Managing Polling Place Resources

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Caltech/MIT Voting Technology Project

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About the Caltech/MIT Voting Technology Project

Established by Caltech President David Baltimore and MIT President Charles Vest in December 2000 to prevent a recurrence of the problems that threatened the 2000 U.S. Presidential Election. Since establishment, members of the VTP have studied all aspects of the election process, both in the United States and abroad. VTP faculty, research affiliates, and students have written many working papers, published scores of academic articles and books, and worked on a great array of specific projects.

All of this research and policymaking activity seeks to develop better voting technologies, to improve election administration, and to deepen scientific research in these areas.

About the Polling Place of the Future Project

The Polling Place of the Future Project seeks to improve the performance of America's polling places through research and the development of practical tools for the use by election administrators to better allocate resources that are dedicated to voting. The Project is in direct response to President Obama's declaration that when it comes to long lines at the polls, "we have to fix that," and to the benchmark suggested by the Presidential Commission on Election Administration that no voter wait longer than 30 minutes to check in to cast a ballot.

Acknowledgments

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About the Author

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1. Introduction

Voting is the most important act of a democratic society. In the most recent federal elections in the United States, roughly 75% of voters cast their ballots in a physical location — either in a traditional neighborhood precinct on Election Day or in an early voting center before Election Day.[1] If elections are to fulfill their expected role in society, the polling places voters use must facilitate the act of voting. If they don't, then the quality of our democracy is undermined.

The presidential election of 2012 shone a harsh light on polling places. The press widely reported the existence of long lines of voters in battleground states, many of whom had to wait hours after the polls had closed to cast their ballots. In his victory speech on election night, President Obama was prompted to remark, "we have to fix that."

This report provides a response by the Caltech/MIT Voting Technology Project (VTP) about how election administration officials can address the problem of long lines at the polls. This response is based on a combination of our knowledge about the science of lines — particularly the field of queuing theory — and research we have conducted over the past two years into the dynamics of polling place lines across the United States. Based on this research, we conclude the following:

1. Long lines are not ubiquitous, either across time or space.
2. Where long lines do occur, they are costly, in terms of lost votes, confidence in elections, and time spent by voters.
3. Long lines occur in predictable places on a chronic basis — in a small handful of states, in urban areas, during early voting, and in areas with many non-English speakers
4. Long lines are fundamentally due to a mismatch between the number of voters who show up and the resources available to accommodate them; insights from queuing theory provide reliable guidance about how to minimize this mismatch.
5. A few localities already provide models of best practices that are addressing voter-election resource mismatches.
6. An important first step in addressing long polling place lines is for local jurisdictions to get into the habit of regularly collecting the data necessary to diagnose the presence of congestion and analyzing it in a way that helps them to allocate the resources they have, or to advocate more effectively for new resources.

[1] *Increasingly states have adopted a third, hybrid in-person voting method: a vote center that is open both before and on Election Day.*

Readers will be unsurprised that a report by researchers associated with Caltech and MIT calls for the collection and analysis of more data. However, as we will show, the amount of data needed to better manage polling places is actually quite modest, can be gathered using simple procedures, and can be analyzed using simple web-based applications. In the words uttered by one voting machine vendor at a meeting of the Presidential Commission on Election Administration, this is not rocket surgery.

The remainder of this report goes into these six summary items in greater detail. We begin by spelling out basic facts about waiting to vote in the United States, based on survey research and careful observation of actual polling places. We then provide a brief overview of queuing theory, focusing on how its findings help illuminate why some — but not all — polling places experience long waits to vote. Next, we develop two case studies that show how the insights of queuing theory can help diagnose some of the root causes of polling place lines. We conclude this report by striking two themes. First, we describe what local election administration officials can do *right now* to gather and analyze data they already have so that they are better prepared for possible lines in 2016. Second, we suggest a roadmap that the election administration community could follow over the next several years so that the problems of long lines at the polls are dealt with on a permanent basis.

2. Basic facts

First, some basic facts about lines at the polls.[2] We start very broadly by identifying the presence of lines at the national level, which can best be determined through survey research. Two national academic surveys provide the necessary data to answer questions about average wait times and where long lines have arisen in recent elections, the Cooperative Congressional Election Study (CCES) and the Survey of the Performance of American Elections (SPAE). [3]

Lines form when there is congestion; congestion is greatest in presidential elections. Therefore, we start by exploring what the data tell us about long lines in the two most recent presidential elections, 2008 and 2012, and also include a discussion that puts the midterm election of 2014 into context.

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[2] *Much of the research reported in this section has appeared previously in reports and articles written by members of the VTP. See particularly Charles Stewart III and Stephen Ansolabehere, "Waiting to Vote," Election Law Journal 14(1): 47–53.*

[3] *Both the CCES and SPAE are Internet surveys. They both ask an identical question concerning the amount of time voters waited at the polls. In 2012, the CCES interviewed 54,535 adults, 39,675 of whom voted; the SPAE interviewed 10,200 registered voters, 9,336 of whom voted. The CCES asks fewer questions about election administration, but has a larger sample size that is distributed across the nation in proportion to population. The SPAE focuses its questions entirely on election administration, with a smaller sample size distributed within states in proportion to population. Depending on the nature of the analysis, one survey will be more appropriate to use than the other and in some cases, the two surveys can be combined to create more precise estimates such as specifically estimating waiting times within states*

TABLE 1
Average waiting times to vote, 2008 and 2012

	2008	2012
Not at all	36.8%	37.3%
Less than 10 minutes	27.6%	31.8%
10-30 minutes	19.0%	18.4%
31-60 minutes	10.3%	8.6%
More than one hour	6.3%	3.9%
Average (min.)	16.7	13.3
95% margin of error (min.)	0.1	0.1
N	18,836	30,124

Source: CCES, 2008 and 2012.

Relying on responses to the 2008 and 2012 CCES, the following table reports the distribution of responses to the question, "Approximately, how long did you have to wait in line to vote?"

Most voters in the past two general elections did not wait very long to vote. Roughly one-third reported not waiting at all, and roughly two-thirds reported waiting ten minutes or less.

It is important to note, though, that among those who waited more than an hour, the waits were quite long. Among those waiting more than an hour in these two presidential elections, the average reported wait time was 109 minutes in 2008 and 110 minutes in 2012.

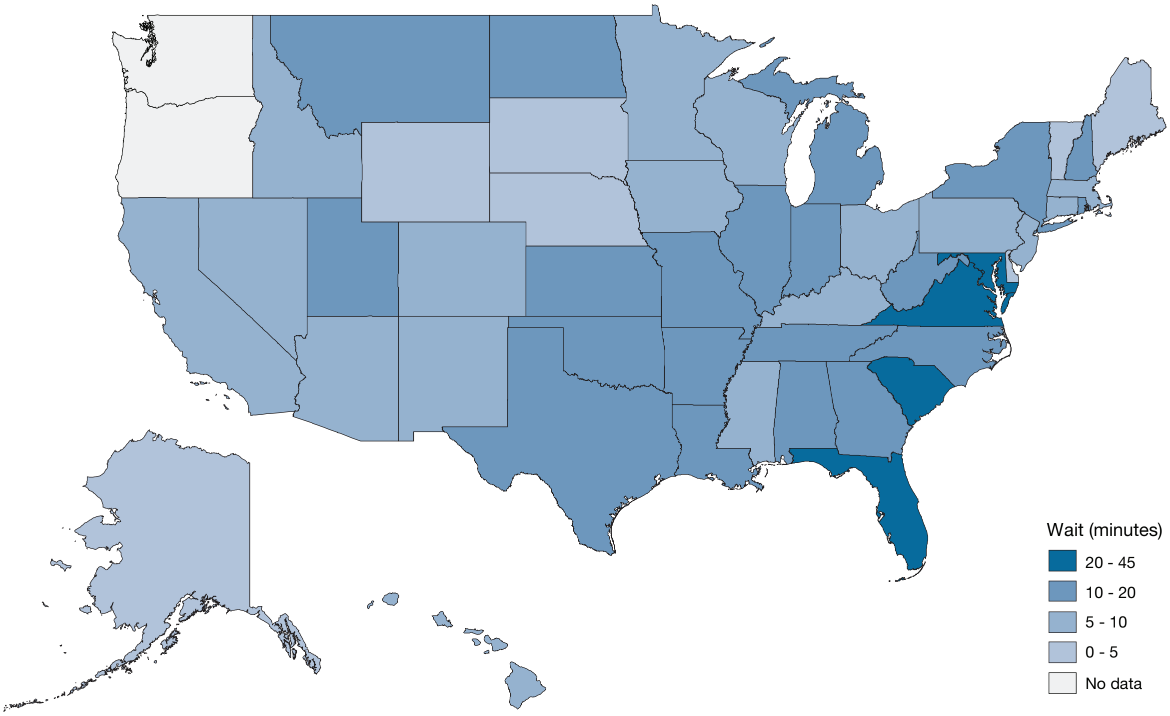
Variation in wait times is not distributed randomly among voters. We next review the geographic distribution of lines, followed by demographic characteristics of voters who wait.

The geography of waiting

The factor that is associated with the biggest differences in wait times is the state where the voter lives. According to estimates derived by combining responses to the CCES and SPAE, average wait times in 2012 ranged from 1.7 minutes in Vermont to 42.3 minutes in Florida — a difference of a factor of 25 between these two states. The table in Appendix 1 reports all state estimates, along with 95% margins of error.

The following map helps to highlight the regions of the country where line length tended to be longer or shorter in 2012. (Oregon and Washington, which primarily use vote-by-mail, are not shaded in this map.) The shortest waiting times tend to occur in the western half of the country and in the northeast, while the longest waits tend to occur in the lower eastern seaboard.

FIGURE 1
Arrival rates and average wait times by time of arriving at the polling place, 2010



Source: CCES and SPAE, 2012.

Waiting times also vary within states. Consider two urbanized states that are toward the opposite ends of the line-length spectrum, New Jersey and Florida. (The statewide averages for New Jersey and Florida, respectively, were 5 and 39 minutes.) In New Jersey, average wait times ranged from 3.6 minutes in Gloucester County to 10 minutes in Union County.[4] In Florida, average estimated wait times range from 5.7 minutes in Marion County to 136.6 minutes in Lee County.[5]

There was also variation within counties. An interesting example was provided by Broward County, Florida, which in 2012 posted regular updates about estimated waiting times at the 17 early voting sites in the county. The following graph shows the average posted waiting times, for each day of the early voting period, by early voting location. These graphs illustrate that wait times varied from an average of 14 minutes at the Supervisor of Elections branch office at the E. Pat Larkins Community Center, to 2.6 hours at the Tamarac Branch Library.

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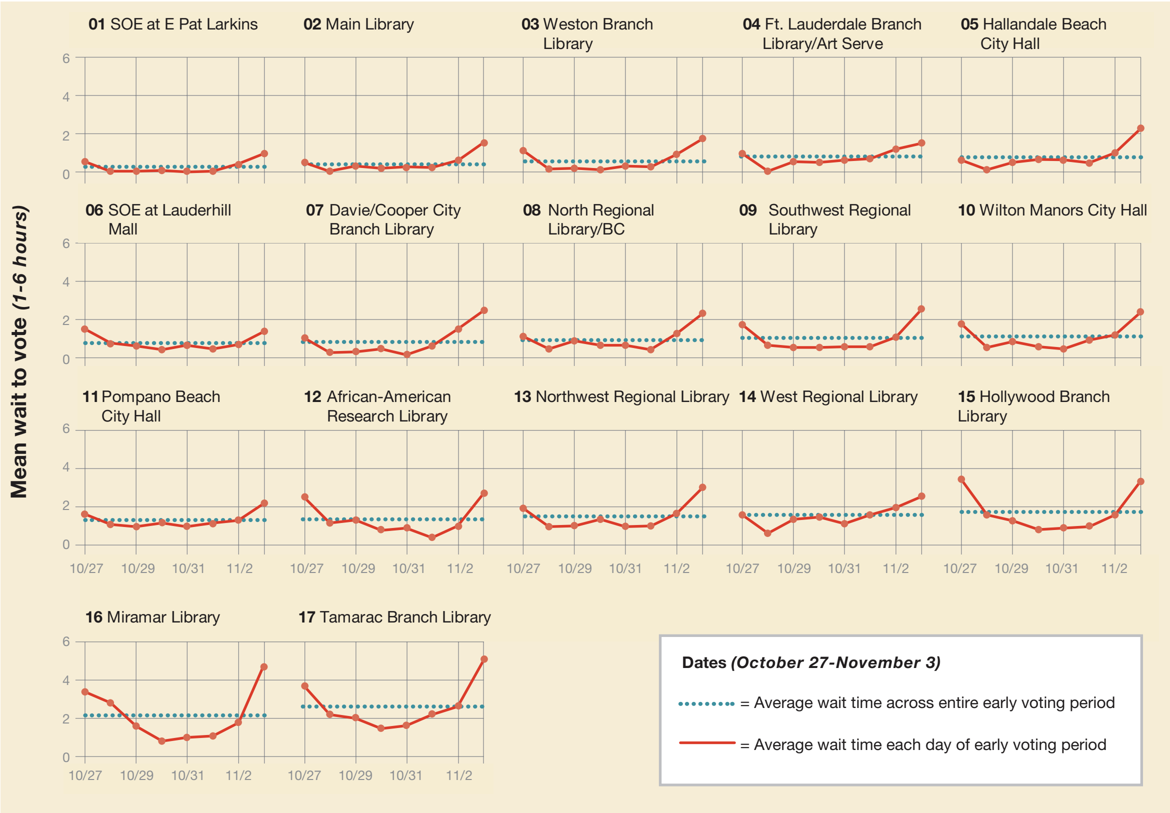
4 *These estimates take into account counties for which we have 25 or more observations per county. The 95% confidence intervals are 1.6 minutes for Gloucester and 4.5 for Union.*

5 *The 95% confidence intervals are 1.6 minutes for Marion County and 11.4 minutes for Lee County.*

FIGURE 2
Average waiting time, Broward County, Florida early voting sites, 2012.
(Sorted in ascending order according to average wait times.)



Note: The solid line in each graph plots the average posted wait time each day at the location. The dotted blue line shows the average across the entire early voting period for the location.

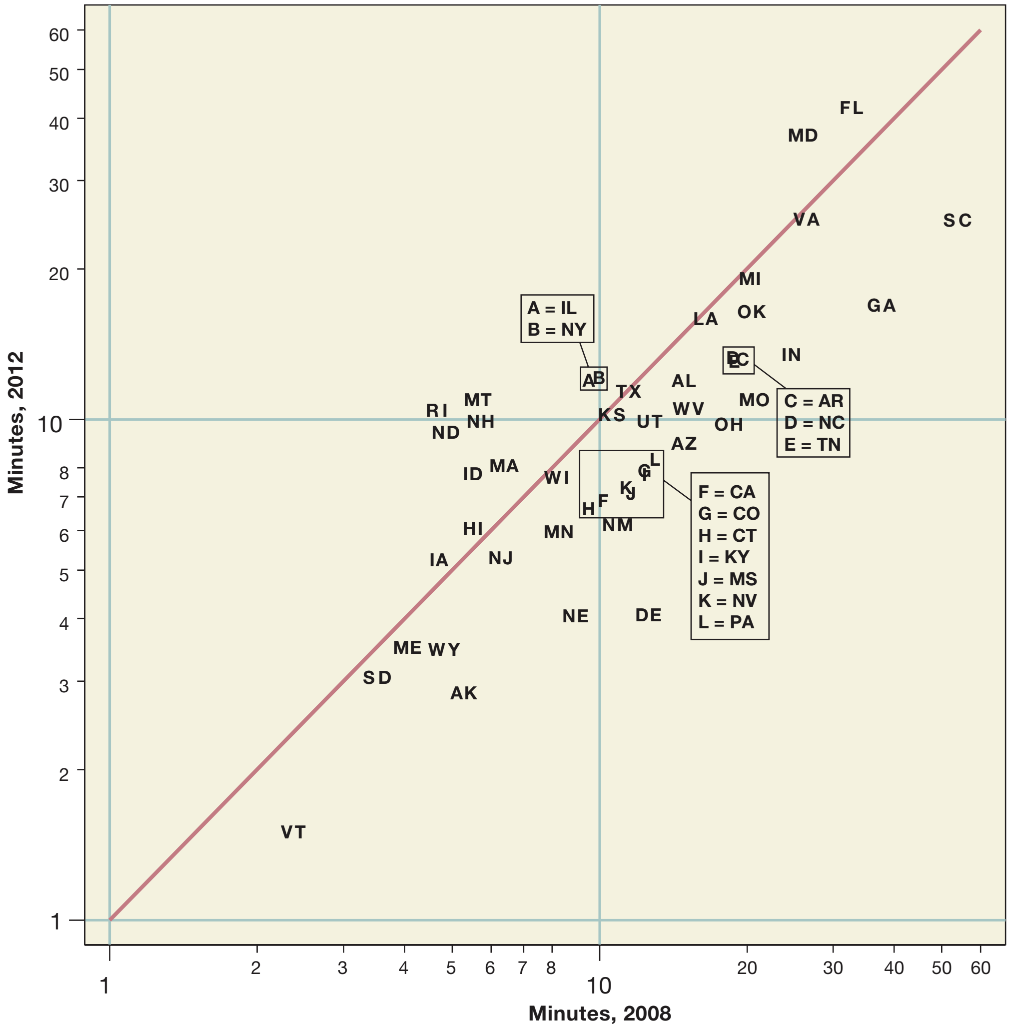
Source: Broward County, Florida Supervisor of Elections Web site.

The great variation across states suggests there are state-specific factors, such as laws, regulations, ballot types, voting technology, demographics, and state norms, which influence how long voters wait to vote. The great variation within states suggests there is further influence of demographics and local administrative practices in determining line lengths at the polls.

Why we have such geographic variation in wait times both between and within states remains largely a matter of speculation. As we show below, demographics explain some of these differences. However, demographics are insufficient to explain why the average Floridian waited 26 times longer to vote in 2012 than the average Vermonter, or why the average early voter at the Tamarac Branch Library waited three times longer than the average early voter at the E. Pat Larkins Community Center.

There is one final topic to be visited under the heading of the geography of waiting: the persistence of waiting times from one election to the next. When we compare the estimated average wait times at the state level in 2012 with 2008, we see remarkable consistency. This is illustrated in the following graph. Here, we plot the average wait time by state in 2012 along the *y*-axis, and the 2008 average along the *x*-axis.[6] The diagonal line helps to orient us and inform us which states showed increases in wait time in 2012 compared to 2008 (above the line), and which showed decreases (below the line).

FIGURE 3
Average wait time at the state level, 2012 and 2008 *(minutes, logarithmic scale).*



Source: CCES and SPAE, 2008 and 2012.

[6] *The axis scales are logarithmic, which aids in the legibility of the individual data points.*

States with long wait times in 2012 generally had long wait times in 2008. While there are some exceptions, if we wanted to predict which states would have long wait times in 2012, the best place to start would be to identify those states with long wait times in 2008.

This observation is important for thinking about how to tackle the problem of long lines. In trying to pinpoint the source of long lines, it is tempting to focus on problems caused by short-term factors and one-off events. Such things might include an unusually long ballot in one year, for instance. While such one-off events may increase waiting times on the margin, the major factors leading to long lines in particular states appear to be baked into the voting process at a deeper level.

Thus, to be effective in tackling the problem of long lines at the polls, it is important to understand both the long-term and short-term factors that lead to them. It would be a mistake to fix short-term problems that lead to a slight increase in voting times and to ignore deeper problems that lead to long lines in every election.

The demography of waiting

Not only are wait times unevenly distributed geographically, they are unevenly distributed demographically.

1. *Mode of voting.* Early voters in 2012 waited an average of 18 minutes, compared to 12 minutes for Election Day voters.
2. *Race of voters.* Minority voters waited longer to vote than white voters. White voters waited an average of 12 minutes to vote in 2012, compared to 24 minutes for African American voters and 19 minutes for Hispanic voters. (See the table below.)
3. *Population density.* Voters in densely populated neighborhoods wait longer to vote than voters from sparsely populated areas. Respondents to the CCES who lived

TABLE 2
Average wait time by racial groups, 2012

Race	Avg.	95% margin of error
White	11.6	0.3
Black	23.3	1.6
Hispanic	18.7	2.2
Asian	15.4	3.0
Native American	13.3	3.2
Mixed	13.6	2.0
Other	13.3	2.0
Middle Eastern	11.7	6.0

Source: CCES, 2012

in the least densely populated ZIP Codes waited an average of 6 minutes to vote, compared to 18 minutes for residents of the most densely populated ZIP Codes.[7]

The timing of waiting

Long lines occur when the arrival rates of voters exceed the capacity of polling place resources — particularly check-in stations, voting booths, and scanners — to keep up with the arrivals. Planning for arrivals depends on knowing something about the nature of arrival rates. Are they constant throughout the day, or do arrival rates vary?

While the answer to this question will be different in each voting location, survey research gives us the overall picture of the nation as a whole. (See Table 3.) For those who vote on Election Day, there is a pre-workday surge, relatively high turnout throughout the morning followed by a drop in arrivals in the afternoon which continues through the end of the day. For early voting — which is much more of a mid-day phenomenon, most arrivals occur in the 10:00 a.m. – 3:00 p.m. window.

TABLE 3
Arrival rates and average wait times by time of arriving at the polling place, 2012.

<table>
<tr><th></th><th colspan="2">Election Day</th><th colspan="2">Early voting</th></tr>
<tr><th>Time of arrival at polling place</th><th>Pct. arriving</th><th>Avg. wait time</th><th>Pct. arriving</th><th>Avg. wait time</th></tr>
<tr><td>Before 8:00 a.m.</td><td>15.6%</td><td>16.5</td><td rowspan="2">8.9%</td><td rowspan="2">29.8</td></tr>
<tr><td>8:00-9:00</td><td>8.7%</td><td>15.8</td></tr>
<tr><td>9:00-10:00</td><td>9.5%</td><td>10.3</td><td>8.5%</td><td>18.5</td></tr>
<tr><td>10:00-11:00</td><td>11.2%</td><td>12.6</td><td>14.8%</td><td>12.7</td></tr>
<tr><td>11:00-12:00</td><td>8.7%</td><td>10.7</td><td>13.7%</td><td>15.2</td></tr>
<tr><td>12:00-1:00 p.m.</td><td>5.4%</td><td>8.6</td><td>8.3%</td><td>17.3</td></tr>
<tr><td>1:00-2:00</td><td>7.2%</td><td>8.6</td><td>10.7%</td><td>26.8</td></tr>
<tr><td>2:00-3:00</td><td>6.7%</td><td>6.7</td><td>13.1%</td><td>15.1</td></tr>
<tr><td>3:00-4:00</td><td>6.3%</td><td>9.8</td><td>7.3%</td><td>14.2</td></tr>
<tr><td>4:00-5:00</td><td>6.7%</td><td>9.7</td><td>7.1%</td><td>28.3</td></tr>
<tr><td>5:00-6:00</td><td>6.8%</td><td>10.3</td><td rowspan="3">7.6%</td><td rowspan="3">22.0</td></tr>
<tr><td>6:00-7:00</td><td>5.3%</td><td>10.5</td></tr>
<tr><td>After 7:00 p.m.</td><td>2.0%</td><td>6.0</td></tr>
</table>

Source: 2012 SPAE

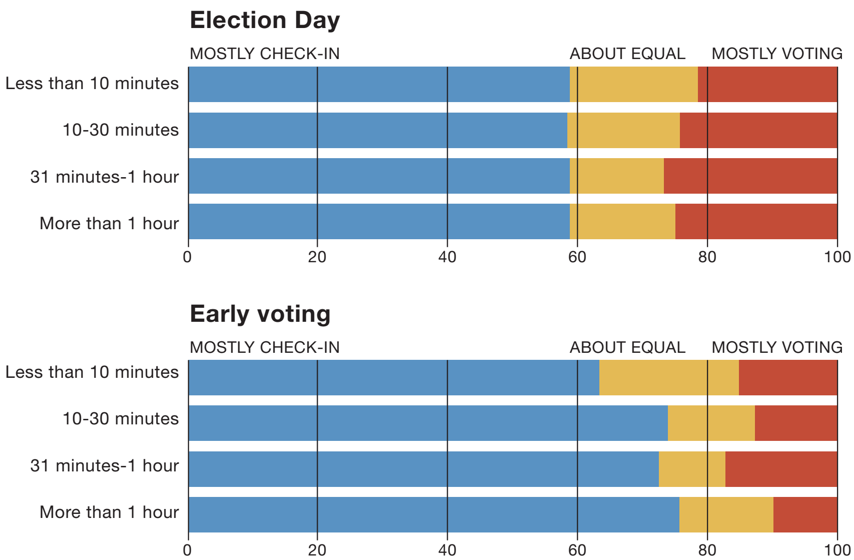
[7] *This analysis was performed, first, by merging population density data to the CCES, using ZIP Code, and then dividing the sample into equally populated quartiles. Respondents from the least densely populated areas lived in ZIP Codes with a population density of 75 persons per square mile or less. Residents from the most densely populated areas lived in ZIP Codes with a population density of 2,739 persons per square mile or more.*

When voters arrive is associated with how long they wait. For Election Day voters, the earliest arrivers — often arriving even before the polls are open — wait the longest. The after-work surge also leads to a small up-tick in waiting time. However, note that after-work voters arrive at polling places after lines that had formed earlier have dissipated, in contrast to voters in the morning, who often arrive to encounter lines that may be the result of queuing ahead of the polls opening.

Wait times for early voting are quite different. Because early voting mostly occurs during traditional business hours, a larger fraction of voters tend to arrive for each hour of the voting day, except for the times before and after work. Wait times at the start of the day of early voting tend to be twice as long as the waits during comparable times on Election Day. Because there is no general downward trend in arrival rates over the day, lines remain long, and thus wait times do not decline over the course of a day of early voting.

Wait times also occur at different locations in a polling place. There are generally two or three places in a polling place where lines can build up (depending on the equipment used) — to check-in, to claim a voting booth, and (possibly) to scan a ballot. Knowing where congestion can occur can guide policymakers in deciding how to address lines. If lines are backing up because of problems at the check-in table, it certainly won't help to add more voting machines.

FIGURE 4
Primary location of waiting in 2012 election.



Source: 2012 SPAE

As Figure 4 illustrates, the location of lines depends on the mode of voting and the length of the back-up. Early voting lines are more likely to appear at check-in than Election Day lines. As lines get longer, especially on Election Day, the problem voters experience becomes increasingly likely to occur at the registration table.[8]

Midterm elections

Because lines occur when there is a mismatch between the arrival rate of voters and the resources available to process them, it follows that the longest lines should occur in the highest-turnout elections. Up until now, evidence about lines in non-presidential elections has been light. However, because the SPAE was conducted in 2014, we now have hard evidence to show how much lines are reduced when turnout is lower.

Average wait time to vote in 2014 was 4.3 minutes — 4.1 minutes on Election Day and 5.1 minutes during early voting. Thus, while turnout dropped 38% between 2012 and 2014, average waits dropped 68%. Not surprisingly, lines were not a major issue in most of the country in 2014. This is not because the problems that led to long lines in 2012 were fixed by 2014 — it is simply because fewer voters went to the polls.

The costs of lines

What is wrong with long lines? Aren't lines a sign that the public is excited by an election or the candidates? Because election officials can't plan for every contingency, it is natural that an unusually enthusiastic electorate will produce unusually long lines at the polls.

Furthermore, when we shift our gaze away from the United States, long lines at the polls often illustrate the hope felt by citizens of emerging democracies about the future of their country — think about elections such as Iraq in 2005, where voters risked mortar attacks and suicide bombers to stand in line for hours to cast a ballot.

Stories of long lines to vote in the face of intense violence in foreign lands can certainly inspire Americans to be more appreciative of their democratic rights, but it seems incorrect to equate long lines in a war-torn developing country with long lines in a peaceful, prosperous industrial power such as the United States. Indeed, in the American setting, it can be shown that long lines discourage voting, lower voter confidence, and impose economic costs.

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8 *The survey question asks voters who experienced a line the location of where the line was. It is possible for poll workers to slow down the check-in process in order to accommodate lines of voters waiting for voting booths and/or scanners. However, the fact that those who wait the least amount of time tend to report that the wait was at the check-in table suggests that, as a general matter, bottlenecks are more common checking in than in being able to cast the ballot after check-in.*

Long lines discourage voting.

Long lines may discourage some from voting, thus undermining the quality of elections as an expression of the people's will. Responses to the 2012 Voting and Registration Supplement (VRS) of the Current Population Survey suggest that over 500,000 eligible voters failed to vote for a variety of polling place problems that included long lines — inconvenient hours or polling place location, or lines too long. On the other hand, among non-voting respondents to the 2012 Cooperative Congressional Election Study (CCES), 0.8% stated that the main reason they did not vote was that "lines at the polls were too long." If we apply this percentage to the 91.6 million eligible voters who failed to vote in 2012, we calculate that there were 730,000 non-voters due to long lines in the most recent federal election.

These "lost votes" due to long lines are not as great as those the VTP has previously documented that can occur due to malfunctioning voting machines and voter registration problems. Still, any problem that keeps hundreds of thousands of voters from the polls in a presidential election is a significant challenge to democracy.

Long lines can reduce voter confidence in elections.

While long lines can cause voters to be turned away at the polls, the greater effect is on those who stay to vote. Responses to the 2012 SPAE suggest that waiting a long time to vote reduces the confidence voters have that their votes are counted. For instance, among Election Day voters, 68% of those who waited ten minutes or less to vote stated they were very confident their own vote was counted as intended, compared to 47% of voters who waited over an hour.[9] For early voters, the difference in confidence was only slightly less: 69% of those waiting ten minutes or less were very confident, compared to 54% who waited an hour or more.

What is more, the experience of waiting in a long line influences the judgments that form in voters' minds about the quality of vote counting throughout the nation. Among Election Day voters in 2012 who waited 10 minutes or less, 68% were very confident *their own vote* was counted as intended, 56% were very confident that votes *throughout their county* were counted as intended, etc.[10]

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[9] *Research by Sances and Stewart, among others, has shown that the most important influence on answers to the question about whether one's vote was counted as intended is the partisanship of the respondent — respondents who voted for the winning candidate are generally more confident their vote was counted properly than those who voted for the losing candidate. See Michael W. Sances and Charles Stewart III, "Partisanship and Confidence in the Vote Count: Evidence from U.S. National Elections since 2000," Electoral Studies 40 (Dec. 2015): 176–188. In a multivariate statistical analysis that adds controls for partisanship and state of residence of the voter, the relationship reported here, between voter confidence and wait times, remains.*

[10] *With the exception of the last cell entry — attitudes among early voters about whether votes nationwide were counted as intended — the differences reported in Table 1 remain once we control statistically for the party identification of the respondent and the respondent's home state.*

[11] *These states were Florida, the District of Columbia, Maryland, South Carolina, and Virginia. Oregon and Washington are excluded from this analysis, because so few voters in those states vote in-person.*

Finally, the existence of long lines influences assessments made about the accuracy of vote counting *even among those who do not experience long lines.* Consider, for instance, individual voters who live in states with long average wait times, but who did not experience long lines themselves. Among voters who live in the five states with the longest average wait times in 2012[11] but who reported that they, themselves, did not have to wait at all to vote, 23% said they were very confident that votes in their state were counted as intended. This compares to similarly-situated voters in the five states with the shortest average wait times, 63% of whom were very confident that votes in their state were counted as intended.

Long lines impose monetary costs on voters.

Finally, there are monetary costs to waiting in line to vote. Even if these costs are regarded by voters and society as a reasonable price to pay for exercising the franchise, and even if voters receive paid time off to vote, time spent waiting to vote represents the lost opportunity of voters to engage in productive work or leisure time activities. If costly solutions are proposed to reduce waiting times, it would be useful to have an estimate of what waiting in line to vote costs Americans in economic terms.

A simple way to produce a ballpark estimate is to multiply the total number of hours waiting in line by average hourly earnings. Based on an average wait time in 2012 of 13.1 minutes as reported below and an estimate that 105.2 million people voted in-person in 2012 (either on Election Day or in early voting), we calculate that voters spent a total of 23.0 million hours waiting to vote in 2012.[12] According to the U.S. Bureau of Labor Statistics, average hourly earnings were $23.67 in November 2012. Multiplying the number of hours waiting to vote by average hourly earnings yields an economic cost estimate of $544.4 million.

We have no opinion about whether this amount is "too high," "too low," or "just right." However, it is of a similar magnitude to previous estimates about the annual costs of administering elections in the U.S. For instance, based on data from a survey of election officials that the VTP conducted for the PCEA in 2013, we can estimate that local governments spent about $2 billion administering elections in 2012. If we combine the estimated costs borne by local governments conducting elections with the economic cost of waiting in line, a significant fraction of the economic cost of conducting a presidential election is the time spent by voters waiting in line.

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[12] *The in-person turnout estimate starts with Professor Michael McDonald's 2012 turnout estimate of 129.1 million. http://elections.gmu.edu/Turnout_2012G.html. Using the 2012 Voter Registration Supplement of the CPS, we can estimate that 81.5% of voters voted in-person. Multiplying the turnout estimate by the estimate of the rate of in-person voting yields 105.2 million.*

3. Queuing Theory

Managing lines is a well-known task in both the private and public sectors. Much of modern life is spent in customer service. A science has grown up over the past century that helps managers cope with customer demand in light of constraints on time and resources. At the core of this science is operations research; within operations research, queuing theory — the science of waiting lines — provides important insights into how to organize customer service so that waits are minimized and resources are used most efficiently.

Unfortunately, queuing theory has not penetrated very far in the field of election administration. Based on our experience working with election officials, we conclude that very few allocation decisions are based on even the simplest tools that are used in the customer service field. Instead, decisions such as how many voting machines to buy or how to deploy poll books are based on less efficient rules of thumb, the most common being, "what did we do last time?"

Everyone encounters queuing theory many times each day, even when they don't know it. Obvious applications include deciding how many cash registers to deploy at grocery stores, how to schedule subway and bus service, how to schedule staff time in health clinics, and how many lines to open up at an amusement park. Queuing theory is encountered daily in non-obvious ways, too, such as in the design of customer service call centers.

We are convinced that if simple, textbook applications of queuing theory were regularly applied to the field of election administration, not only would the long lines that exist be shortened, but that election administration budgets would be spent more efficiently. While we do not believe that queuing theory provides a road to election Nirvana — shorter lines *and* lower costs everywhere — we do know that the application of queuing theory to voting can help guide officials in figuring out how best to deploy new resources and, in some cases, actually save money over current practice.

Some basics

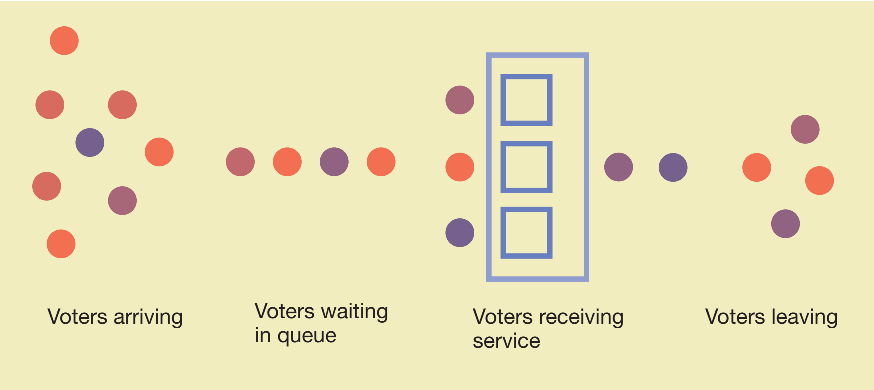
Long lines occur when resources are inadequate. Yet, resources are always constrained, especially in election administration. Thus, managers must decide how best to allocate scarce resources to get the best overall performance. Tools that are based on the science of queuing theory can help managers understand the various trade-offs involved in allocating resources and make the tough decisions that face them.

In voting, queuing theory can help answer the following questions:

- How best to allocate a given number of poll books, machines, and staff across a set of precincts?
- How many poll books, machines, and staff are needed to achieve a particular waiting time service target?
- What if…? …we move a poll book from Precinct A to Precinct B? …we reduce check-in time by 15 seconds? …we buy 10 new scanners and deploy them in our largest precincts?

The central organizing idea in queuing theory is (not surprisingly) the queuing system, which is composed of three parts: (1) the arrival of users, (2) the queue itself, and (3) the service that users receive. This is illustrated in the following figure.

FIGURE 5



To understand a system like this, we need to answer the following questions about each part of the queuing system:

- **Arrival of voters:** At what rate do voters arrive, and how variable is the arrival process?
- **The queue itself:** How do voters wait for service? For instance, do voters queue in the order of arrival so that the first users to arrive the first to be served? And are there multiple queues, one for each server, or just a single queue that feeds a set of parallel service stations?
- **The service that voters receive:** How many service stations are available to receive voters, how quickly are voters processed, and how variable is the processing time?

To see how answers to these questions can help guide common line management decisions, let us imagine we are running a check-in desk at a health clinic. We have been informed by management to keep wait times to no more than 1 minute, because the patients arriving are often sick and in distress. Because of measurements we have taken, we know that patients arrive randomly at a rate of about one every minute, and that it takes an average of 2 ½ minutes to check in a patient. This time, though, is highly variable from patient to patient. Finally, when patients arrive, they stand in a single line; the first to arrive is the first to be served.

How many receptionists do we need at any given time to keep wait times to less than one minute?

With these simple facts (and with specific assumptions about the nature of the uncertainty in the arrival and service processes), we can consult standard textbook queuing models, which would tell us that we would need 8 receptionists to ensure that virtually no one would experience a wait longer than 1 minute in line. If we could only afford to employ 5 receptionists, the standard textbook models tell us that average waits would still be short — only 8 seconds on average — but that 5% of customers would have to wait more than one minute to reach the front of the line.

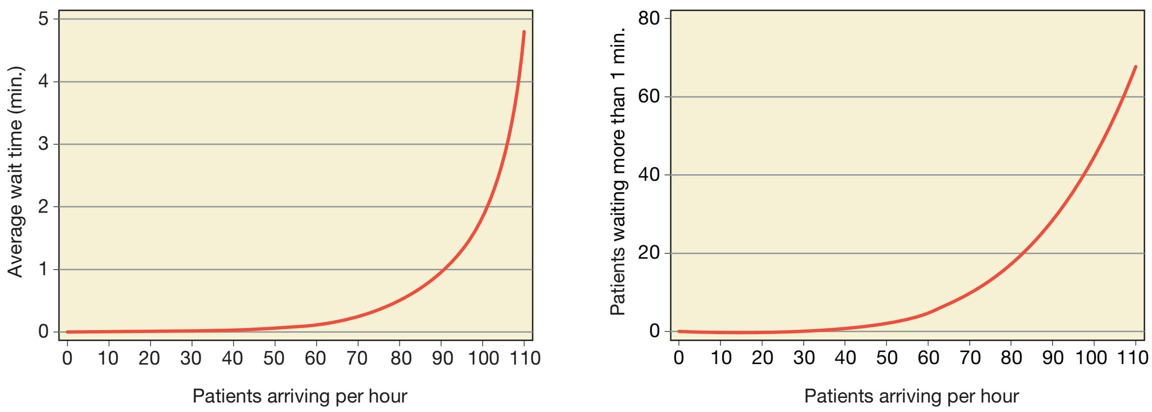
This is a simple example, but it is representative of the problems that queuing theory sets out to solve. Basic, commonly used queuing models help us grasp some very important features of line dynamics. The most important is this: line dynamics are highly non-linear. In other words, line lengths and waiting times do not grow in strict proportion to the arrival rate of customers. When arrival rates are very slow, it may be possible to speed up arrivals substantially without increasing lines and wait times. On the other hand, when arrival rates are very fast, even a small increase in the arrival rate can cause lines and wait times to grow uncontrollably.

Queuing models

Queuing models are summarized using a notation called "Kendall's notation," which looks like this: A/S/c. The letter "A" records the type of arrival process in the system, the letter "S" records the service time distribution, and the letter "c" records the number of servers. The most common assumption about both the arrival process and the service time distribution is that the interarrival times and service times are both drawn from random distributions that are "Markovian" or "memoryless." When the process is Markovian, the letter "M" is substituted for the "A" and "S" in the generic notation. Thus, the form of queueing model we discuss in this example is described with the notation M/M/c, meaning that both the arrival process and the service time distribution follow a Markovian process, and the number of servers (which we must choose) is described with the placeholder "c".

This pattern is illustrated below, using the numbers from the health clinic example above — five receptionists who each can check in a patient in 2 ½ minutes on average. The graphs show what happens to average wait times (left graph) and the percentage of new arrivals who have to wait more than 1 minute (right graph) as the arrival rate varies from 0 to 120 patients per hour.

FIGURE 6A AND 6B

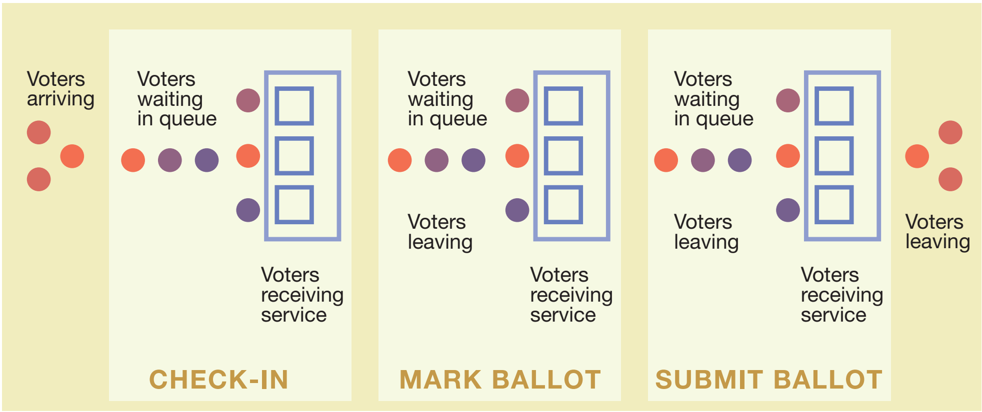


Note that each of these graphs is flat for a long time, and then at some point starts to grow at a faster and faster rate. When the system goes from 50 patients to 60 patients per hour, the amount of strain on the system barely changes: average wait times only go from 4 to 8 seconds, and the percentage waiting more than 1 minute only goes from 2% to 5%. However, if the system goes from 100 patients to 110 patients an hour, average wait times more than double — from 1.9 minutes to 4.8 minutes. The percentage of patients waiting longer than the benchmark 1 minute goes from 44% to 68%.

Beyond the basics: the complexities of polling places

Of course, polling places are more complex than a single check-in desk at a health clinic. Polling places typically have two or three service steps, depending on the voting technology. The following figure illustrates a typical set-up for voting. Queues can form at each step of the process. In the most extreme cases, a long line at the voting booths or scanners might require registration check-in to suspend operations to allow the downstream queues to shorten.

FIGURE 7



Even though precincts involve a chain of service steps and associated queues, it is possible to break the chain apart and ask about whether each place where voters receive service has adequate resources so that lines don't get out of control. Later in this report, we show how that might be done.

4. Applying Queuing Theory to Manage Actual Polling Places

Although it may seem that applying queuing theory to the management of polling places requires the use of complicated math, operations researchers and software designers have developed some easy-to-use tools to help managers of polling places apply the tools, even without a background in probability and statistics. What is needed to use these tools, more than a background in operations research, is attention to how polling places are organized. In addition, some care needs to be taken in consistently measuring the rates and patterns in which voters arrive at polling places and how long it takes to complete each step or task in the voting process.

The URL for the polling place resource toolbox is http://web.mit.edu/vtp/

At the request of the Presidential Commission on Election Administration, the VTP developed a series of web-based software tools that administrators can use to manage the allocation of critical resources to precincts and to control the length of lines. The purpose of this section is to illustrate how these tools can be used to understand and manage lines in actual polling places. We start by describing the process of using the tools in a very general way. Then, we apply the tools to two specific settings — one is in a large, densely-populated city, and the other is in a large county with a mix of city and suburbs.

General considerations

We define a five-step procedure to help describe how to apply the tools of queuing theory to managing lines at polling places. The five steps are these:

1. Identify where lines might form
2. Measure arrival rates
3. Measure service times
4. Enter the data from steps 2 and 3 into the online tools
5. Use the results from step 4 to consider how resources might be adjusted

Step 1: *Identifying where lines might form.* The first step in applying queuing theory to lines at polling places is to identify where voters receive service, and thus where lines might form. The purpose of this first step is to identify those places where you will need to take measurement, to estimate how frequently voters arrive and how long it takes for them to be served.

As a general matter, jurisdictions that use optically scanned paper ballots will have three relevant places:

1. Registration table, where voters check in
2. Voting booths, where voters cast a ballot
3. Scanners, where voters scan and cast their ballots

In jurisdictions that use electronic voting machines, only the first two locations will be relevant. There may be other service locations to be aware of, depending on local laws. For instance, in Massachusetts, voters must check out before they scan their ballots. This adds a fourth service station that must be accounted for.

Step 2: *Measuring arrival rates.* The next step is to estimate how many voters will arrive at the polling place over some period of time.

There are two general strategies one can follow in estimating arrival rates. The first is simply to take the number of voters anticipated to arrive over a given period of time, and then divide by that amount of time. For instance, if a precinct typically has an Election Day turnout of 1,200 voters and polls are open from 6:00 a.m. to 6:00 p.m. (i.e., 12 hours), the average arrival rate is 100 voters per hour or 1 2/3 voters per minute. This is the easiest method to estimate arrival rates, and in many cases will be sufficient.

However, there will be other cases in which the second method is more appropriate — measure arrival rates by observing when voters actually arrive at the polls. To implement this method, someone must actually observe people arriving at the polls, counting the number of voters who arrive at regular intervals during the voting day. This is the method that was used in some of the cases we discuss below.

Deciding how much effort to invest in gathering data about arrival rates at the polls is a trade-off between administrative simplicity and cost and accuracy. The most accurate methods require a commitment to careful training.

The second method is more labor intensive than the first, so why would an election jurisdiction use it? The main reason is to be able to take into account the fact that arrival rates fluctuate significantly throughout the day. If a precinct experiences a period of intense demand — for instance, if half of all voters show up in the two to three hours before the start of the work-day, while the other half show up during the rest of Election Day — lines will actually be longer than if the same number of voters arrived evenly throughout the day.

Local jurisdictions sometimes try to take a short-cut in measuring arrival rates throughout the day, by relying on statistics they keep that record how many voters have checked-in by different times of the day — or similarly, the number of voters who have scanned a ballot at different times of the day.

For instance, the Elections Department of the City of Boston, Massachusetts receives reports from the city's precincts about the cumulative number of voters who have cast ballots by certain times of the day: 9:00 a.m., noon, 3:00 p.m., and 6:00 p.m. (Polls open at 7:00 a.m. and close at 8:00 p.m.) If 360 voters cast a ballot at a precinct between 9:00 a.m. and noon, it is tempting to estimate that voters have arrived at a rate of 120 per hour during this period. However, we don't know when these voters *arrived* at the polling place, only when they got to the end of the process and scanned their ballot. Most importantly, if a very long line formed before 9:00 a.m., then it is possible that a significant portion of the voters who cast a ballot between 9:00 and noon actually arrived before 9:00. (Similarly, anyone waiting in line at 12 noon would not be counted as having arrived prior to noon.) The same point could be made of using the number of voters checked-in at a registration table during a slice of Election Day. If there is a line to check in, then the check-in time may not accurately reflect the arrival time. The longer the line, the less reliable check-in time data will be in figuring out arrival rates.

A method that tries to measure arrival rates during peak hours using an indirect method . . . is guaranteed to under-estimate the arrival rate at peak time.

The bottom line is this: If a polling place tends to experience a big rush of voters at one specific time of the day — typically before or after work —the most reliable method of estimating arrival rates during these times, by far, is to station someone at the end of the line (or entrance to the precinct), and have them record the number of people arriving at regular intervals. A method that tries to measure arrival rates during peak hours using an indirect method, such as counting the number of ballots scanned during the time period, is guaranteed to under estimate the arrival rate at peak times.

Step 3: *Measuring service times.* Next, one must measure how long it takes voters to be served at the various steps along the chain of voting, typically checking-in at the voter registration table, casting a ballot, and (if the ballot is scanned) scanning the ballot.

We define the duration of a service task as being the time from when the voter is being served at a particular station in the voting process, until the next voter is served (assuming one is waiting). If it is the check-in table, the duration of the service time is the period between one voter beginning to check in and the next voter starting the process; for voting booths, it is the time between one voter arriving at the booth and the next voter going into the booth.

Often someone might only measure the time, say, when the voter is actually filling out the ballot, and neglect other elements of the service time, such as the time to get settled and the time to move into and out of a voting booth.

Before discussing various methods of measuring service times, one critical point must be made up front: The purpose of measuring service times is not to see how long it would take an *ideal* voter to be served. Rather, it is to see how long it takes an *average* voter to be served or to accomplish the task.

The most accurate data will be gathered by watching individual voters actually navigate a polling place. It is usually possible to station observers in precincts whose job it is to time how long it takes a voter to complete each of the tasks necessary to vote. In doing this timing, every second matters. Therefore, it is not overkill to time voters using a stopwatch. In the two case studies we examine below, voters were actually timed by researchers who sat in polling places with clipboards and stopwatches.

Such an exercise may not always be feasible — it may not be possible to recruit enough observers. Or, having observers timing voters during Election Day may seem too intrusive. Therefore, a workable substitute could be timing voters and poll workers in more controlled environments, such as an office.

For instance, to test how long it takes to fill out a ballot, an election official might take sample ballots to various locations around the city — to senior centers, churches, schools, or even co-workers in other city departments — and ask them to time themselves in completing a ballot.

If this second tactic of taking measurements in a controlled setting is used, one thing is crucial: the "test subjects" must be representative of the voters who will cast ballots on Election Day. And again, they must be *typical* voters, not *ideal* voters. It is our experience that election officials too often estimate how long it takes to check a voter's registration or fill out a ballot based on a best-case scenario.

Step 4: *Entering data into the online tools.* With the data at your disposal, it is now possible to enter this data into an online tool and get feedback. Here, we demonstrate the use of two tools on the VTP Election Toolkit web site.

The first tool is the one developed by Stephen Graves and Rong Yuan (the "Graves-Yuan Tool"). In this example, we have chosen a precinct that typically experiences 1500 voters during a 13-hour Election Day, or roughly 115 voters per hour on average. In this precinct it takes an average of 30 seconds to check-in at the registration table (or 0.5 minutes). There is one person doing the checking-in. For this example, we have set a maximum wait-time target or benchmark of 30 minutes to check-in a voter; that is, we would like for very few voters, if any, to wait more than 30 minutes to register. Knowing that it will be impossible to ensure that *everyone* is checked-in within 15 minutes of waiting, we specify as a goal that 95% of voters to be checked-in with the 30-minute benchmark.

FIGURE 8

Enter Data

select Check-In Voting Machine + Add Precinct

Clear Data

Precinct #	Arrival rate (voters per hour) [1,10000]	Average time for check-in (minutes) [0,100]	Arrival rate (voters per hour) [1,10000]	Number of Check-in Stations [1,100]	Service level (%)	
	115	0.5	1	30	95	✖

Calculate

Results

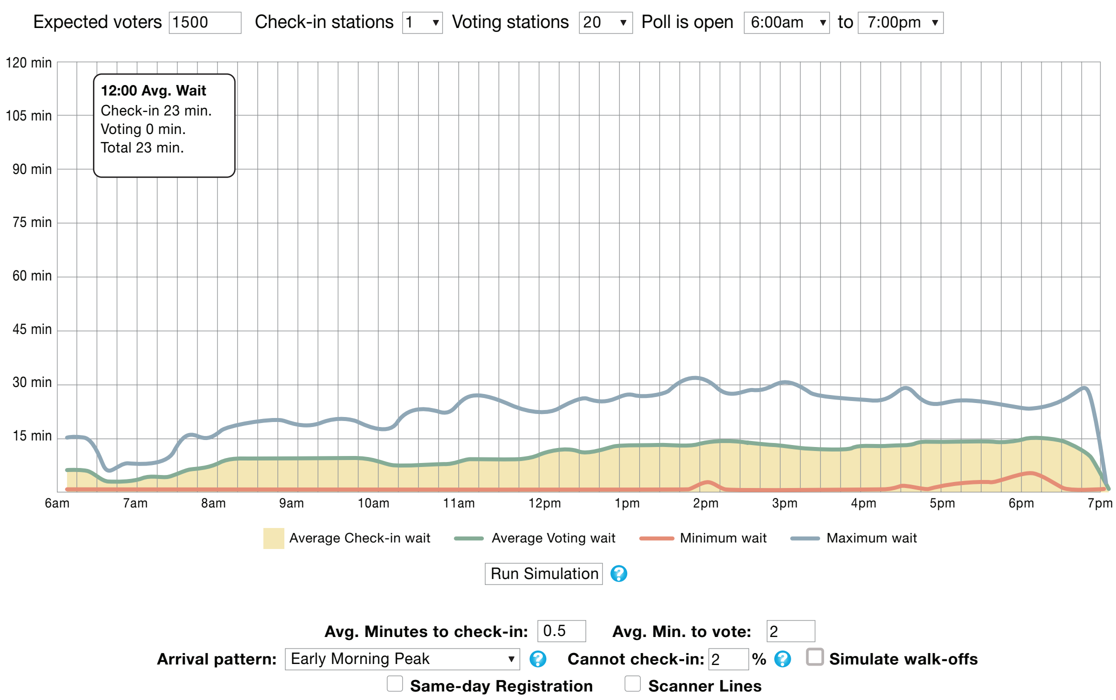
Clear Data

Precinct	Average Wait Time (minutes)	Percent of voters that wait longer than the target	Number of Check-in Stations required to meet the service level	Alert
	11.5	7.9	2	

The upper part of the tool lists the inputs we entered. The lower part lists the results. Based on the inputs, the tool calculates that the average voter will wait 11.5 minutes prior to registration. The tool further calculates that 7.9% of voters will wait longer than our benchmark of 30 minutes, and that we would need two registration tables in order to ensure that 95% of the voters wait less than 30 minutes.

The second tool is the one developed by Mark Pelczarski (the "Pelczarski Tool"). This tool was developed to show wait times throughout the day, and to account for two possible bottlenecks at the same time — checking-in and casting a ballot. In this example, we have filled in data for a similar scenario to the previous one. We are expecting 1500 voters during the time the polls are open, from 6:00 a.m. to 7:00 p.m. There is 1 check-in station. (To focus our attention on check-in, we have set the number of voting stations to 20, which is more than enough for anticipated demand.) As before, the average check-in time is 0.5 minutes. (The average time to vote is set to 2 minutes, but this does not affect the estimates of how long it takes to check in.)

FIGURE 9



The output of this tool emphasizes the average wait time to check in throughout the day, indicated by yellow area in the figure. By moving the cursor over the graph, the tool reports the average wait time for that moment — the sample shows an average check-in wait of 6 minutes at noon. The dashed lines show the variability around the estimates of the average. In this example, some precincts will experience no wait at all during the day, while other precincts could experience waits of as much as 30 minutes — it all depends on the actual arrival pattern of voters.

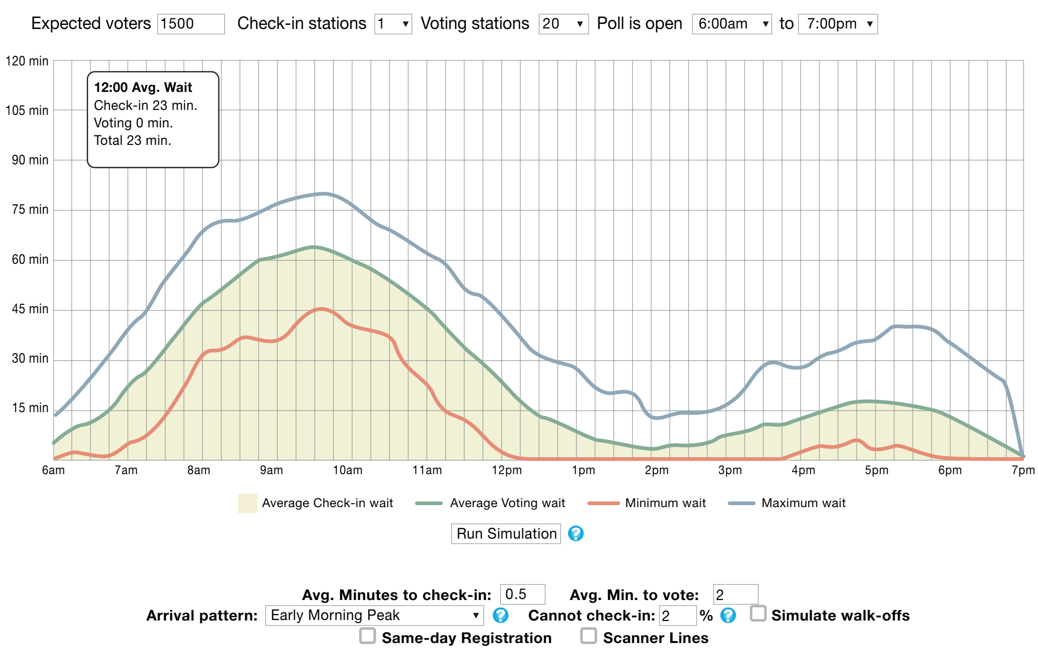
Step 5: *Fine-tune the inputs.* Finally, if the results of the simulations don't show acceptable results, adjust the inputs to see if you can improve performance.

In the previous step, the results from the Graves-Yuan Tool indicate that we need 2 check-in stations to meet our benchmark service level and that if we add this additional check-in station, average wait times will be reduced by 681 seconds (nearly 11 ½ minutes) per voters. If we type the number "2" into the box for number of voting stations, the Tool confirms that we would reduce average wait times down to a paltry 9 seconds, and that no one would wait more than 30 minutes. In a similar fashion, if we change the number of check-in stations to 2 in the Pelczarski Tool, the yellow part of the graph disappears, indicating that the wait throughout the day is virtually zero.

The Pelczarski Tool allows you to experiment with other parameters, as well, to take into account variations across polling places in factors such as the pattern of arrivals during the day. In the example above, we chose the arrival pattern that corresponds with "Saturday: steady," which means that the arrival rate is steady throughout the day. We could choose other arrival patterns, such as "Early Morning Peak." This pattern would take the same 1,500 voters, and instead of assuming they arrive at the same rate throughout the day, simulate what would happen if there was a surge of arrivals at the beginning of the day. The results of that simulation are shown below.

Note that the results are quite different when arrivals are front-loaded during the day. A line builds right off the bat, rising to an average wait time of over an hour by 9:00 a.m. The wait then dissipates, but not entirely. By noon, the average wait is 23 minutes, compared to 6 minutes when arrivals were steady throughout the day.

FIGURE 10



The great advantage to using tools such as these is that they can help election administrators understand various "what-if" scenarios, especially in light of trying to fix problems with long lines.

Having now discussed a general approach to the use of polling place tools to help understand polling place dynamics and correct unacceptably long lines, we turn our attention to two case studies. These case studies draw on data from actual local election jurisdictions. So that we can focus on the technique, we have used fictitious names for each locality. The first case is a city in a state without early voting, and which regularly has reports of Election Day lines scattered throughout the city in presidential election year, but not at midterm. The second case is a county that has a substantial amount of early voting, and which experienced widespread lines in the 2014 midterm election.

Case Study 1: Metro City[13]

Metro City is a dense central city within a large, prosperous metropolitan area. It has over 380,000 registered voters, with turnout in presidential elections approximately 255,000, and 160,000 in midterm elections. Election Day is 13 hours long. Because the state in which Metro City is located does not have early voting and sets high barriers to absentee voting, virtually all votes are cast on Election Day in traditional neighborhood precincts. Voting is done on paper ballots that are optically scanned. Metro City uses paper poll books to check-in voters.

There are 255 precincts in Metro City, which means that the average precinct processes 1,000 voters in a presidential election year, but only 627 voters in midterm elections. However, the range in the number of voters who cast ballots in precincts varies greatly. The largest Metro City precinct saw over 2,600 voters cast ballots in 2012, compared to only 21 voters in the smallest. Despite the wide variability in voters at each precinct, the number of clerks checking in voters varies very little. In 2012, the check-in was done at a single line in each precinct. In 2014, a second check-in clerk was added to four of the largest precincts.

In the 2014 midterm election, the Voting Technology Project sent a team of student researchers into a random sample of precincts throughout Metro City. These researchers counted voters as they arrived and timed how long it took a sample of voters to perform the following tasks: check-in, vote, and check-out.

Basic queuing statistics in 2014 for average voter and precinct in Metro City

Average check-in time: 37 sec. (0.62 min.)

Arrival rate in average precinct: 48/hr.

1 check-in station

12 places to mark a ballot

Let us first consider the check-in process. Our researchers observed a total of 413 voters checking in during the day. These voters took an average of 37 seconds to check in. Using the Graves-Yuan line optimization calculator discussed previously, we can plug in the relevant information from the average precinct (48 arrivals per hour, 0.62 of a minute to check-in, and 1 check-in station) and see that the average wait time in the average precinct would be 0.61 minutes, or 36.6

[13] *In this case, and the one that follows, we have masked the name of the jurisdiction, so that we can focus on the process and findings.*

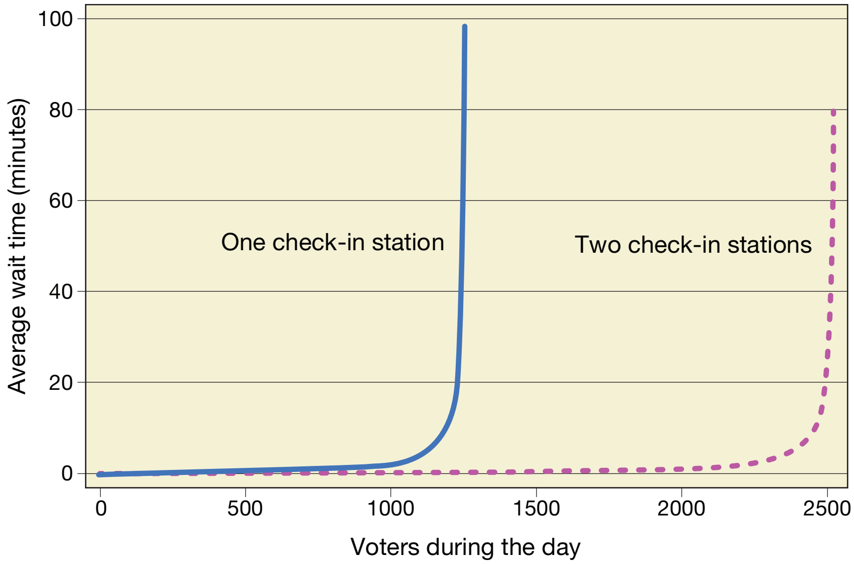
seconds. For a precinct at the 90th percentile of arrivals (997, or 77 per hour), average wait time would be 2.4 minutes.

As we noted above, in 2014, Metro City allocated two check-in clerks to four precincts, including the largest, which saw 1,763 voters on Election Day. The Graves-Yuan calculator confirms that with two check-in stations, the average wait time should be only 36 seconds in this precinct. If only one check-in line had been used, the calculator predicts unstable results — indicating a line growing constantly during the day, as voters arrive at a rate faster than the station can check them in.

The Pelczarski tool shows the dynamics of wait times, and can help show what would have happened in this largest precinct had there been only one check-in station. The Pelczarski tool predicted that the line to check in at this precinct would have grown linearly throughout the day: from 7 minutes at the start of the day to 143 minutes (over two hours) at noon, all the way up to 405 minutes (nearly 7 hours) at closing time.[14] Clearly, the presence of this additional check-in station at the largest precinct prevented a potentially chaotic situation in 2014.

The following graph shows the relationship between the number of voters coming to the polls in Metro City and the average time to check in, assuming it takes an average of 37 seconds to check in at each precinct. The two lines show the average time for one check-in line (the blue line) and two check-in lines (the dashed red line).

FIGURE 11



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[14] *The Pelczarski tool allows the user to choose a variety of arrival patterns. We have chosen to use the "steady" arrival pattern.*

Note that the solid line goes vertical around 1,250 voters, while the dashed line goes vertical at about 2,500 voters. These are the points at which line dynamics become unstable, and wait times start to grow without bound. (An average service time of 37 seconds translates into a service rate of 1.62 voters per minute; for a 13 hour day, this means that the single registration station, working without breaks or idle time, would have the capacity to register at most 1265 voters.)

In the case of Metro City in the 2014 midterm, 7 precincts had more than 1,250 voters, and thus would have been well served by a second check-in line. However, the city was only able to assign a second check-in clerk to four of these seven precincts, meaning that these three other precincts likely had to manage with very long lines throughout the day, despite the fact that this was a low-turnout election.

This analysis shows that Metro City is in a bit of a pickle for presidential elections. In 2012, over one-fifth of Metro City's precincts (53) had more than 1,250 voters and one had over 2,500. With only one check-in clerk assigned to each precinct in that election, queuing models tell us that it was virtually guaranteed for over one-third of Metro City's voters to wait longer than 30 minutes to vote in 2012, the benchmark established by the PCEA. The theory's predictions are borne out by survey research evidence, which shows that 29.5% of Metro City's voters reported waiting more than 30 minutes to vote in 2012.

What should Metro City do if it wants to reduce wait times in the 2016 presidential election so that only a small fraction of its voters wait more than 30 minutes to check in? It is possible to use the Graves-Yuan tool to run what-if scenarios to answer this question. From what we have seen in the graphs above, the tipping point appears to be in precincts with more than 1,250 voters turning out. If Metro City had been able to assign a second check-in clerk to the 53 precincts with turnout above 1,250, a little manipulation of the Graves-Yuan tool reveals that only 2% of Metro City's voters would have waited more than 30 minutes.

Is this an easy fix? On the one hand, Metro City employed nearly 2,000 poll workers in 2012, and 53 additional clerks would represent a growth of only 2.7%. On the other hand, most local election departments list finding qualified, high-quality poll workers as among their greatest challenges. Whether it would be possible to find "only" 53 more poll workers to staff the check-in tables in 2016 is a question most local election directors don't want to answer.

We end this section on Metro City with what we believe is the most important point: Metro City faces a serious challenge in moving its voters through the polls in presidential election years, yet it is possible to use basic tools derived from queuing theory to identify simple actions that would make the situation much better. The solution suggested — find a way to add a check-in line to 53 polling places — is clear. It may even be achievable.

Case 2: Magnolia County

Magnolia County presents different challenges compared to Metro City, and can illustrate how queuing tools can give local jurisdictions a menu of choices in deciding how to address the challenge of long lines at the polls.

Magnolia is a large county located in a fast-growing part of the country. It consists of virtually every type of residential setting seen in the U.S., from high-density urban areas to rural areas that border on wilderness. It has over 700,000 registered voters, with turnout ranging from 300,000 in midterms to over 470,000 in presidential elections. Unlike Metro City, the state in which Magnolia County is located has early in-person voting as well as "no-excuse" absentee voting. As a consequence, the Election Day turnout in Magnolia County is similar to that of Metro City — roughly 130,000 in midterms and 200,000 in presidential years — despite the fact that Magnolia County has nearly twice as many registered voters.

Ballots are cast on optically scanned paper ballots, and voters check in on electronic poll books. The polls are open for 12 hours on Election Day.

Magnolia County has 227 precincts, meaning that the average precinct processes 573 Election Day voters in midterms and 881 in presidential elections.

For the typical precinct, Magnolia County deploys three electronic poll books that can be used to check-in voters. However, a few small precincts have only two devices, and a few larger ones have four or five. Regardless of how many poll books are at the precinct, one of them is designated for use at the "help desk," and thus may not be available for the regular check-in of voters, because it is reserved for any registration problems that arise.

As we did in Metro City, in 2014 we also sent a team of student researchers into a random sample of precincts throughout Magnolia County. Similarly, the researchers counted voters as they arrived, and also timed how long it took a sample as they arrived to check in and cast ballots.

Our researchers observed 327 voters checking in during the day. These voters took an average of 128 seconds to check in. Using the Graves-Yuan line optimization calculator discussed previously, we can plug in the relevant information from the average precinct (48 arrivals per hour, 2.13 minutes to check-in, and 3 check-in stations) and see that the average wait time in the typical precinct would be 0.52 minutes, or 31 seconds. We can perform a what-if analysis, and ask what would happen if one fewer check-in station were available at the typical precinct. That results in an estimated average wait of over 5 minutes, with 1.2% of voters waiting more than 30 minutes.

Basic queuing statistics in 2014 for average voter and precinct in Magnolia County

Average check-in time: 128 sec. (2.13 min.)

Arrival rate in average precinct: 48/hr.

3 check-in stations

Magnolia County provided us with information about the number of check-in stations available at all precincts during Election Day 2014. If we assume a 2.13 minute average check-in time for each precinct, then the Graves-Yuan tool predicts that a significant[15] number of voters would have waited more than 30 minutes in eight precincts. In five of these precincts, the tool predicts that line length will reach steady-state during the day, with the steady-state wait times ranging from 12 to 46 minutes. In three of these precincts, line length grows throughout the day because the average arrival rate exceeds the average service rate. In such a case, the tool cannot calculate a steady-state average line length, as the length of the line continues to grow over the day. (See sidebar.)

As with Metro City, we can push the what-if analysis to ask, "if turnout had been at levels typically seen in presidential election years, what would lines look like?" And, just like Metro City, the answer is that lines would have been much longer. However, in this case, it is more accurate to say that the lines would have been much, *much* longer.

Simply plugging in the number of Election Day voters into the Graves-Yuan line optimization calculator reveals that lines would have been unstable — growing continually throughout the day — in 88 of 227 precincts.[16] In the remaining precincts — the ones we predict would develop lines that would reach a steady state — another 20 would develop lines in which a significant number of voters would wait longer than the 30 minute PCEA benchmark to vote.

We can further investigate two scenarios to examine what it would take to reduce waiting times to the 30-minute benchmark. One is to ask how many additional check-in stations would be necessary to reduce waits to be within the 30 minute benchmark. When we do that, we see that Magnolia would need to add over 100 check-in stations throughout the county—a similar prescription to the situation in Metro City, where it was necessary to add an additional 50 check-in stations to bring the city within the 30-minute benchmark.

Unstable line dynamics.

Standard queuing models have been developed for cases where line lengths reach an equilibrium, or a "steady state." For most applications, this is a useful approach. In some cases, however, the average arrival rate exceeds the average service rate, causing lines to grow without bound; for instance, if the arrival rate is 60 voters per hour and if the registration desk can only register 45 voters per hour, then we expect for the line to grow by 15 voters each hour. The system does not reach a natural equilibrium, and the only thing that brings order is outside intervention — usually just turning off access to the service, such as closing the doors and not letting anybody else in.

When lines are unstable, the Graves-Yuan tool cannot estimate the average wait time, because in a sense, there is no average to estimate. However, it is possible to figure out approximately how many people wait longer than the target maximum wait time by equating the maximum wait time to a line length, and then by estimating at what time of day that line length will be reached. Everyone who arrives after this time will wait longer than the maximum wait time.

For instance, if the system can process 60 voters per hour, then a line length of 30 corresponds to a wait time of 30 minutes. If the arrival rate is 70 voters per hour, then it will take 3 hours for the line to build to 30 voters; we expect that any voters who arrive after 3 hours to experience wait times of at least 30 minutes.

In the case of Magnolia County, for instance, it might be reasonable to assume that everyone who arrived after the polls had been open for an hour had to wait more than 30 minutes. While this rule-of-thumb would produce a less precise estimate of the number of people who waited longer than the target, it may be sufficiently precise for planning purposes.

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15 *"Significant" in this case is defined as more than 5% of voters in a precinct waiting longer than the target of 30 minutes.*

16 *We did not change the number of poll books from 2014, in order to simulate the type of what-if analysis might be done if a jurisdiction deployed all its poll books in each federal election.*

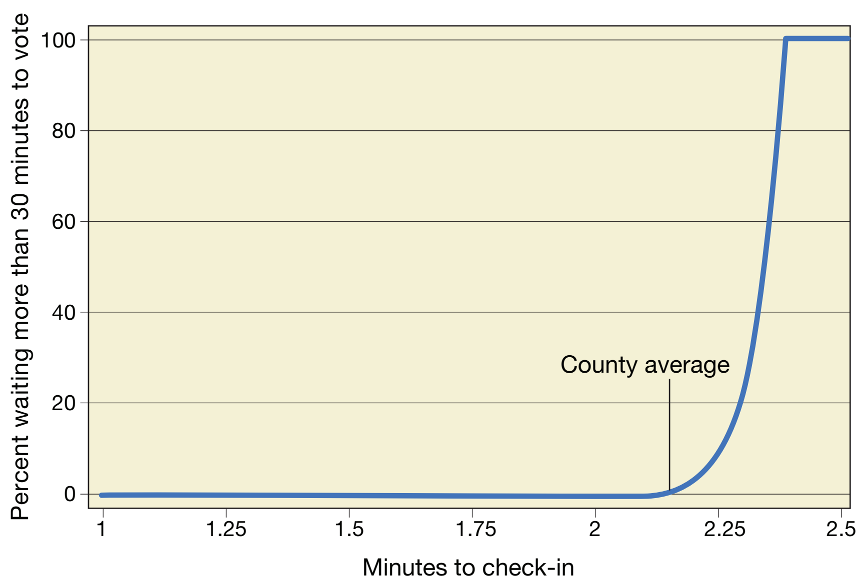
However, it is quite different from the Metro City prescription for this simple reason: Each additional Magnolia County check-in station also must have an additional electronic poll book, whereas adding check-in stations to Metro City only requires that the paper poll book be divided into parts, according to the alphabet. In Metro City, adding an additional check-in station would cost an extra couple of hundred dollars; in Magnolia County, an additional check-in station could cost thousands of dollars, once the personnel and technology costs are calculated.

Thus, before exploring the expenditure of hundreds of thousands of dollars to add check-in stations, Magnolia County could explore another avenue: reducing check-in times. Note that Magnolia's check-in time, at 128 seconds, is almost three and a half times longer than the average check-in time at Metro City.

The following graph shows the estimated percentage of voters in a precinct who would wait more than 30 minutes to check in, as a function of the amount of time it takes for a single voter to check in at a precinct. In estimating these percentages (using the Graves-Yuan calculator), we have set the size of Election Day voting in the precinct at 900 or 75 per hour (which is close to the Magnolia County average) and equipped the precinct with 3 check-in stations, which is also typical.

As before, there is a sharp "elbow" in this graph that appears right around 2 ¼ minutes of check-in time. Once check-in times exceed 2.4 minutes, virtually everyone has to wait more than 30 minutes in order to check in at the precinct. Note that the county average, 2.13, is right around this inflection point. This suggests two things. First, it suggests that the "average" precinct in a presidential election is teetering on the edge of uncontrollably long lines. Second, it also suggests that if Magnolia County could shave a few seconds off the average check-in time, lines would be considerably shorter in many precincts.

FIGURE 12



To explore the possibility that reducing check-in times would help Magnolia County address its potential problem with lines in presidential elections, we experimented with different values for check-in times, utilizing 2012 Election Day turnout and the number of check-in stations in 2014 for the simulation. If check-in times could be reduced by 8 seconds, down to exactly 2 minutes, the fraction of voters waiting in line for more than 30 minutes would fall from 57% to 46%. If the check-in times were reduced another 15 seconds, to 1 ¾ minutes, only 21% of voters would need to wait more than 30 minutes to check-in. Finally, if check-in times could be reduced even further, to a minute and a half, only 8% of voters would need to wait more than 30 minutes.

Reducing check-in times would not be a trivial task. Much more goes on when a voter checks in in Magnolia County than simply checking their name off an electronic list. Magnolia County is in a voter ID state, so the ID needs to be verified before voting, which is not true for Metro City. (However, Magnolia County is able to read information off of a voter's driver's license electronically, which should speed up the process.) When they check in, voters are asked if their addresses are up-to-date in Magnolia County, which is not the case in Metro City. These additional time-consuming tasks may be mandated by the state, or may pay off in other ways.

Magnolia County has no clear path to reducing wait times to check in. Adding more check-in stations would impose a serious financial challenge to the county. Cutting the amount of time to check in would involve more than simply talking faster, but would require a thorough review of administrative practices and a revamping of training. However, despite the fact that substantially reducing check-in times in Magnolia County would be expensive, the use of resource allocation tools gives the county something to aim for, and makes the case for any additional resource needs.

5. Moving Forward

The purpose of this report is to help introduce the election administration community to tools that can be used to help effectively manage capacity on Election Day. While the tools are based on the application of a sophisticated field of operations research science, the inputs are easy to conceptualize and measure; and the tools are straightforward to use.

In our work with state and local election officials, we have run across several jurisdictions that attempt to manage capacity in a systematic way. Notable recent examples include jurisdictions, such as Travis County, Texas; Orange County, California; Denver, Colorado; and Bernalillo County, New Mexico.

The most systematic application of queuing-based tools undertaken at the initiative of local administrators since the 2012 presidential election was done by the District of Columbia Board of Elections in 2014. As part of a comprehensive review of polling place practices, the DC Board of Elections sent Election Day Data Teams to five precincts. These teams engaged in intensive measurement of arrival rates and service times at each of the precincts they visited.

The Elections Board staff was able to input the data gathered by the data teams into the VTP polling place tools, which helped to provide feedback about whether the allocation of resources to precincts was optimal.

A particular problem confronting DC was the fact that voters in most precincts could choose to vote on either touchscreen voting machines or optically scanned paper ballots. Board staff believed that some of the problems the District was facing with long lines stemmed from the choice of many voters to vote on the touchscreen machines. However, without close observation of polling place dynamics, they could not say precisely how the choice of electronic voting machines slowed things down.

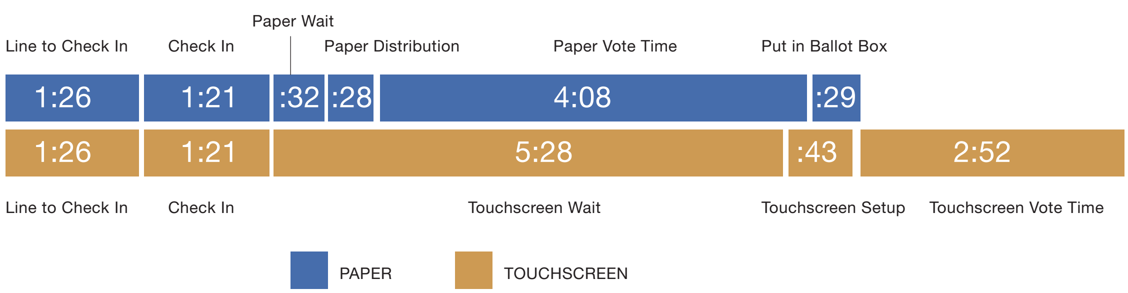
The accompanying graph, prepared by Board staff, provides a stark contrast in the experience of voters depending on the mode of voting chosen. Interestingly enough, although it took voters less time to vote on the touchscreen machines, the wait to gain access to the machines was so long that electronic voting overall was much more prone to delay.

The 2014 study of polling places in DC is an exemplary case of a local jurisdiction taking the tools discussed in the previous section and building on them to improve the voting process. The long-term payoff will not only be fewer frayed nerves among voters and election administrators, but also fewer potential voters walking away because of long lines and, ultimately, greater confidence by local voters in the legitimacy of election outcomes.

There have been interesting recent developments internationally as well. For instance, in the 2015 Danish parliamentary election, DemTech — with the approval of the Danish election authority — ran a small pilot project in which they used sensors to track and record the location of voters in polling places, based on cell phone signals. This method, which preserves the anonymity of the voter, suggests that it may be possible to gather rich performance data about the functioning of polling places unobtrusively, and without adding to the burden of election workers. Of course, using cell phone signals to track the location of voters in a polling place, even if done anonymously, raises privacy concerns that would need to be addressed before being deployed in the United States.

FIGURE 13

Paper Ballot vs. Touchscreen Voting



Source: DC Board of Elections, "Data Team Findings," PowerPoint presentation, May 28, 2015.

The goal of this report is to highlight how it is possible, today, to harness the power of systematic observation to generate and analyze the data to develop concrete proposals that improve the management of polling places. The tools and methods outlined in this report are used by thousands of businesses across the country to ensure that their customers are served quickly and efficiently. With scrutiny recently focused on how long it takes to vote in some parts of the United States, it is inexcusable for election officials and policymakers not to take advantage of these tools and methods.

Systematic observation of arrival rates and service times at polling places is a critical piece of the puzzle that must be assembled to move election administration more fully into the metrics-driven age.

A state or locality wanting to base its resource allocation decisions on hard facts needs access to a basic suite of information in order to make these decisions. Among these facts are:

- Historical turnout figures, broken down by precinct and mode of voting (in-person on Election Day, in-person during early voting, and by mail/absentee).
- Service times at the critical bottlenecks of the voting process — check-in, printing ballots, gaining access to machines/booths, marking ballots, gaining access to scanners, scanning ballots, and checking out. (The actual bottlenecks will depend on the type of in-person voting conducted in each jurisdiction.)
- The number and type of equipment used to perform service functions, as well as their physical layout. (For instance, how many check-in stations were available and where at each precinct and what hours were each functioning? The same goes for voting machines as well.)
- The geo-location of voters.

Not only is it necessary for local jurisdictions to collect this data for analysis, it is important that jurisdictions archive this data and make it publicly available. We have been struck, for instance, by the number of times we have asked localities if they have records about how many check-in stations or voting machines were allocated to each precinct in the 2012 presidential election, only to be told that this information is discarded soon after the election. Without an archive of past allocation decisions and statistics such as precinct-level turnout, a local election jurisdiction will be unable to learn from the past as it makes allocation decisions for the future.

Polling place technologies will play an important part in the future in collecting the data needed by election managers as they make allocation decisions. In fact, we have been surprised and disappointed that existing technologies aren't already facilitating data collection — after all, the computers that run the poll books, scanners, and DREs are built around clocks and thus are in a position to record, for instance, how long check-in transactions occur or how long it takes to scan in a ballot.

However, despite the fact that computer-based election technologies have the internal capacity to deliver relevant metrics to election managers, election systems are rarely designed to make retrieving that information easy. We strongly urge local election jurisdictions, when they buy new computerized voting equipment — poll books, balloting marking devices, and scanners — to require as part of the RFP process, that the equipment provide event logs in ways that are easily retrievable and easily portable into commonly used software tools such as Excel.

Poll workers also have a role to play in the improved collection of polling place data. We are sensitive to the many tasks poll workers must perform in a polling place, and do not wish for them to be burdened any more than they already are. That is one reason we believe it is so important that computerized voting technologies take on the lion's share of the responsibility for recording and reporting relevant election management data.

Still, there will be times when poll workers will need to take an active role in data gathering. This is particularly true in measuring how long lines are at regular intervals which, at the present time, requires significant human intervention.

While we need more extensive and systematic data collection to manage polling places better, we also need new tools to turn this data into actionable information. The resource allocation tools highlighted on the VTP web site are one example of the types of tools needed, but there could be more, including the following two:

- Methods to estimate how long it takes to vote a ballot without pre-testing all configurations of ballot layouts. While there is no substitute to asking a sample of voters to test ballot completion time ahead of an election, in large jurisdictions it will often be impossible to produce estimated timings for every ballot style used in that jurisdiction. Thus, there is the need for a simple method that tells an administrator, if s/he has a ballot with twelve "choose one" offices, five ballot questions, and seven judicial retentions, what the average amount of time it should take to fill out that ballot.
- Tools to estimate likely in-person turnout. Many jurisdictions have rules-of-thumb in estimating how many people will turn out to vote in-person at each polling place. Usually, this involves looking back over the most recent two or three "similar" elections, choosing the number from the year with the highest turnout, and then adding a "cushion," such as 10%.[17] However, with the rise of early voting and mail absentee voting, there is also the need to take into account alternative ways that people might vote, and thus take pressure off a polling place. Incorporating information about early voting and mail absentee voting into estimates of Election Day turnout are particularly tricky, since Election Day allocation decisions must generally be made well in advance—often even before the beginning of absentee or early voting.

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[17] *In states that have rigid formulas about resource allocation — such as requiring the printing of as many ballots as there are registered voters in a precinct, or the allocation of one poll book for a certain number of registered voters — it may be less critical to estimate turnout in an election. However, even in these states, there will be other reasons to estimate turnout, such as in assigning "floater" poll workers to handle surges during peak turnout times.*

We conclude by noting how much work needs to be done, if we are to meet the challenge set by the Presidential Commission on Election Administration, that no voter wait longer than 30 minutes to vote. However, we also note the encouraging first steps taken by state and local election administrators toward reaching that goal, including the positive feedback we have received as they experiment with our online data tools.

The challenge is to stay focused on the task of improving the performance of polling places, so that lines are shorter, and the public sees elections run more smoothly. The problem of long lines is in many ways more complex than previous challenges in voting technology and election administration, because there is no one, silver bullet "fix" that will solve the problem in all places. We are confident, however, that with more systematic and complete collection of data, along with the application of simple queuing tools and concepts, we will see significant improvements in 2016.

6. Further Reading

Richard C. Larson and Amedeo R. Odoni, *Urban Operations Research*, Prentice-Hall, 1981.

Classic textbook in operations research available free online at **http://web.mit.edu/urban_or_book/www/book/**. Chapter 4 provides a straightforward introduction to queuing theory.

Floyd H. Grant III, "Reducing Voter Waiting Time," *INTERFACES* 10, no. 5 (1980): 19–25.

Earliest published application of queuing theory to the problem of long lines at the polls.

Alexander S. Belenky and Richard C. Larson, "To Queue or Note to Queue?" *OR/MS Today* 2006: **http://www.orms-today.org/orms-6-06/queues.html.**

Brief, accessible discussion of queuing-related issues related to the problem of long lines at the polls.

Theodore Allen and Mikhail Bernshteyn, "Mitigating Voter Waiting Times," *Chance* 19, no. 4 (2006): 25–34.

Illustrates how statistical techniques can illustrate and address problems of long lines at the polling place.

Douglas M. Spencer and Zachary S. Markovits, "Long Lines at Polling Stations? Observations from an Election Day Field Study," *Election Law Journal* 9, no. 1 (2010): 3–17.

Reports results of a systematic study of wait times at 30 polling stations across three counties in the San Francisco Bay area during the 2008 presidential election.

William A Edelstein and Arthur D Edelstein, "Queuing and Elections: Long Lines, DREs and Paper Ballots," *Proceedings of EVT/WOTE 2010* (2010), **https://www.usenix.org/legacy/event/evtwote10/tech/full_papers/Edelstein.pdf.**

Develops a "Queue Stop Rule" that can be applied to prevent long lines at polling places.

Mauer Yang, Michael J. Fry, W. David Kelton, and Theodore T. Allen. "Improving Voting Systems through Service-Operations Management," *Production & Operations Management* 23, no. 7 (2014): 1083–1097.

Develops methods to allocate voting machines optimally to precincts and presents a case study based on data from the 2008 general election in Franklin County, Ohio.

Xinfang (Jocelyn) Wang, Mauer Yang, and Michael J. Fry. "Efficiency and Equity Tradeoffs in Voting Machine Allocation Problems," *Journal of the Operational Research Society* 66: 1363–1369.

Develops a technique to allocate voting machines that balances efficiency and equity in waiting times across a local election jurisdiction. Applies this technique to data from Franklin County, Ohio.

Charles Stewart III and Stephen Ansolabehere. "Waiting to Vote," *Election Law Journal* 14, no. 1 (2015): 47–53.

Summary academic revision of white paper prepared for the Presidential Commission on Election Administration about long lines at the polls.

Appendix 1

State	Avg. wait (min.)	95% confid. interval	State	Avg. wait (min.)	95% confid. interval
Alabama	12.4	2.1	Montana	11.8	4.4
Alaska	3.1	3.5	Nebraska	4.3	2.5
Arizona	9.4	2.6	Nevada	7.7	2.2
Arkansas	13.8	2.4	New Hampshire	10.5	2.5
California	7.0	1.3	New Jersey	5.5	1.7
Colorado	8.1	3.3	New Mexico	6.4	2.6
Connecticut	6.9	2.3	New York	12.3	1.2
Delaware	4.5	2.9	North Carolina	13.8	1.5
D.C.	36.9	3.5	North Dakota	10.2	4.5
Florida	42.3	1.3	Ohio	10.0	1.6
Georgia	17.3	1.5	Oklahoma	16.9	2.2
Hawaii	6.6	4.1	Oregon	na	na
Idaho	8.2	2.8	Pennsylvania	8.5	1.3
Illinois	12.2	1.4	Rhode Island	11.0	2.8
Indiana	13.8	1.9	South Carolina	25.6	2.0
Iowa	5.5	2.6	South Dakota	3.4	3.3
Kansas	10.6	2.3	Tennessee	13.7	1.8
Kentucky	8.0	2.0	Texas	11.7	1.1
Louisiana	16.4	2.2	Utah	10.4	2.5
Maine	3.7	2.8	Vermont	1.7	3.4
Maryland	37.6	1.8	Virginia	25.6	1.6
Massachusetts	8.4	1.7	Washington	na	na
Michigan	19.6	1.7	West Virginia	11.1	2.7
Minnesota	6.2	1.8	Wisconsin	7.9	1.8
Mississippi	7.5	2.6	Wyoming	3.9	3.4
Missouri	11.3	1.7			

NOTE: *The entries in the table are estimated average wait times to vote in-person in the 2012 general election. The entries are a weighted average of the results obtained through identical questions in the Survey of the Performance of American Elections and the Cooperative Congressional Election Study.*