notwithstanding, the process that Hanover voters use when casting their ballots is generic.

Our contribution consists of two elements, a data gathering protocol and a simulation. The former used two separate web-based applications, both of which respect voter anonymity and can be conducted unobtrusively, without compromising voting processes. As long as precinct officials allow researchers to observe voting processes, voters can be timed so as to generate distributions of voting-step times. Alternatively, precinct officials can time voters themselves if this is preferable based on local legal arrangements.

Our simulation allows us to estimate the effects on lines of changing resources in Hanover's single voting precinct. As it turns out, this precinct is highly resourced, particularly with respect to voting booths, so much so that lines in November, 2014, were not an issue. However, suppose that Hanover were to transition from 76 voting booths to, say, either eight or ten. And suppose as well that Hanover were to use one tabulating machine instead of two.

Perhaps, say, an unanticipated maintenance issue were to force voting in Hanover to move from the high school where it normally takes place to a location with severe space constraints or that one of town's optical scan machines broke down immediately prior to an election and a replacement was unavailable. Roughly speaking, assuming that the voter arrival process was approximately the same as what our researchers observed, our simulation shows that median line lengths would be over an hour (around 4300 s) if Hanover used one tabulator and eight voting booths and versus around ten minutes if voters had access to two tabulators and ten booths. This shows, namely, that a small change in resources can have very large consequence in voter wait times—irrespective of voter turnout. With this in mind, one might consider the decision faced by the Hanover election supervisor if forced to leave the high school: would a location that houses two tabulators and ten booths be preferable to one that houses one tabulator and eight booths? Based on our simulation, the answer is clearly yes.

Our simulation can also be used to address the question, should a jurisdiction purchase another tabulating machine for a precinct or, say, a set of voting booths/stations whose cost equals a tabulator. To answer this question, one must be able to assess the marginal effects on lines of these different purchases, and we have demonstrated how our simulations can handle this.

Looking beyond such a within-precinct resource allocation problem—i.e., optical scan machines versus voting booths—municipalities face tradeoffs involving budgeting for elections and other functions, such as policing, education, and public works. If, say, a municipality were forced to consider the tradeoff between reducing funding for its election day precincts versus adding a part-time substitute teacher at a local elementary school, the municipality would need a way to conceptualize the election-based cost of such a reduction. That said, we have provided here an analytical approach that would inform municipality governance of the cost paid to voters of reduced precinct staffing, and this cost is paid for in minutes spent in line.

We have noted several times that the literature on voting lines is not extensive. With this in mind, we believe that the field of election administration would benefit greatly if common data collection protocols on voter arrival times, voting step times, and precinct resources were established across the American states and beyond. If, for example, there were to exist a central data repository that described empirical distributions of these variables, then researchers could develop metrics that quantify the costs—in terms of minutes in line—of particular precinct configurations. Moreover, with data on arrivals, voting step times, and resources, researchers could approach the key question of fairness and consider how to equalize voter experiences across precincts.

We conclude by encouraging scholars of election administration to think carefully about the political consequences of voting lines. Our model of line formation is ultimately of service to the extent that it helps us understand what line evolution might do to voters. Earlier we alluded to the political consequences of lines, but it bears repeating here that the twin phenomena of balking (not joining a voting line after seeing it) and renegeing (leaving a line after joining it but before voting) may be serious issues that affect perceived election legitimacy. Almost nothing is known about balking and renegeing rates in democracies across the world. But, time taxes notwithstanding, if there is a downside to long lines, it is that they might drive away voters. Even small renegeing rates—Spencer and Markovits's estimates from the 2008 California Primary are under two percent—can be pivotal in a close election. Future research in the area of election administration should seek to characterize balking and renegeing rates and in particular to estimate how these rates respond to line lengths. Are there certain line lengths that will drive voters away? Do voters who were driven away typically voter

<sup>20</sup> Implicit in this argument is the idea that, say, a 30 min line to vote in a large precinct is equivalent to a 30 min wait to vote in a small precinct. It seems logical that these two waits would be evaluated similarly by voters insofar as they are both 30 min in duration. Nonetheless, future research might want to engage the question of whether the scale of a precinct affects voter perceptions, holding wait times constant.

later, or is being deterred once by a long line sufficient to prevent voting? And, are voters more or less likely to tolerate lines in national elections as opposed to, say, very local elections?

Election legitimacy presumably suffers when intended voters run into barriers that prevent them from exercising their rights. Gerber et al. (2013) show that a non-trivial percentage of American voters are skeptical about ballot secrecy, and there is some evidence in Herron et al. (2015) that voters forced to wait in line have greater doubts about election integrity. It behooves scholars to study lines and the correlates so that election officials, whose jobs involve managing and safeguarding elections, may better understand the political consequences of lines and how voters are affected by them.

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