Resilient voting systems during the COVID-19 pandemic: A discrete event simulation approach

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September 21, 2020

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Executive Summary

The 2020 General Election will occur during a global outbreak of the COVID-19 virus. Planning for an election requires months of preparation to ensure that voting is effective, equitable, accessible, and that the risk from the COVID-19 virus to voters and poll workers is minimal. Preparing for the 2020 General Election is challenging given these multiple objectives and the time required to implement mitigating strategies.

The Spring 2020 Election and Presidential Preference Primary on April 7, 2020 in Wisconsin occurred during the statewide "Stay-at-home" order associated with the COVID-19 pandemic. This election was extraordinarily challenging for election officials, poll workers, and voters. The 2020 Wisconsin Spring Primary experienced a record-setting number of ballots cast by mail, and some polling locations experienced long waiting times caused by consolidated polling locations and longer-than-typical check-in and voting times due to increased social distancing and protective measures. A number of lawsuits followed the 2020 Wisconsin Spring Primary, highlighting the need for more robust planning for the 2020 General Election on November 3, 2020.

This paper studies how to design and operate in-person voting for the 2020 General Election. We consider and evaluate different design alternatives using discrete event simulation, since this methodology captures the key facets of how voters cast their votes and has been widely used in the scientific literature to model voting systems. Through a discrete event simulation analysis, we identify election design principles that are likely to have short wait times, have a low-risk of COVID-19 transmission for voters and poll workers, and can accommodate sanitation procedures and personal protective equipment (PPE).

We analyze a case study based on Milwaukee, Wisconsin data. The analysis considers different election conditions, including different levels of voter turnout, early voting participation, the number of check-in booths, and the polling location capacity to consider a range of operating conditions. Additionally, we evaluate the impact of COVID-19 protective measures on check-in and voting times. We consider several design choices for mitigating the risks of long wait times and the risks of the COVID-19 virus, including consolidating polling locations to a small number of locations, using an National Basketball Association (NBA) arena as an alternative polling location, and implementing a priority queue for voters who are at high-risk for severe illness from COVID-19.

As we look toward the General Election on November 3, 2020, we make the following observations based on the discrete event simulation results that consider a variety of voting conditions using the Milwaukee case study.

1. Many polling locations may experience unprecedented waiting times, which can be caused by at least one of three main factors: 1) a high turnout for in-person voting on Election Day, 2) not having enough poll workers to staff an adequate number of check-in booths, 3) an increased time spent checking in, marking a ballot, and submitting a ballot due to personal protective equipment (PPE) usage and other protective measures taken to reduce COVID-19 transmission. Any one of these factors is enough to result in long wait times, and as a result,

election officials must implement strategies to mitigate all three of these factors.

2. The amount of time spent inside may be long enough for voters to acquire the COVID-19 virus. The risk to voters and poll workers from COVID-19 can be mitigated by adopting strategies to reduce voter wait times, especially for those who are at increased risk of severe illness from COVID-19, and encourage physical distancing through the placement and spacing of voting booths.

3. Consolidating polling locations into a few large polling locations offers the potential to use fewer poll workers and decrease average voter wait times. However, the consolidated polling locations likely cannot support the large number of check-in booths required to maintain low voter wait times without creating confusion for voters and interfering with the socially distant placement of check-in and voting booths. As a result, consolidated polling locations require high levels of staffing and could result in long voter wait times.

4. The NBA has offered the use of its basketball arenas as an alternative polling location for voters to use on Election Day as a resource to mitigate long voter wait times. An NBA arena introduces complexity into the voting process, since all voters have a choice between their standard polling location and the arena. This could create a mismatch between where voters choose to vote and where resources are allocated. As a result, some voters may face long wait times at both locations.

We recommend that entities overseeing elections make the following preparations for the 2020 General Election. Our recommendations have five main elements:

1. More poll workers are required for the 2020 General Election than for previous presidential elections. Protective measures such as sanitation of voting booths and PPE usage to reduce COVID-19 transmission will lead to slightly longer times for voters to check-in and to fill out ballots, possibly causing unprecedented waiting times at many polling locations if in-person voter turnout on Election Day is high. We recommend having enough poll workers to staff one additional check-in booth per polling location (based on prior presidential elections or based on what election management toolkits recommend), to sanitize voting areas and to manage lines outside of polling locations.

2. To reduce the transmission of COVID-19 to vulnerable populations during the voting process, election officials should consider the use of a priority queue, where voters who self-identify as being at high-risk for severe illness from COVID-19 (e.g., voters with compromised immune systems) can enter the front of the check-in queue.

3. In-person voting on Election Day should occur at the standard polling locations instead of at consolidated polling locations. Consolidated polling locations require many check-in booths to ensure short voting queues, and doing so requires high staffing levels. Election officials should ensure that an adequate number of voting booths (based on prior presidential elections or

based on what election management toolkits recommend) can be safely located within the voting area at the standard polling locations, placing booths outside if necessary.

4. We do not recommend using sports arenas as supplementary polling locations for in-person voting on Election Day. Alternative polling locations introduce complexity and could create a mismatch between where voters choose to go and where resources are allocated, potentially leading to longer waiting times for many voters. This drawback can be avoided by instead allocating the would-be resources at the sports arena to the standard polling locations.

5. The results emphasize the importance of high levels of early voting for preventing long voter queues (i.e., one half to three quarters of all votes being cast early). This can be achieved by expanding in-person early voting, in terms of both the timeframe and locations for early in-person early voting, adding new drop box locations for voters to deposit absentee ballots on or before Election Day, and educating voters on properly completing and submitting a mail-in absentee ballot.

The results are based on a detailed case study using data from Milwaukee, Wisconsin. It is worth noting that the discrete event simulation model reflects standard voting procedures used throughout the country and can be applied to other settings. Since the data from the Milwaukee case study are reflective of many other settings, the results, observations, and recommendations can be applied to voting precincts throughout Wisconsin and in other states that hold in-person voting on Election Day.

Abstract

The 2020 General election will occur while many parts of the nation are under emergency orders related to the COVID-19 pandemic, placing new requirements and considerations on voting systems. We study how to design in-person voting systems whose performance are robust across many election conditions, including different levels of voter turnout, early voting participation, the number of check-in booths, and the polling location capacity. We evaluate the impact of COVID-19 protective measures on check-in and voting times, and we consider several design choices for mitigating the risks of long wait times and the risks of the COVID-19 virus, including consolidating polling locations to a small number of locations, using a sports arena as an alternative polling location, and implementing a priority queue for voters who are at high-risk for severe illness from COVID-19. We evaluate voting system design alternatives to assess the waiting times, sojourn times, line length, time spent inside, and the number of voters inside. We evaluate the model using a case study from Milwaukee, Wisconsin. The analysis indicates that poll worker shortages, personalized protective equipment usage and associated protective measures, high voter turnout, or low rates of early voting can lead to extremely long voter wait times. Long wait times can be avoided by higher than typical poll worker staffing levels, staffing additional check-in locations, expanding early voting, and by not consolidating polling locations. Additionally, the analysis supports implementing a priority queue discipline effectively to reduce waiting times for vulnerable populations at increased risk of severe illness from COVID-19.

1 Introduction

The 2020 General election will occur while many states operate under emergency orders related to the COVID-19 pandemic. The World Health Organization declared the COVID-19 outbreak to be pandemic on March 11, 2020 [12]. The United States (US) Centers for Disease Control and Prevention (CDC) followed suit and currently considers the COVID-19 outbreak to be a global health threat [11]. As of September 1, 2020, there are approximately 6M COVID-19 cases in the US with approximately $45,000$ new cases per day [9].

Election officials spend months preparing for an election and implement strategies to ensure that voting is effective, equitable, accessible, and quick [44]. In most elections, voters are assigned one polling location to which they travel to cast a vote on the day of the election. Voters in the United States are typically assigned a polling location by partitioning an area into geographic regions called voting precincts or wards. These polling locations can be consolidated in anticipation of staffing levels that are too low or unusual circumstances. Voters can also vote absentee prior to the day of the election, and the requirements for voting absentee vary according to state. There are two primary methods for voting absentee: (1) in-person voting, where a vote is cast in a centralized location, such as city hall or a library, or (2) by mail. This paper focuses on the design and operating of in-person voting on an election day, particularly on the 2020 General Election.

Election boards and commissions must make strategic decisions regarding the design and operation of voting systems given the resources available to them. Resources should be allocated to polling locations such that on Election Day voters can cast their votes in-person without facing long voting queues, and voting operations in the voting process must not disenfranchise voters [10]. The COVID-19 pandemic places unusual strains on the voting system in several ways. For example, voting systems are reliant on volunteer poll workers, and most election volunteers are over the age of 60 and at high-risk for COVID-19 [2, 41]. Poll worker and voter exposure to COVID-19 should be minimized, particularly for individuals from high-risk groups [10]. Performance criteria for elections have expanded to include maintaining the health and safety of voters due to onset of the COVID-19 pandemic. This has led to new considerations and challenges for the design and operation of in-person voting systems including sanitation of public areas [51], enforcement of social distancing [51], recruiting of an appropriate number of poll workers [29], and the possible consolidation of polling locations [32, 39].

The 2020 primary elections suggest that mitigating the risks associated with COVID-19 without impacting voting systems is extremely challenging. The Wisconsin Spring 2020 Election and Presidential Preference Primary on April 7, 2020 was the first election in the US with in-person voting to be held after stay-at-home orders were issued [33] and occurred during the statewide "Stay-at-home" order associated with the pandemic. The election was extraordinarily challenging for Wisconsin election officials, poll workers, and the public. A total of 1,555,263 votes were cast, with 62.0% and 12.4% of these votes being cast through the mail and through in-person early voting, respectively [50]. This was the most mail-in ballots ever cast in a Wisconsin election, let alone a Spring Primary [50], and reports indicate that many requested mail-in ballots did not arrive by the election [50]. Wisconsin also saw the most in-person absentee ballots cast in a Spring Primary [50]. Moreover, Wisconsin faced a shortage of poll workers [5, 17, 41] causing some cities to consolidate polling locations. The City of Milwaukee held its Spring Primary at five consolidated polling locations, instead of the standard 182 polling sites, to allow for social distancing and to mitigate the impact of poll worker shortages. A number of lawsuits followed the Wisconsin Spring Primary, highlighting the need for more robust planning for the 2020 General Election on November 3, 2020.

The primary elections held throughout the United States raise key concerns about the resilience of voting systems, particularly voting processes that occur in-person on Election Day. In this paper, we study how to design and operate in-person voting systems that are robust to poll worker shortages, high levels of voter turnout, low levels of early voting, and new requirements and processes to mitigate the risk of infectious disease transmission. We focus on the 2020 General Election, and our analysis considers the impact of consolidating polling locations, implementing social distancing, introducing personal protective equipment (PPE) and sanitation requirements, reducing the number of check-in booths and ballot reading machines, implementing a priority queue for high-risk voters, and promoting early voting.

The operation of in-person voting systems has drawn the attention of many researchers. There are multiple criteria for evaluating the performance of voting systems [27], and voter queueing times has emerged as one of the most important considerations for designing in-person voting systems. The queueing of voters must be taken into account when considering voting access [43]. Allen [3] notes that more than $200,000$ voters may have been deterred to vote in the 2012 Presidential

Election due to long voting queues [37]. Three mechanisms to reduce wait times have been noted in the literature. The first is to reduce the number of voters coming to a polling place [43]. The second is to increase the number of service points (e.g. check-in booths, voting booths, and ballot reading machines) [43]. The third is to reduce the average "transaction" time of voters [43].

Long waiting times at voting sites have also drawn attention to the issue of allocating election resources. A stream of papers has focused on the allocation of voting machines to polling locations, since voting machines have been recognized as a voting bottleneck in the voting process [53]. Methods to allocate voting booths or machines to reduce waiting times include simulation [53], simulation optimization [52], integer programming [47], a combination of queueing and simulation [54], and robust optimization [55]. Li et al. [22] use simulation optimization to demonstrate that average voting times can be reduced by better allocating voting booths to voting polling locations. Wang et al. [47] examine how to allocate resources such as voting machines that balance trade-offs across equity and efficiency using integer programming models. Yang et al. [55] develop a robust optimization model to study how to mitigate worst-case voting queues. All models in these papers assume first-come, first-served (FCFS) check-in queues and consider resource allocation decisions.

Few papers study how to design voting systems in addition to resource allocation decisions. Stein et al. [42] present a multi-county observational study of voting during the 2016 Presidential election. They investigate the time it takes to complete steps within the voting process and how some changes in the voting system, such as the introduction of voting identification requirements, impact voting times. Morris and Miller [30] investigate the impact of consolidating polling locations in Milwaukee for the Spring 2020 Election on voter turnout. Their findings suggest overall turnout was reduced by 8.5 percentage points and among the Black population the turnout was decreased by 10.2 percentage points. The 2019 COVID-19 pandemic motivates the need to consider the impact of virus transmission and patient safety during elections [33]. To our knowledge, there are no studies that have investigated the operation of voting systems in terms of the health and safety of voters during a pandemic.

In this paper we investigate resource allotment and voting system design changes to improve the resiliency of the voting system during a pandemic. In terms of resilience, we consider the impact on health and safety of the voters in addition to the traditional metrics such as voter waiting and access to election resources. Novel aspects of the model and analysis include the consideration of consolidated polling locations, using National Basketball Association (NBA) arenas as additional polling locations, the adoption of priority queues, and an analysis of the impact of personal protective equipment and protective measures on voter waiting times.

This paper makes the following contributions:

- We introduce a discrete event simulation model of the in-person voting process on Election Day.

- We analyze the discrete event simulation model outputs using a detailed case study from Milwaukee, Wisconsin to evaluate how different operating conditions can affect election performance measures. The analysis indicates that poll worker shortages, personalized protective equipment usage and associated protective measures, and low rates of early voting lead to extremely long waiting times.

- We evaluate design alternatives to understand their impact on election performance measures, which provides a set of design and operation recommendations to improve the resiliency of the voting system during a pandemic. The analysis suggests that long waiting times can be avoided with higher than typical poll worker staffing levels, expanded early voting, and non-consolidated polling locations. The analysis supports implementing a priority queue discipline to reduce waiting times for vulnerable populations at high-risk to the COVID-19 virus.

The remainder of this paper is organized as follows. Section 2 introduces a discrete simulation model of the voting process. Section 3 summarizes the case study of Milwaukee, Wisconsin. Section 4 presents the results of the case study. Section 5 provides a discussion of case study results and offers recommendations for election officials.

2 Simulation modeling approach

We introduce a discrete event simulation model of the voting process that represents in-person voting on an Election Day. This model captures steps related to voter arrival, check-in, ballot marking, and ballot submission. Figure 1 outlines the logic of the voting process. The distribution describing the time to complete each step within the voting process for our case study is provided in Figure 2. We consider multiple polling locations within the community. The basic voting process is identical across polling locations, however, the inputs may vary to capture the location specific details.

This model can be used to study a range of potential operating conditions by adjusting the input parameters to account for voter turnout, the proportion of voters who vote absentee (prior to Election Day), the number of check-in booths, and the polling location capacity. We let the capacity of each polling location restrict the combined number of voters between (inclusive) the check-in process and the ballot submission steps and any volunteers actively sanitizing the voting area. The capacity can be adjusted to allow for appropriate social distancing and reduce the viral load. Election officials plan to adopt social distancing, sanitation, and PPE into this process, and therefore, these factors are included in the input parameters. We explore the impact of social distancing, sanitation, and PPE on the output in our analysis in Section 4. Finally, the model can be used to explore voting system design issues. We consider a priority queueing discipline as a mechanism for protecting high-risk voters in addition to a first-come, first-served queueing policy. We investigate the consolidation of polling locations. An analysis of the design issues helps us understand the drawbacks of typical voting systems and sheds light on mitigating actions to improve in-person voting systems.

The steps of the voting process are described in detail:

1. A voter arrives and they enter a queue to check-in to vote. Voters arrive according to a non-stationary Poisson process. The percentage of voters, on average, that arrive during each 30 minute interval is shown in Figure 3. This distribution has been used in previously published research and comes from a survey of Ohio voters in 2005 [54]. This distribution may be different for the 2020 General Election with more voters working from home, but no research could be found describing a new pattern. The interarrival times are therefore exponentially distributed with a rate of $r = \frac{f \times p \times v \times (1-e)}{30}$ where f = fraction of voters arriving during the 30 minutes period, p = the voting age population assigned to the polling location, v = voter turnout, and e = the proportion of voters who vote early or absentee.

2. Once a check-in resource is available and the polling location is not at capacity, the next voter in the queue begins the check-in process. Traditionally, queues at polling locations follow a first-come, first-served queueing discipline. The number of check-in booths is dependent on

the number of volunteers at the polling location. The time to complete this process may be dependent on social distancing, sanitation, and PPE practices. The time to complete the check-in process without PPE, sanitation, or social distancing (denoted as "No PPE") follows a lognormal distribution described in Figure 2a and with PPE, sanitation, and social distancing (denoted as "PPE") in Figure 2b. The "No PPE" distribution is fit to data in published research describing time studies of voting times [42]. The "PPE" distribution is scaled up by 20 seconds on average to account for additional time to verify the voter's photo-identification while the voter wears a face covering, ensure the voter has appropriate PPE, provide the voter with a pen, and ensure adequate social distancing during the check-in process. The recommended number of check-in booths at each polling location can be estimated using a tool provided by MIT based on the number of registered voters [44].

3. Once the voter has completed the check-in process, they begin marking their ballots or "vote." Depending on the election location, votes can be cast in-person on paper ballots or using electronic voting machines. We assume votes are cast on paper; if this is not the case, the components of steps 4 and 5 related to submitting a ballot may not occur. We assume the time to vote depends on if voters are wearing PPE and if social distancing is practiced. The time to vote with "No PPE" is described by the distribution in Figure 2c. The time to vote with "PPE" is described by the distribution in Figure 2d. We assume the average time to vote increases by two minutes. Both distributions are adopted from previously published elections research [54].

4. Once the ballot is filled out, the voter enters a queue to submit their ballot to a ballot reading machine. At the same time, a volunteer cleans the voting area if sanitation measures are in place. We assume that there are a sufficient number of volunteers to ensure the cleaning can begin immediately after the voter completes the ballot. A volunteer must recognize the voting area needs to be cleaned, walk to the location, sanitize the location, and then indicate to workers at the check-in booths that the area has been cleaned if the building capacity is reached. The time for the voting area to be cleaned by a volunteer follows the distribution illustrated in Figure 2e.

5. Once a ballot reading machine becomes available, the voter leaves the queue, walks to the

ballot reading machine, and submits the ballot. Once the ballot is approved, the voter leaves. When sanitation practices are in place, a volunteer may also sanitize the machines, but we assume the additional time required is negligible to the output of the simulation. The time to submit a ballot is described by the distribution in Figure 2f. The recommended number of ballot reading machines at each polling location can be estimated using a tool provided by MIT based on the number of registered voters [44].

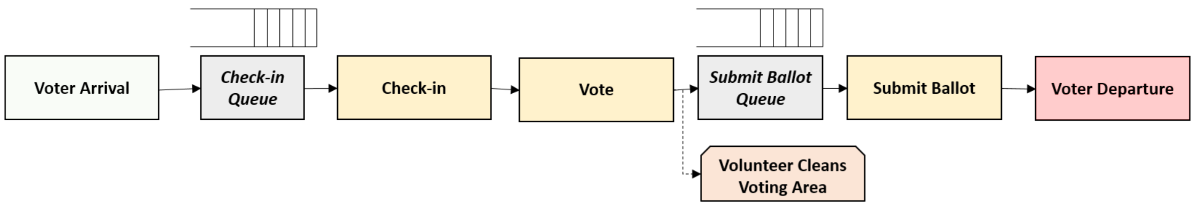


Figure 1: Overview of simulation design

The model in Figure 1 captures the main operations required for a voter to cast a ballot. We note that additional processes take place at a polling location during in election that are not explicitly modeled in the discrete event simulation model, including the registration process and additional processes for accessibility. These issues are discussed in Section 5.

In terms of simulation outputs, there are many metrics for evaluating voting systems, and there are trade-offs between many of these metrics [27]. Some well-known metrics include voting wait time, line length, sojourn time, voter turnout, and ballot rejection rate [27]. Voter waiting times is a major area of focus. The Presidential Commission on Election Administration has set a goal that no citizen should have to wait more than 30 minutes to vote [36]. The City of Madison, Wisconsin has set a goal that no voter wait more than 15 minutes to vote [4]. Due to COVID-19, additional metrics are of interest including the amount of time spent inside, especially for high-risk voters, and the number of voters inside, since they are indicators for risk of COVID-19 spread [10]. Table 1 describes the performance measures and metrics of interest for all voters, in-person (election day) voters, and polling locations. Note that wait time and sojourn time are in the table twice, since these times can be computed in two ways that reflect different goals. Both wait and sojourn times can be computed by taking the average either over all voters or per polling location by taking the average over all voters at each polling location. The wait and sojourn times we consider are in-person voter metrics unless otherwise specified.

Table 1: Voter, in-person voter, and polling location metrics and their descriptions.

Voter Metrics

Metric	Description
Ballots Accepted	The number of ballots not rejected after being cast.

In-person Voter Metrics

Metric	Description
Wait Time (minutes)	Time spent in the queue before checking in to vote
Time Inside (minutes)	Time from start checking until departing
Sojourn Time (minutes)	Time from entering initial queue until departing
15 Minute Wait	Proportion of voters waiting 15 minutes or more
30 Minute Wait	Proportion of voters waiting 30 minutes or more
Distance to Poll (mi)	The distance between the voter and polling location

Polling Location Metrics

Metric	Description
Wait time (minutes)	The average wait time at the polling location
Sojourn Time (minutes)	The average time to complete the voting process
Line Length (voters)	The average length of the line before checking in
Voters Inside	The number of voters checking-in through submitting a ballot

3 Case study: Milwaukee, Wisconsin data

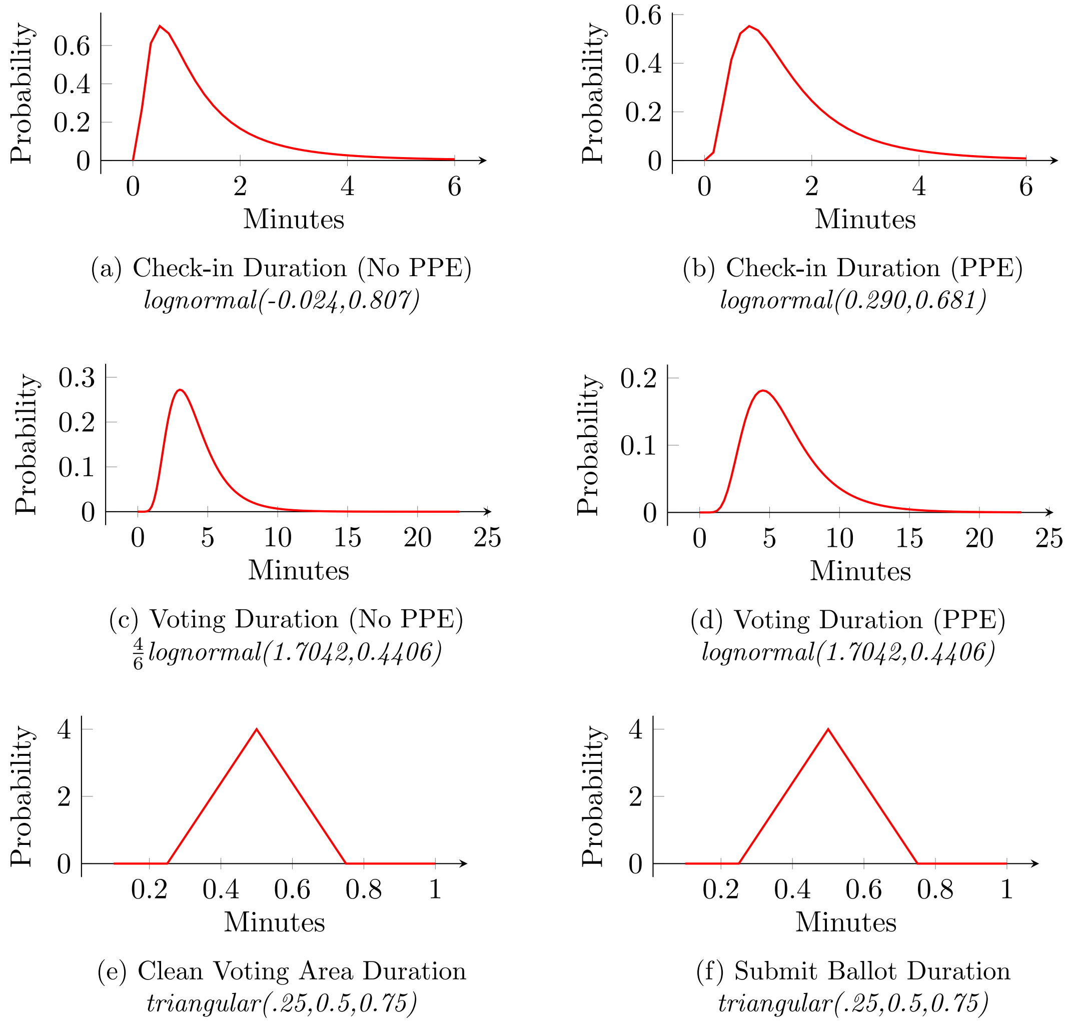
Milwaukee is the largest city in the state of Wisconsin with an estimated 590,157 residents [46]. The city of Milwaukee has 182 standard polling locations spread throughout the city [15, 25]. For the Spring 2020 Election, the Milwaukee Elections Commission reduced the number of polling locations in Milwaukee to five locations [8] due to the anticipated lack of qualified poll workers and uncertainty related to the pandemic. The decision to consolidate polling location drew national attention to the issues surrounding the design of in-person voting processes to mitigate COVID-19 risks. We use a case study based on data from Milwaukee as a case study to explore the performance of voting systems in the 2020 General Election and to understand how design changes may affect election metrics of interest.

The City of Milwaukee has 327 voting wards, which have an official assignment to one of the 182 standard polling locations throughout the city [15, 25]. To estimate the voting aged population in each of the voting wards, we use the 2011 voting age population in each ward, which is the most recent report provided by the city [15]. Between 2010 and 2019, there was an estimated population change of -0.72% [18], so we assume the 2011 population in each ward is a reasonable estimate for the voting age population in 2020. We assume that voter turnout and the early voting rate is the same in all voting wards. We also assume that the number of individuals who vote in every ward is independent of the polling location to which the ward is assigned. In reality, each voting ward is likely to have different turnout and percent of voters using early/absentee voting, but these values will be unknown at the time of strategic election planning. A sensitivity analysis evaluates the metrics across a range of different input parameters to shed light on actual performance with different inputs, such as different voter turnout levels, at different polling locations.

We set the number of check-in booths and ballot reading machines at each polling location to be the level suggested by the MIT tool [44]. However, instead of the number of registered voters at each polling location as the input, we use 70% of the number of voting aged individuals in each district, since we are using population estimates from 2011. This resulted in four fewer check-in booths and one fewer ballot reading machine than if the number of registered voters in April 2020 was used. In total, we assume there are 382 check-in booths and 196 optical ballot reading machines available for the City of Milwaukee polling locations.

Due to the COVID-19 outbreak, election officials have placed an increased emphasis on ensuring the health and safety of voters, particularly in-person voters who are vulnerable to risks associated with the COVID-19 disease. We assume that each location has a proportion of voters who self-identify as *high-risk*. We assume these voters are the most susceptible to high viral load resulting from a long wait times, long time spent indoors, and congregation of many individuals. An estimated 10.2% of population in the City of Milwaukee are 65 years old or over and 73.9% are 18 or older, thus 13.8% of the voting age population is 65 or older [46]. We use the fraction of voting age population at or over 65 years of age, 13.8%, as the fraction of in-person voters who are high-risk. According to the CDC, individuals younger than 65 years of age with preexisting conditions may be at high-risk [13], which would increase the percentage of voters who are high-risk. However, we assume that a disproportionate number of high-risk individuals will use early/absentee voting methods or they will not self-identify as high-risk for in-person voting, leading to 13.8% of in-person voters on election day self-identifying as high-risk.

The actual conditions on the 2020 Election Day are uncertain, so we address this uncertainty



(a) Check-in Duration (No PPE)
lognormal(-0.024,0.807)

(b) Check-in Duration (PPE)
lognormal(0.290,0.681)

(c) Voting Duration (No PPE)
$\frac{4}{6}$*lognormal(1.7042,0.4406)*

(d) Voting Duration (PPE)
lognormal(1.7042,0.4406)

(e) Clean Voting Area Duration
triangular(.25,0.5,0.75)

(f) Submit Ballot Duration
triangular(.25,0.5,0.75)

Figure 2: Distributions describing the time to complete each step of the voting process.

using a sensitivity analysis. We consider six combinations of voter turnout and early/absentee voting, which may be seen across the United States during the 2020 General Election. In addition to these, we consider five changes to the design and operation of the voting process to understand and improve the resiliency of the voting system. These five changes are the queueing style, the capacity of polling locations, the number of check-in booths, the additional process time due to PPE, social distancing, and sanitation of public spaces, and the number of polling locations. Table 2 summarizes the parameter values considered in this simulation study.

1. **Voter Turnout (V):** In Wisconsin, voter turnout is reported as the percent of voting aged individuals who vote, including early voters [49]. Voter turnout in Wisconsin for presidential elections has ranged between 57.9% and 72.9% between 1988 and 2016, with voter turnout

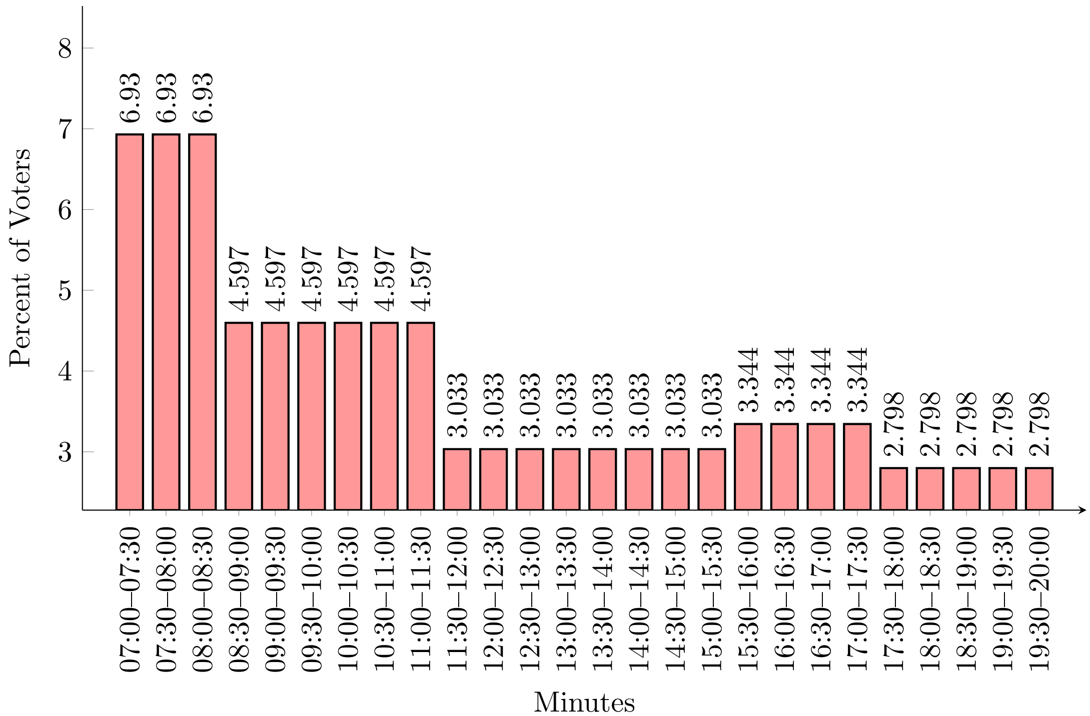


Figure 3: Percent of voters arriving during the 30 minute increments on average.

above 67.34% since 2008 [49]. The COVID-19 pandemic may result in low voter turnout during the November election due to fears of exposure to the virus. However, turnout in the Wisconsin Spring 2020 Election was among the highest seen in a spring election [50], suggesting a high turnout for the 2020 General Election. We consider two levels for voter turnout (60% and 75%) to capture a range of potential turnout levels. Note that since we randomize arrivals within each replication of the discrete event simulation, the actual turnout may be higher or lower than the assigned turnout in each replication, with the average turnout level being equal to the assigned turnout across all replications.

2. **Early Voters (E):** The early voting rate is considered as the proportion of voters (i.e., proportion of voter turnout) who vote early through in-person early voting prior to the election day or who vote by mail with an absentee ballot. The highest percent of ballots cast early in Wisconsin seen since 1992, before April 2020, in Wisconsin was 27.27% [49]. In November 2018, the national average of voters voting in-person before the election was 16.6% and by mail 23.1% for an early voting rate of 39.7% [45]. A Marquette poll conducted in May 2020 found that 43% of Wisconsin voters plan on voting by mail and 11% plan on

voting early in-person, for a total early voting rate of 54% [19]. In the Wisconsin Spring 2020 Election, 74.4% of Wisconsin voters voted early [50]. We use consider three values of early voting (30%, 54%, and 75%) to capture a wide range for the early voting rate in Milwaukee.

3. **Queue Style (Q):** During elections, queues (lines) at polling locations follow a first-come-first served (FCFS) queueing discipline at each check-in booth. A FCFS queueing discipline is widely viewed as equitable. However, a FCFS queueing discipline can lead to disparate health outcomes when high-risk voters wait in long voting queues. A *nonpreemptive priority queue* could be implemented to ensure high-risk individuals do not have to wait long in queues and can begin the check-in and ballot submission processes quicker. A priority queue before the check-in and ballot submission would allow self-identifying high-risk voters to move to the front of the queue, but behind other high-risk voters already waiting, which would reduce the waiting time for voters who enter the priority queue. By having voters self-identify, no additional poll workers are needed to manage this system. We consider both the FCFS and priority queue policies.

4. **Check-in Booths (B):** Check-in booths are a critical resource during the election process that are run by poll workers. As described earlier, we use the suggested number of check-in booths by the MIT tool [44], 382, as the high level. However, low poll worker turnout was experienced during the Wisconsin Spring 2020 Election [5], and reports indicate that many locations will struggle to find poll workers for the 2020 General Election [29]. In November of 2018, 68% of poll workers were 61 years old or older, and 16.4% were 40 or younger [2]. Even with the same or higher number of poll workers as in previous years, additional tasks required for the 2020 General election, such as line management, sanitation, and enforcement of social distancing, may result in fewer poll workers to station check-in booths. Moreover, check-in booths take up space, and therefore, spacing check-in booths to adhere to social distancing requirements may require the number of booths to be lower than recommended. To capture this situation, we consider a reduced number of check-in booths. The low value is calculated as half of the recommended number of booths (rounded up) at each of the 182 polling locations, leaving 232 check-in booths distributed to the 182 polling locations.

5. **Polling Location Capacity (C):** The amount of individuals allowed within a polling loca-

tion is normally restricted by the fire code occupancy limit and the number of voting areas. An election held during a pandemic may also restrict the number of voters that can be inside to ensure social distancing and to limit the viral load inside. We let the capacity restrict voters from the beginning of the check-in process if the number of voters inside plus the number of poll workers actively sanitizing the voting area equals the capacity of the polling location. We consider two levels of the capacity. The actual capacity of buildings is not readily available to the public; therefore, we estimate the capacity of the polling locations using the number of voting aged individuals assigned to the polling location, p, and a scalar. The high capacity is $\lceil 0.00969p \rceil$, which reflects the capacity during an election with no social distancing or an election with social distancing but an expanded physical footprint (e.g., outdoor voting areas) to maintain the standard capacity. With 182 polling locations, the average capacity is 23.6 voters and with five polling locations the average capacity is 840.6 voters. The low level captures a situation where the capacity is reduced to half of the high level to allow for social distancing with the original physical footprint. The low capacity is $\lceil 0.00484p \rceil$. With 182 polling locations the average capacity is 12.1 and with five polling locations the average capacity is 420.4. We assume the polling capacity is limiting to a polling location before the number of voting booths; the needed number of voting booths is at most the capacity of the polling location.

6. **PPE/Sanitation Time (T):** In previous elections, a minimal amount of PPE has been used, minimal sanitation of voting space conducted, and social distancing not enforced. For the 2020 General Election, the WEC and CDC suggest rigorous PPE usage, sanitation, and social distancing policies at all polling locations [51, 10]. We assume that PPE usage, social distancing, and sanitation affect in the check-in time distribution and the voting time distribution, and that it requires a poll worker to clean the voting area. The low value ($-$) indicates the simulation does not consider the implementation of PPE, sanitation, or social distancing. Check-in times follow the distribution illustrated in Figure 2a. We assume the voting process takes 4.038 minutes on average and follows the distribution shown in Figure 2c. The high value ($+$) considers the voting process with PPE, sanitation, and social distancing. The check-in time is 20 second longer on average and follows the distribution illustrated in

Figure 2b. We assume the voting time takes 6.057 minutes on average and follows the distribution outlined in Figure 2d. We also consider the step which models a volunteer cleaning the voting area after each voter. The two distributions for voting time were adapted from [54]. An additional study [42] also identifies an average time to fill out a ballot at approximately 4 minutes during a previous, non-pandemic election.

7. **Polling Locations (P):** The standard 182 polling locations represent the high level, and the five consolidated polling locations represent the low level, as observed in the Wisconsin Spring 2020 Election. We assume there there is no change in voter or poll worker turnout due to the change in polling locations during the simulation. When five consolidated polling locations are considered, we maintain the same number of resources and redistribute the check-in booths and ballot reading machines according to how alderman districts were assigned to the five polling locations in the Spring 2020 Election [8]. The assumption that the number of resources within the system is fixed is likely an optimistic estimate due to space requirements. We relax this assumption through an additional sensitivity analysis.

Table 2: Parameter values considered during the sensitivity analysis.

Parameter	ID	Level		
		$-$	0	$+$
Voter Turnout	V	60%	-	75%
Early Voters	E	30%	54%	75%
Queue Style	Q	FCFS	-	Priority Queue
Check-in Booths	B	$\lceil 0.5\times\text{recommended}\rceil$	-	$\lceil 1\times\text{recommended}\rceil$
Polling Location Capacity	C	$\lceil 0.00484p\rceil$	-	$\lceil 0.00969p\rceil$
PPE/Sanitation Time	T	No	-	Yes
Polling Locations	P	5	-	182

3.1 Validation

We use two elections as validation for our simulation. The first is the 2016 General Election, held in November 2016. The second is the Wisconsin Spring 2020 Election, which was the first election held in Wisconsin after the onset of the COVID-19 pandemic.

3.1.1 November 2016 Election

In November 2016, 247,836 ballots were cast in the City of Milwaukee [24] equaling a 57.2% voter turnout given the number of voting aged individuals we consider. In Wisconsin, 27.3% of ballots cast were using early/absentee methods [49]. We ran 50 replications of a simulation using these values and FCFS queueing policy (Q-), high polling location capacity (C+), recommended number of check-in booths (B+), no PPE time, social distancing, or sanitation steps (T-), and the standard number (182) of polling locations (P+).

Using these assumptions, a voter could expect to wait, on average, 34.66 minutes to vote and 42.87 minutes to complete the entire voting process (sojourn time). The average wait time calculated by polling location is estimated to be 29.22 minutes. The average line length throughout the day across the different polling locations is estimated to be 43.3 voters.

No report of wait time in the City of Milwaukee could be found for comparison. Chen et al. [14] estimate the average wait time to be 19.13 minutes in the United States for the 2016 General Election using data from smartphones. However, they report that wait times were higher in urban areas with a high proportion of Black and Hispanic voters and a large proportion of residents below the poverty line; the city of Milwaukee had 38.8% Black and 18.8% Hispanic residents and a poverty rate of 26.6% in 2019 [46]. Moreover, reports indicate that early voting was more prevalent in Milwaukee County, which the City of Milwaukee is in, than in Wisconsin as a whole. According to data provided by the county, the percent of ballots cast early/absentee was 29.4% [23, 48]. Using this early voting percentage, the average wait time is estimated to be 29.2 minutes. If the City of Milwaukee actually had a early voting rate of 31.0% so that the other municipalities in Milwaukee County participated in early voting at the same rate as Wisconsin as a whole, the average wait time is estimated to be 25.5 minutes. This suggests the difference between experienced wait times at the polls and the output from the simulation is likely a result of small uncertainties in model inputs rather than an significantly flawed model of the voting process.

3.1.2 April 2020 Election

In April 2020, 95,168 ballots were cast in the City of Milwaukee [26] equaling a 22.0% voter turnout given the number of voting aged individuals we consider. In Wisconsin, 74.4% of voters used early/absentee voting methods [50]. During the April 2020 election, a FCFS queue was used (Q-), social distancing was implemented on a limited physical footprint (C-), sanitation practices were implemented and PPE worn (T+), and 5 polling locations were used (P-).

From a review of the video footage available from the Wisconsin Spring 2020 Election, it appears that a limited number of check-in booths and ballot reading machines were available at a polling location [16]. This likely due both to the lack of space in the five polling locations (high schools) and the fact that there was a shortage of poll workers at the Spring 2020 Election. Based on the videos, we set the number of check-in booths and number of ballot reading machines to 10 at each location. A total of 50 replications were run with these parameters.

The average wait time for each voter was 96.72 minutes and the average sojourn time 104.96 minutes. The average line length throughout the day across the different polling locations was 554.6 voters. The average maximum time a voter had to wait was 178.23 minutes. The average of the maximum average wait time at a polling location was 125.34 minutes. This aligns with media reports that there were long lines and voters waited on average 1.5 – 2.5 hours to vote [16, 6, 40, 1].

4 Case Study Results

We use the discrete event simulation model to evaluate voting system metrics under different operating criteria using the Milwaukee case study, which allows us to evaluate the impact of potential changes to the voting system for the 2020 General Election. We present and discuss the results of the case study within this section. In the first five subsections, we consider a voting system with 182 polling locations. In each of these subsections, we focus on the impact of one of the following components of the voting system: turnout and early voting (V and E), queueing discipline (Q) for voters waiting to check-in, number of check-in booths (B), polling location capacity (C), and PPE/sanitation policies (T). In the sixth subsection, we investigate the impact of five consolidated polling locations instead of 182. In the seventh subsection, we consider a hybrid approach with the original 182 polling location with an alternative polling location at an additional, large arena style polling location. The metrics in Table 1 are used to evaluate different design alternatives. Tables 11 - 18 in Appendix 5 provide the average and standard deviation, across replications, of the average and maximum of metrics within each replication for the scenarios discussed in this section.

For each combination of factors, we run 50 replications.

4.1 Turnout and Early Voting

Voter turnout and the early voting rate determine the number of in-person voters on Election Day. A high voter turnout is desired, but it can result in longer wait times at the polls. A high early voting rate reduces the number of voters at the polls on Election Day. We study the impact of voter turnout and early voting on the election metrics. We do so by assuming that PPE/sanitation policies are implemented (T+), there are the recommended number of check-in booths at each location (B+), and that social distancing is enforced with the same physical footprint at polling locations (C-). We consider two levels of voter turnout (V), with V+ = 60% and V- = 75%, and three levels of early voting (E)). The values of key metrics are presented in Table 3.

If the early voting rate is 30% (E-), the discrete event simulation forecasts that the average voter's sojourn time, the time from entering the initial queue until completing the voting process, will be among the highest ever seen during a Milwaukee election for either level of voter turnout. With 60% voter turnout (V-), we expect the average sojourn time to be 127.9 minutes. With 75% voter turnout (V+), the average sojourn time increases to 238.6 minutes. If early voting rate is 54% (E0), the level found by the Marquette poll [19], then the waiting times will be lower on average, but this still results in long sojourn times. When voter turnout is 60%, the average sojourn time is 22.1 minutes. When the voter turnout is 75%, the average sojourn time is 57.9 minutes. Moreover, 19% and 62% of voters wait 30 minutes or longer before starting the check-in process for low and high voter turnout, respectively. We find that if the early voting rate is 75% (E+), a voter can expect to wait under 1.5 minutes and that there is rarely a line for either level of voter turnout.

Table 3: Impact of turnout and early voting on the voting system. Average (standard deviation) of key metrics assuming low capacity (C-), recommended number of check-in (B+), implementation of PPE/sanitation policies (T+), and FCFS queue (Q-). All times are measured in minutes.

V	E	Wait Time	Time Inside	15 min Wait	30 min Wait	Line Length	Voters Inside
-	-	119.4 (19.4)	8.6 (0.0)	0.94 (0.02)	0.9 (0.03)	128.8 (21.8)	9.5 (0.1)
-	0	13.6 (5.8)	8.5 (0.0)	0.33 (0.11)	0.19 (0.11)	11.5 (5.4)	7.1 (0.3)
-	+	0.5 (0.3)	8.3 (0.0)	0.0 (0.0)	0.0 (0.0)	0.2 (0.1)	3.8 (0.2)
+	-	230.0 (21.2)	8.6 (0.0)	0.98 (0.0)	0.95 (0.01)	252.1 (23.9)	9.6 (0.0)
+	0	49.3 (13.8)	8.5 (0.0)	0.72 (0.09)	0.62 (0.11)	50.4 (15.3)	8.8 (0.3)
+	+	1.4 (0.9)	8.4 (0.0)	0.02 (0.02)	0.0 (0.0)	0.8 (0.5)	4.8 (0.3)

These results suggest that early voting, either in-person or through mail voting, will be critical for the 2020 General Election. The early voting rate can be increased by expanding access to early in-person voting or mail-in absentee voting. In-person early voting can be increased by expanding the number polling locations and number of days voters can vote absentee. Mail in voting can be increased by allowing voters to request ballots without a reason and by ensuring ballots are delivered to voters with enough time for them to be returned by Election Day. Additionally, election officials can arrange for supplemental dropboxes for voters to submit their absentee ballots in-person. While mail in ballots may be an easier technique to expand early/absentee voting, the benefit of in-person voting is the low rejection rate for cast ballots. Mail-in ballots can pose a higher risk of fraud, logistical oversight, and incorrectly cast ballots. Reported fraud is extremely low with mail-in ballots, but scholars argue it is higher than with in-person voting [28]. Moreover, in some cases requested ballots never reach the voter or returned ballots never reach the clerk's office in time to be counted [50]. Even when ballots are returned, historically, they are rejected at a much higher rate than ballots submitted in-person due to missing signatures, addresses, or over voting. It is estimated that voting in-person has a ballot rejection rate of 0.03% [5] while for the Wisconsin Spring 2020 Election the rejection rate for returned absentee ballots was 1.96%, which is on par with previous elections [50].

Table 4 presents the expected number of rejected ballots and the rejection rates for the Milwaukee case study for different levels of voter turnout (55%, 60%, 65%, 70%, 75%) and early voting (30%, 54%, 75%). According to a Marquette poll for the state of Wisconsin, of the 54% of voters expecting to vote absentee, 20.37% expect to vote early in-person and 79.63% expect to vote early by mail [19]. We assume these percentages hold for any rate of early voting. We find that in the City of Milwaukee between 1000 and 4000 ballots can be expected to be rejected with rates between 0.49% and 1.18%, with the highest rejection rate occurring when mail-in voting is highly practiced. One method to reduce the rejection rate of mail-in ballots is to provide additional resources to better educate voters on properly completing and submitting a mail-in absentee ballot [20].

4.2 Queueing Style

Protecting the health of voters, especially those at high-risk to the COVID-19 disease, is critical during the 2020 General Election. Nearly all polling locations implement a first-come, first-served

Table 4: Expected number of ballots rejected for various turnout levels and early voting levels assuming early voters cast 79.63% by mail, 20.37% in-person. Assuming a rejection rate of 0.03% for ballots cast in-person and 1.96% for ballots cast by mail.

Ballots Cast		Voting Method Distribution			Expected Number of Rejected Ballots	
Turnout %	Total Ballots Cast	In-Peron %	In-Person Early %	By Mail Absentee %	Ballots Rejected	Rejection Rate
55	238,417	70	6	24	1,171	0.49%
60	260,092	70	6	24	1,277	0.49%
65	2817,66	70	6	24	1,384	0.49%
70	303,440	70	6	24	1,490	0.49%
75	325,115	70	6	24	1,596	0.49%
55	238,417	46	11	43	2,050	0.86%
60	260,092	46	11	43	2,237	0.86%
65	281,766	46	11	43	2,423	0.86%
70	303,440	46	11	43	2,609	0.86%
75	325,115	46	11	43	2,796	0.86%
55	238,417	25	15	60	2,820	1.18%
60	260,092	25	15	60	3,076	1.18%
65	281,766	25	15	60	3,332	1.18%
70	303,440	25	15	60	3,589	1.18%
75	325,115	25	15	60	3,845	1.18%

(FCFS) queueing discipline as standard procedure. This causes each voter to wait approximately the same amount of time in line, although the health risk is higher for a subgroup of voters. We consider implementing a priority queue as a mitigating process to protect those at high-risk to COVID-19. Table 5 highlights the impact of the queueing style (Q) on average voter wait time and sojourn time stratified by risk groups. We again assume PPE/sanitation policies are implemented (T+), there are the recommended number of check-in booths at each location (B+), and that social distancing is enforced with the same physical footprint (C-).

A priority queue reduces the wait time for any high-risk voter to no more than 1.5 minutes on average. By reducing the wait time for high-risk voters, the voters are in close proximity with other voters for less time. This lowers the risk of transmitting COVID-19 to these high-risk voters

[10]. However, this does increase the wait time of the low-risk voters that make up 86.2% of the in-person voters. With 30% early voting (E-), the wait time for low-risk voters is increased by 15.9% (19 minutes) and 16.0% (36.8 minutes) compared to a FCFS policy for low and high turnout, respectively. With 54% early voting (E0), low-risk voters wait on average 15.4% (2.1 minutes) and 15.8% (7.8 minutes) longer than with a FCFS policy for low and high turnout, respectively. With 75% early voting (E+), there is essentially no wait for high or low-risk voters with either a FCFS or priority queueing policy.

There is a trade-off between reducing the exposure of high-risk voters to the virus and ensuring all voters can cast a ballot quickly. By implementing a priority queueing system, the community can protect those at highest risk of the virus with little relative impact to low-risk voters within the system. If a priority queue is implemented, election officials should take care to address the psychological "injustice" associated with priority queues [21]. For the remainder of this section, we assume that the priority queue is implemented.

Table 5: Impact of queueing policy stratified by risk group. Average (standard deviation) of wait time and sojourn time low capacity (C-), recommended number of check-in booths (B+), and PPE/sanitation policies (T+). All times are measured in minutes.

			Wait Time		Sojourn Time	
V	E	Q	High-Risk	Low-Risk	High-Risk	Low-Risk
-	-	-	119.4 (19.4)	119.4 (19.4)	128.0 (19.4)	127.9 (19.4)
-	-	+	0.8 (0.0)	138.4 (22.5)	9.2 (0.0)	147.0 (22.5)
-	0	-	13.6 (5.8)	13.6 (5.8)	22.1 (5.8)	22.1 (5.8)
-	0	+	0.5 (0.0)	15.7 (6.7)	8.9 (0.1)	24.2 (6.7)
-	+	-	0.5 (0.3)	0.5 (0.3)	8.9 (0.3)	8.9 (0.3)
-	+	+	0.2 (0.0)	0.6 (0.3)	8.5 (0.1)	8.9 (0.4)
+	-	-	230.1 (21.2)	230.0 (21.2)	238.7 (21.2)	238.5 (21.2)
+	-	+	0.9 (0.0)	266.8 (24.6)	9.3 (0.0)	275.4 (24.6)
+	0	-	49.3 (13.9)	49.3 (13.8)	57.8 (13.9)	57.9 (13.8)
+	0	+	0.7 (0.0)	57.1 (16.1)	9.1 (0.0)	65.7 (16.1)
+	+	-	1.4 (0.8)	1.4 (0.9)	9.7 (0.9)	9.7 (0.9)
+	+	+	0.3 (0.0)	1.5 (1.0)	8.6 (0.1)	9.9 (1.0)

4.3 Number of Check-in Booths

Poll workers are critical to voting systems. When an insufficient number of poll workers are recruited, the efficient operation of voting systems is threatened. The major way poll worker shortages affects voting systems is by limiting the number of check-in booths a polling location can support. We investigate the impact of different allotments of check-in booths on voting metrics. Table 6 presents the metrics stratified by the low and high levels of check-in booths when the capacity (C) and PPE/sanitation policy (T) are varied assuming 75% voter turnout (V+) and 54% early voting (E0). Figure 4 describes the average voter sojourn time as a function of the average number of check-in booths and the average number of ballot reading machines, where the averages are taken across all polling locations. The results from Table 6 suggest that with half the recommended number of check-in booths at each polling location (B-), the time to cast a ballot increases substantially; the sojourn time increases by ≥ 4.8 times compared to the scenario with the recommended number of check-in booths.

Increasing the number of poll workers even past the recommended number is beneficial to the voting system. As the number of check-in booths is reduced from the recommended level (changing from 2.1 booths, on average, to 1.3), we see the steep increase in voter wait time. On the other hand, increasing the number of check-in booths by a approximately 50% (changing from 2.1 booths, on average, to 3.2) decreases the average wait time to 5.3 minutes, with the recommended number of ballot reading machines. Additionally, the fraction of voters waiting 30 minutes or more to vote reduces from 0.44 to 0.06. This implies that election officials should make substantial efforts to recruit more poll workers than in previous elections. Doing so may require state governors to call the National Guard to serve as poll workers, as was done in Milwaukee for the Spring 2020 Primary and August Partisan Primary.

We also consider different levels for the number of ballot reading machines at each polling location by multiplying the recommended number by 0.5, 1, and 2 and then rounding up. Each line in Figure 4 represents one of these levels. We find the voting metrics are robust to changes in the number of ballot reading machines at each polling location.

Table 6: Impact of check-in resources on key metrics. Average (standard deviation) of key metrics assuming high voter turnout (V+), middle early voting (E0), and priority queue (Q+). All times are measured in minutes.

		Wait Time		Time Inside		Sojourn Time	
C	T	B-	B+	B-	B+	B-	B+
-	-	157.4 (20.0)	13.6 (5.2)	6.1 (0.0)	6.5 (0.0)	163.5 (20.0)	20.1 (5.2)
-	+	270.4 (26.3)	49.3 (13.9)	8.4 (0.0)	8.5 (0.0)	278.8 (26.3)	57.9 (13.9)
+	-	156.9 (19.9)	11.2 (4.4)	6.1 (0.0)	7.4 (0.2)	163.0 (19.9)	18.6 (4.6)
+	+	267.8 (25.8)	37.4 (10.7)	8.4 (0.0)	8.7 (0.0)	276.1 (25.8)	46.1 (10.7)

		Line Length		Voters Inside	
C	T	B-	B+	B-	B+
-	-	118.8 (17.0)	14.5 (6.0)	5.3 (0.1)	6.8 (0.3)
-	+	170.9 (18.6)	50.4 (15.3)	6.0 (0.0)	8.8 (0.3)
+	-	118.3 (16.8)	11.9 (5.1)	5.3 (0.1)	7.7 (0.6)
+	+	168.6 (18.1)	38.4 (12.0)	6.0 (0.0)	9.0 (0.3)

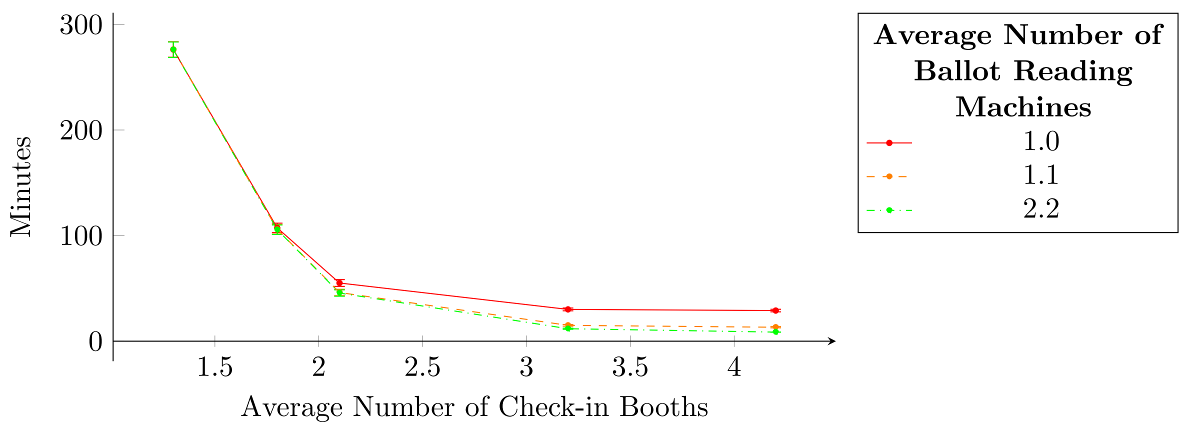


Figure 4: The average sojourn time in minutes for voters with different number of ballot reading machines and check-in booths assuming 75% voter turnout (V+), 54% early voting (E0), priority queueing policy (Q+), PPE time (T+), and high capacity (C+).

4.4 Polling Location Capacity

Social distancing is suggested by the CDC to reduce the transmission of COVID-19 during elections [10]. In many cases polling locations are small, and therefore, social distancing is difficult to enforce without reducing the number of individuals allowed in the polling location. Experts believe that reducing the number of voters inside the polling location at any one time also reduces the risk of disease transmission [10]. The low capacity (C-) captures the case when election officials must reduce the number of individuals inside at any given time. As an alternative to reducing the number of voters in a polling location at any given time, election officials may expand the physical footprint of a polling location to maintain its regular capacity while also adhering so social distancing guidelines. This could be achieved by setting up outdoor voting areas, for example [51]. The high capacity (C+) captures the case when the capacity of a polling location is roughly the same as in a non-pandemic election. We compare these two approaches by altering the capacity of the polling locations to the low capacity (C-) and a high capacity (C+). Table 7 describes the impact of polling location capacity on key metrics using 75% turnout (V+) and 54% early voting (E0).

The impact of the polling location capacity on key metrics is dependent on both the number of check-in booths and PPE/sanitation policies, and therefore, we consider both the low and high values of the number of check-in booths (B) and the PPE/sanitation policies (T). When considering the low number of check-in booths (B-), the increase in wait time is less than 1% compared to when the polling locations have a high capacity. This occurs since the number of check-in booths are the bottleneck in voting process and naturally limit the number of voters inside so that the capacity is almost never reached. Likewise, there is little impact on the time inside, the sojourn time, the line length, or the number of voters inside. When the number of check-in booths is less than what is recommended, then restricting the number of voters inside, rather than expanding the physical footprint is the appropriate approach.

When the number of check-in booths are at the recommended level at each polling location (B+), there is a substantial increase in wait time with a small benefit to the time spent inside and the number of voters inside when capacity is reduced (C-). When there is no PPE/sanitation policy in place (T-), the increase in wait time due to a reduced capacity is 21.4% (2.4 minutes), while there is a 12.2% decrease in the amount of time spent inside (0.9 minutes) and 11.7% decrease number of voters inside (0.9 voters), on average. When there is a PPE/sanitation policy in place (T+), the increase in wait time due to a reduced capacity is 31.8% (11.9 minutes), while there is only a 2.3% decrease in the amount of time spent inside (0.2 minutes) and 2.2% decrease number of voters inside (0.2 voters), on average. Moreover, reducing the capacity increases the total time to vote in both cases. In some locations, extending the wait outside is undesirable due to poor weather, logistical issues with longer lines, and difficulty enforcing social distancing. When the recommended number of check-in booths are staffed at a polling location, especially when PPE and sanitation policies are in place (T+), efforts should be made to expand the physical footprint of the polling location to maintain the capacity of past elections, when possible.

Table 7: Impact of restricting polling location capacity on key metrics. Average (standard deviation) of key metrics assuming high voter turnout (V+), middle early voting (E0), and priority queue (Q+). All times are measured in minutes.

		Wait Time		Time Inside		Sojourn Time	
B	T	C-	C+	C-	C+	C-	C+
-	-	157.4 (20.0)	156.9 (19.9)	6.1 (0.0)	6.1 (0.0)	163.5 (20.0)	163.0 (19.9)
-	+	270.4 (26.3)	267.8 (25.8)	8.4 (0.0)	8.4 (0.0)	278.8 (26.3)	276.1 (25.8)
+	-	13.6 (5.2)	11.2 (4.4)	6.5 (0.0)	7.4 (0.2)	20.1 (5.2)	18.6 (4.6)
+	+	49.3 (13.9)	37.4 (10.7)	8.5 (0.0)	8.7 (0.0)	57.9 (13.9)	46.1 (10.7)

		Line Length		Voters Inside	
B	T	C-	C+	C-	C+
-	-	118.8 (17.0)	118.3 (16.8)	5.3 (0.1)	5.3 (0.1)
-	+	170.9 (18.6)	168.6 (18.1)	6.0 (0.0)	6.0 (0.0)
+	-	14.5 (6.0)	11.9 (5.1)	6.8 (0.3)	7.7 (0.6)
+	+	50.4 (15.3)	38.4 (12.0)	8.8 (0.3)	9.0 (0.3)

4.5 PPE and Sanitation Time

Ensuring PPE, social distancing, and sanitation within polling locations is critical for reducing the risk of disease spread during the voting process [10]. PPE, social distancing, and sanitation was implemented during Milwaukee's Spring 2020 Primary election, and there was no clear increases in COVID-19 cases, hospitalizations, or deaths [33]. Polling locations must ensure they have the appropriate resources to mitigate the spread of disease. However, it is important to understand the impact of these protective policies on the voting process.

Table 8 reports the impact of the implementation of PPE, social distancing, and sanitation policies when assuming 75% voter turnout (V+) and 54% early/absentee voting (E0). For either level of the capacity (C) or number of check-in booths (B), the PPE/sanitation policy substantially increases the wait time, time inside, time to vote, line length, and the number of voters inside, on average. For example, the average sojourn times increase by 27.5 – 115.3 minutes across the four cases considered in Table 8, which indicates that PPE/sanitation leads to considerably longer voting times. The reason these metrics increase is three fold. First, we assume the PPE/sanitation policy increases the time for a voter to check-in by 20 seconds, on average. This increases the utilization of the check-in resources and effectively reduces the number of check-in resources compared to an election for which no health precautions are in place. Second, we assume that some individuals take longer to vote with a PPE and social distancing policy, increasing the time to vote by 2 minutes on average. This increases the time voters spend inside as well as the proportion of time the polling location is at capacity. Third, we assume that after each voter marks their ballot, a volunteer sanitizes the voting area, stopping voters from checking-in when the polling location is at capacity.

Table 8: Impact of a PPE, social distancing, and sanitation policy on key metrics. Average (standard deviation) of key metrics assuming high voter turnout (V+), middle early voting (E0), and priority queue (Q+). All times are measured in minutes.

		Wait Time		Time Inside		Sojourn Time	
C	B	T-	T+	T-	T+	T-	T+
-	-	157.4 (20.0)	270.4 (26.3)	6.1 (0.0)	8.4 (0.0)	163.5 (20.0)	278.8 (26.3)
-	+	13.6 (5.2)	49.3 (13.9)	6.5 (0.0)	8.5 (0.0)	20.1 (5.2)	57.9 (13.9)
+	-	156.9 (19.9)	267.8 (25.8)	6.1 (0.0)	8.4 (0.0)	163.0 (19.9)	276.1 (25.8)
+	+	11.2 (4.4)	37.4 (10.7)	7.4 (0.2)	8.7 (0.0)	18.6 (4.6)	46.1 (10.7)

		Line Length		Voters Inside	
C	B	T-	T+	T-	T+
-	-	118.8 (17.0)	170.9 (18.6)	5.3 (0.1)	6.0 (0.0)
-	+	14.5 (6.0)	50.4 (15.3)	6.8 (0.3)	8.8 (0.3)
+	-	118.3 (16.8)	168.6 (18.1)	5.3 (0.1)	6.0 (0.0)
+	+	11.9 (5.1)	38.4 (12.0)	7.7 (0.6)	9.0 (0.3)

4.6 Number of Polling Locations

Poll worker shortages have required some areas in the nation to consider consolidating polling locations for the 2020 General Election [39, 32]. The idea is to consolidate polling locations at a new location with larger facilities that may allow for greater social distancing [34]. Reducing the number of polling locations, in theory, offers the potential to more efficiently utilize resources in the presence of uncertainty. For example, in a system with many polling locations, when voter turnout is higher than expected in a single polling location, voters may overwhelm the check-in booth(s) and ballot reading machine(s) at that polling location, leading to long waiting times, while voter turnout is low at another polling location and resources are underutilized. By consolidating polling locations, resources are more efficiently allocated such that no voters experience longer than typical waiting times. When we compare voting systems with the same number of check-in booths and ballot reading machines, this is the result we find. Additionally, in a voting system with the more polling locations, key metrics are more responsive to inappropriate allocation of resources compared to a system with a consolidated number of resources.

Table 9 highlights the difference between 5 and 182 polling locations. Both the average and maximum wait time, time inside, and sojourn time decrease with a decreasing number of polling locations. However, with fewer polling locations, more voters will vote at each polling location. This is reflected in the average line length and average number of voters inside. In the best case, the average line length with 5 polling locations is 13.5 times longer than with 182 polling locations. In these cases, individuals may see or hear about long line lengths at the consolidated polling locations and decide not to vote, assuming that long lines correlate with long wait times, although this may not be the case. Likewise, the number of voters inside is at most 32.75 times higher than with 182 polling locations. While the time spent inside is slightly lower with fewer polling locations, there may be an overall increased risk of COVID-19 transmission due to a higher number of voters inside a polling location at any given time [10].

The results presented so far assume that no matter the number of polling locations, the same number of check-in booths and ballot reading machines are used in both systems. However, this may not be logistically feasible. For example, 196 ballot reading machines are recommended when there are 182 polling locations, which yields an average of 1.1 ballot reading machines per polling location. When there are 5 polling locations, an equal distribution of ballot reading machines results in an average of 39.2 machines per polling consolidated polling location. It is unlikely that the 5 consolidated polling locations could fit 40 ballot reading machines, appropriately distanced, and manage the lines to these machines. The same can be argued for check-in booths. There is an average of 2.1 check-in booths for each of 182 polling locations, and an average of 76.4 check-in booths for each of the 5 consolidated polling locations. This many check-in booths at a single consolidated polling location may lead to voter confusion and would require many additional poll workers to direct voters and manage the check-in queues.

We investigate the impact of reducing the number of ballot reading machines and check-in

Table 9: Impact of the number of polling locations on key metrics. Average (standard deviation) of key metrics assuming high voter turnout (V+), middle early voting (E0), and priority queue (Q+). All times are measured in minutes.

			Wait Time		Time Inside		Sojourn Time	
C	B	T	P-	P+	P-	P+	P-	P+
-	-	-	110.4 (21.2)	157.4 (20.0)	5.9 (0.0)	6.1 (0.0)	116.3 (21.2)	163.5 (20.0)
-	-	+	218.2 (25.9)	270.4 (26.3)	8.2 (0.0)	8.4 (0.0)	226.4 (25.9)	278.8 (26.3)
-	+	-	5.1 (3.2)	13.6 (5.2)	5.9 (0.0)	6.5 (0.0)	11.0 (3.2)	20.1 (5.2)
-	+	+	24.8 (8.9)	49.3 (13.9)	8.2 (0.0)	8.5 (0.0)	33.0 (8.9)	57.9 (13.9)
+	-	-	110.4 (21.2)	156.9 (19.9)	5.9 (0.0)	6.1 (0.0)	116.3 (21.2)	163.0 (19.9)
+	-	+	218.2 (25.9)	267.8 (25.8)	8.2 (0.0)	8.4 (0.0)	226.4 (25.9)	276.1 (25.8)
+	+	-	5.1 (3.2)	11.2 (4.4)	5.9 (0.0)	7.4 (0.2)	11.0 (3.2)	18.6 (4.6)
+	+	+	24.1 (8.7)	37.4 (10.7)	8.2 (0.0)	8.7 (0.0)	32.3 (8.7)	46.1 (10.7)

			Line Length		Voters Inside	
C	B	T	P-	P+	P-	P+
-	-	-	3679.6 (725.2)	118.8 (17.0)	198.2 (1.2)	5.3 (0.1)
-	-	+	5859.4 (706.5)	170.9 (18.6)	223.1 (0.5)	6.0 (0.0)
-	+	-	195.7 (130.6)	14.5 (6.0)	222.7 (9.4)	6.8 (0.3)
-	+	+	942.9 (372.0)	50.4 (15.3)	309.4 (13.1)	8.8 (0.3)
+	-	-	3679.6 (725.2)	118.3 (16.8)	198.2 (1.2)	5.3 (0.1)
+	-	+	5859.4 (706.5)	168.6 (18.1)	223.1 (0.5)	6.0 (0.0)
+	+	-	195.7 (130.6)	11.9 (5.1)	222.7 (9.4)	7.7 (0.6)
+	+	+	915.3 (363.6)	38.4 (12.0)	309.4 (13.1)	9.0 (0.3)

booths to lower, more reasonable levels when there are 5 polling locations. We consider new levels that are 12.5%, 25%, 50%, 100%, and 200% of the original number of resources, rounded up. Figure 5 illustrates the average sojourn time of voters. Each line represents a different average number of ballot reading machines at each location. Figure 5 shows that as the number of check-in booths decreases, the wait time for voters increases substantially, since the utilization of the check-in booths increases. The same can be said for the number of ballot reading machines. With 38.6 check-in booths and 23.7 machines on average per location, a voting system with 5 polling locations experience sojourn times of 335.5 minutes on average. As the number of check-in booths and ballot reading machines are reduced, the wait and sojourn times increase at a faster rate.

Consolidating polling locations also increases the distance a voter must travel to a polling location in nearly all cases. We estimate the distance between each voting aged individual and the polling location to which they were assigned when there are 5 and 182 polling locations, using

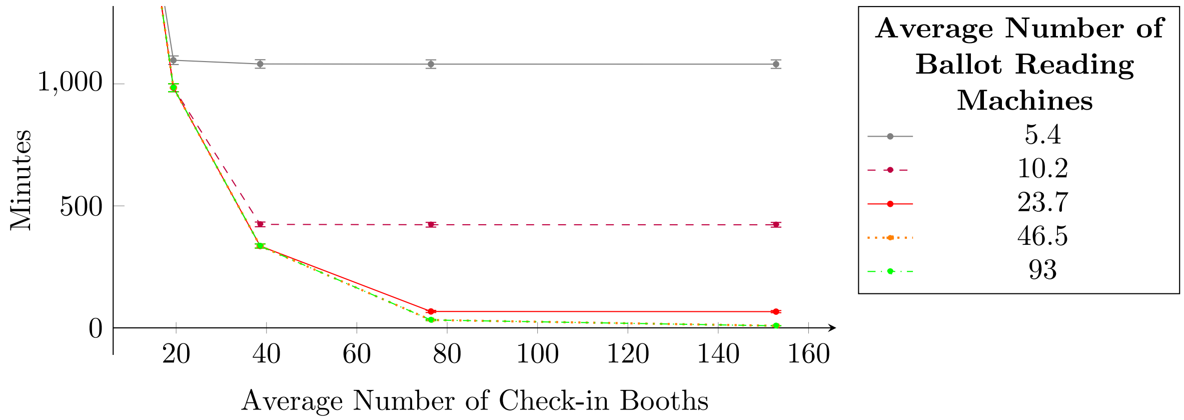


Figure 5: The average sojourn time in minutes for voters with different number of ballot reading machines and check-in booths with different levels of resources assuming 75% voter turnout, 54% early voting, PPE time (T+), high capacity (C+), and 5 polling locations (P-).

the locations of the 5 consolidated polling locations in the Spring 2020 Primary. For each voting aged individual in each voting ward, we randomly assign a location within the ward. Then, we compute the geodesic distance between the voter an the polling location to which the voter is assigned. Using this method, we find that on average a voting aged individual in Milwaukee is 0.38 miles from their polling location when there are 182 polling locations and 2.16 miles from their consolidated polling location when there are 5 polling locations. The maximum distance a voter is from their polling location is 3.04 miles and 7.61 miles for the 182 and 5 polling locations, respectively. The distance traveled by voters with consolidated polling locations is concerning, since research indicates that the likelihood that a voter casts a ballot decreases with the distance they must travel to a polling location [7]. Initial research from the Spring 2020 Primary in Milwaukee suggests the voter turnout decreased by 8.5% and reduced turnout among the black population by 10.2% [30] due to the consolidation of polling locations. Consolidating polling locations requires voters from more locations to congregate in a single, centralized location. This increases the likelihood of inter-community COVID-19 spread while also reducing the ability for public health officials to perform contract tracing.

These considerations indicate that there are major drawbacks to consolidating polling locations. As a result, we recommend that election officials make every effort to maintain the number of polling locations, unless an equal number of check-in booths and ballot reading machines can be maintained within the voting system. Doing so may be particularly difficult when voting systems are unable to recruit poll workers, since there are often legal requirements for the number of election inspectors at each polling location. When the same number of resources can be maintained with fewer polling locations, the decision is nontrivial as there are clear trade-offs between improvements in the time to complete the voting process and the distance voters must travel to their assigned polling location.

4.7 Sports Arena with 182 Polling Locations

In many locations throughout the country, there has been discussion of adding an “arena” polling location while maintaining the standard polling locations. These arenas are to serve as an additional polling location, where any voter within the area can vote on Election Day if they so choose. Sports arenas are spacious, and they have the potential to accommodate a large number of voters while maintaining social distancing throughout the voting process. Major league sports arenas and stadiums have been considered for these sites. In Milwaukee, both the Fiserv Forum and Miller Park will be used as early voting sites prior to the 2020 General Election [31]. In Los Angeles County, Dodger Stadium will be used as a site for in-person voting on Election Day [35]. Across the nation, the NBA has announced that arenas, including the Fiserv Forum in Milwaukee, will by used as additional polling locations in the 2020 General Election [38]. We investigate the impact of such arenas on in-person voting on Election Day. We base our analysis on the Fiserv Forum in Milwaukee.

In the analysis, there are 183 polling locations, and each voter can choose to vote at one of two polling locations: their standard polling location (of the 182 polling locations) or the arena. We assume that a constant proportion of voters “redirect” from the standard polling locations to the arena. We allow the redirect rate to vary between 0% and 12.5%. The analysis seeks to identify an appropriate number of voters to redirect to the arena.

The voting process at the 182 standard polling locations is unchanged from the previous section. We assume that the arena polling location has 26 check-in booths (e.g., one for every letter in the alphabet), 10 ballot reading machines, and a polling location capacity of 500. In the analysis, we assume a voter turnout of 75% and an early voting rate of 54%. We assume the 182 polling locations have the recommended number of check-in booths (B+) and have a high polling location capacity (C+), and at all locations a PPE, social distancing, and sanitation policy is implemented (T+). Fifty replications were run for each rate of redirection.

Table 10 presents the voting metrics across different levels of the redirect rate. As the redirect rate increases, the performance of the arena location worsens while the performance of the standard 182 polling location improves. When the redirect rate is 6.25% (9,367.3 voters), the average sojourn time for voters voting at the 182 standard polling locations is 34.6 minutes and is 22.0 minutes at the arena polling location. This is a decrease of 24.9% (11.5 minutes) in the 182 polling locations compared to a system with no arena (i.e., a redirect rate of 0%). At the same redirect rate of 6.25%, 22% of voters wait at least 30 minutes before check-in at the arena polling location and 34% of voters at the 182 polling locations. This is a decrease of 10% for the 182 polling locations compared to the scenario with a redirect rate of 0%. At approximately a 7% redirection rate, the average sojourn time is equal for voters voting at one of the 182 polling locations as it is in the single arena location. The average sojourn times at the arena and 182 polling locations remain under 50 minutes until about a 7.25% redirect rate (11,240 voters). At this same redirect rate of 7.25%, the average queue length at the arena is long (594.4 voters, on average) and there are many individuals inside the arena (116.7 voters, on average). However, the average wait time for voters at the 182 polling locations is 24.1 minutes, a 29.1% (13.4 minutes) decrease compared to the scenario with a redirect rate of 0%. It is clear that introducing such an arena has the potential to reduce the average wait time, sojourn time, and the time inside. This is not unexpected, since additional resources (e.g., check-in booths, ballot reading machines, volunteers) are introduced at the arena, and therefore, there are more total resources in the voting system.

We explore this issue further in Figures 6a and 6b, respectively, which present the average sojourn time and proportion of voters waiting at least 30 minutes at both the original 182 polling locations and at the arena. Both figures show that the average sojourn time and the proportion of voters waiting at least 30 locations at the 182 polling locations do not substantially reduce as more voters redirect to the arena, since a relatively small proportion of voters vote elsewhere (at the arena). Since voters from all 182 polling locations congregate at the single arena, the arena becomes overwhelmed with voter congestion when the proportion of voters who redirect exceeds a threshold of 7%. In this case, the average sojourn time and proportion of voters waiting at least 30 minutes are longer at the arena than the average polling location (of 182) when approximately 7% or more of the voters redirect.

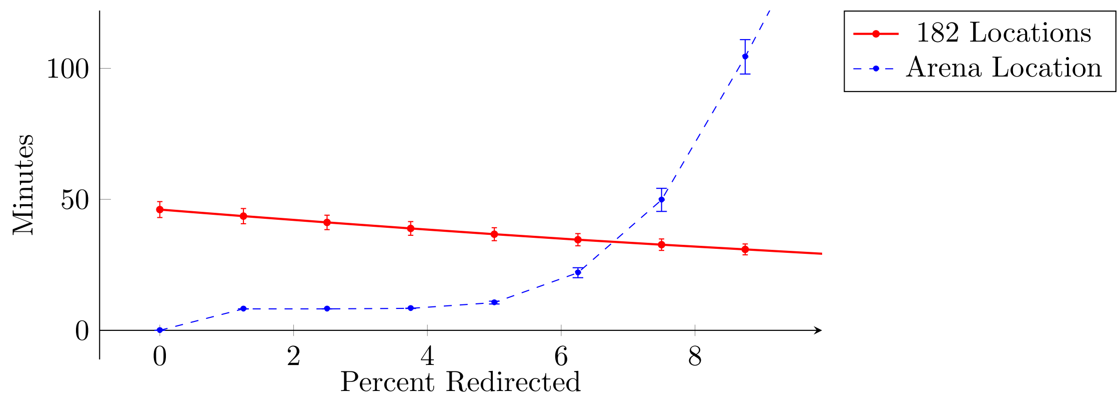
Using a sports arena as an alternative polling location is a mechanism to attempt to make the

Table 10: Average (standard deviation) of key metrics assuming 75% turnout (V+), 54% early voting (E0), high capacity (C+), recommended number of check-in booths (B+), and PPE time (T+). All times are measured in minutes. We assume the arena has 26 check-in booths, 10 machines, and a capacity of 500 individuals.

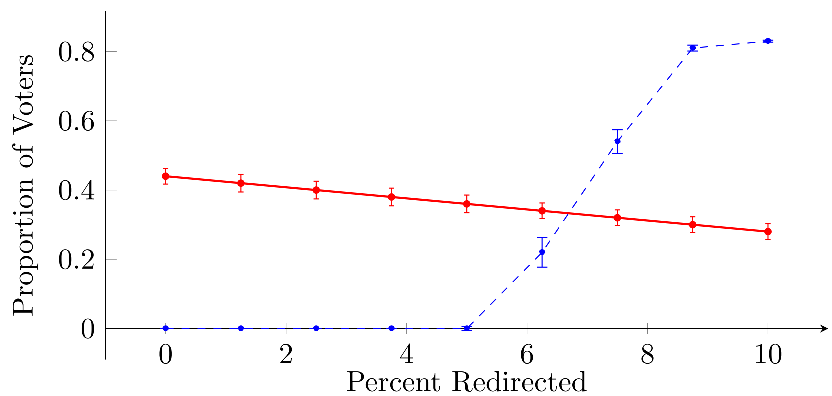
Redirect Rate	Wait Time		Time Inside		Sojourn Time	
	Arena	182	Arena	182	Arena	182
0%	0.0 (0.0)	37.4 (10.7)	0.0 (0.0)	8.7 (0.0)	0.0 (0.0)	46.1 (10.7)
1.25%	0.0 (0.0)	34.9 (10.2)	8.2 (0.1)	8.7 (0.0)	8.2 (0.1)	43.6 (10.2)
2.5%	0.0 (0.0)	32.5 (9.7)	8.2 (0.1)	8.7 (0.0)	8.2 (0.1)	41.2 (9.7)
3.75%	0.1 (0.2)	30.2 (9.2)	8.2 (0.0)	8.7 (0.0)	8.4 (0.2)	38.9 (9.2)
5%	2.3 (1.9)	28.0 (8.7)	8.2 (0.0)	8.6 (0.0)	10.6 (1.9)	36.7 (8.7)
6.25%	13.7 (6.7)	26.0 (8.2)	8.3 (0.0)	8.6 (0.0)	22.0 (6.7)	34.6 (8.2)
7.5%	41.5 (15.5)	24.1 (7.7)	8.3 (0.0)	8.6 (0.0)	49.8 (15.5)	32.7 (7.7)
8.75%	96.1 (23.1)	22.2 (7.2)	8.3 (0.0)	8.6 (0.0)	104.4 (23.1)	30.9 (7.3)
10%	156.4 (25.4)	20.5 (6.8)	8.3 (0.0)	8.6 (0.0)	164.7 (25.4)	29.1 (6.8)
12.5%	278.1 (30.1)	17.4 (6.0)	8.3 (0.0)	8.6 (0.0)	286.4 (30.1)	26.0 (6.0)

Redirect Rate	Line Length		Voters Inside	
	Arena	182	Arena	182
0%	0.0 (0.0)	38.4 (12.0)	0.0 (0.0)	9.0 (0.3)
1.25%	0.0 (0.0)	35.6 (11.4)	19.4 (1.0)	8.9 (0.3)
2.5%	0.0 (0.0)	32.9 (10.7)	38.9 (1.8)	8.8 (0.4)
3.75%	0.8 (1.4)	30.3 (10.1)	58.4 (2.7)	8.7 (0.4)
5%	22.5 (18.9)	27.8 (9.5)	77.8 (3.6)	8.5 (0.4)
6.25%	164.1 (86.3)	25.5 (8.9)	97.2 (4.5)	8.4 (0.4)
7.5%	594.4 (246.0)	23.4 (8.3)	116.7 (5.2)	8.3 (0.4)
8.75%	1454.7 (349.6)	21.3 (7.7)	125.3 (0.9)	8.2 (0.4)
10%	2374.0 (386.6)	19.4 (7.1)	125.7 (0.8)	8.1 (0.4)
12.5%	4235.2 (460.6)	16.0 (6.1)	126.1 (0.7)	7.9 (0.4)

voting process more robust to high voter turnout, particularly in terms of voter wait and sojourn times. However, use of a sports arena does not always achieve this potential, since it introduces complexity to the voting process. Voter wait and sojourn times at the arena are sensitive to the number of voters redirected to that polling location, while these metrics at the standard polling locations are relatively inelastic to voters being redirected. For example, increasing the redirect rate from 6.25% to 7.5% (1872.7 voters) increases the wait time at the arena location by 202.9% (27.8 minutes) while the average wait time for voters voting at the 182 locations decrease by 7.3% (1.9 minutes). However, since not all polling locations would have the same redirect rate in actuality, we would expect some polling locations to experience longer wait times. As a result, some voters



(a) Mean Average Sojourn time



(b) Proportion of voters waiting at least 30 minutes before check-in

Figure 6: Average sojourn time in minutes and proportion of voters waiting at least 30 minutes assuming 75% turnout (V+), 54% early voting (E0), high capacity (C+), priority queue (Q+), recommended number of check-in booths (B+), and PPE time (T+). We assume the arena has 26 check-in booths, 10 machines, and a capacity of 500 individuals.

would face long wait times at both the standard polling location and the sports area.

A limitation of this study is we do not investigate the “self correcting” nature of the additional arena location. It is likely that voters will disproportionately vote at the arena if their local polling location is overwhelmed with voters. Likewise, if the arena is overwhelmed with voters, it is likely voters will decide to vote at their local polling location. However, incorporating this type of voter behavior may result in many voters facing long wait times at both their standard polling location as well as the arena.

Additionally, an arena location adds new logistical challenges to the election process. An arena will require substantial resources and planning that election commissions may not have. For example, additional poll workers would be needed for the arena to direct voters, work check-in booths, and sanitize voting areas. Election officials are already struggling to find poll workers for the standard polling locations. Also, as with consolidated polling locations, voters from many locations will be congregating in a single, centralized location. This increases the likelihood of inter-community COVID-19 spread and reduce the ability for public health officials to perform contract tracing.

If entities overseeing elections can find enough poll workers for the arena polling location, they could instead employ the workers as check-in booth workers at the standard locations and improve system performance in that manner. As previous discussion has highlighted (see Section 4.3), poll workers are a critical resource and increasing the number of check-in booths at the standard polling location has a significant positive impact on voting metrics without the additional cost of added complexity.

5 Discussion

The COVID-19 pandemic creates additional strain on voting systems. Elections held thus far during the COVID-19 pandemic have highlighted the need to consider new alternatives for the design and operation of in-person voting systems to ensure that voting systems are resilient to poll worker shortages, a high number of in-person voters, and new requirements and processes to mitigate the risk of infectious disease transmission. Using a case study of Milwaukee, WI, we provide the following recommendations for election officials who are preparing for the 2020 General Election:

1. More poll workers are required for the 2020 General Election as compared to previous Presidential elections. Protective measures such as PPE usage and voting booth sanitation to reduce the risk of COVID-19 transmission will lead to slightly longer times for voters to check-in and mark ballots, possibly leading to unprecedented waiting times at many polling locations. As a goal, enough poll workers should be recruited to add one additional check-in booth at each polling location, to sanitize voting areas, and to manage lines outside of the polling location. In many areas, a campaign to increase the number of poll workers is needed. If there is not an adequate number of poll workers, governors should consider calling the National Guard to fill poll worker shortages.

2. In-person voting on Election Day should occur at standard polling locations instead of consolidating polling locations. Consolidated polling locations require many check-in booths to

ensure short voting queues, and doing requires high staffing levels and introduces complexity into the voting process. Election officials should explore how to expand the physical footprint of standard polling locations (e.g., expanding voting areas outside) to ensure that the recommended number of check-in booths, voting booths, and ballot reading machines (based on election management toolkit recommendations) can be safely located within the voting area, rather than restricting the number of individuals voting at the same time.

3. We do not recommend using sports arenas as supplementary polling locations for in-person voting on Election Day. Alternative polling locations introduce complexity and could create a mismatch between where voters choose to go and where resources are allocated, potentially leading to longer waiting times for many voters. This drawback can be avoided by instead allocating the would-be resources at the sports arena to the standard polling locations.

4. To reduce the transmission of COVID-19 to vulnerable populations during the voting process, election officials should consider the use of a priority queue, where voters who self-identify as being high-risk to the COVID-19 (e.g., voters with compromised immune systems) can enter the front of the check-in queue.

5. It is critical to promote early voting by expanding in-person early voting opportunities and allowing voters to cast ballots by mail. With mail in voting, ballots and resources should be designed to reduce the rejection rate of cast ballots.

As with any simulation, there are dynamics of the voting process that have not been considered. There are several limitations of the analysis presented in this paper. First, we assume that changes to the voting system have no impact of the voter turnout or early voting rates. It is likely that changes and improvements to the voting process may influence voter choices. For example, mitigating efforts to reduce voter wait times and the distances voters must travel to polling locations may result in higher voter turnout as the "cost" of casting a vote is lower [5]. Our analysis does not account for the impact of long lines on voter turnout. Individuals may see or hear about line lengths at their local polling location and choose not to vote. This is particularly true in areas with inclement weather on Election Day. Due to the COVID-19 pandemic, voters may be required to wait outside before checking-in to reduce the viral load inside, even if there is room within the polling location. Social distancing in line will also likely be practiced. These may give the appearance of longer lines compared to elections that occured before the COVID-19 pandemic. The appearance of long lines may discourage participation in the voting process, since voters may (falsely) assume the “cost” to vote is high [5, 21]. We do not consider curbside voting or registration of voters. This will increase the utilization of existing volunteer resources or require dedicated volunteers. Curbside voting could cause a large strain on the voting system if it is commonly practiced and resources are not dedicated to the process.

The simulation analysis uses real-world data to estimate realistic input parameters, however, most of the data is based on elections that occurred before the COVID-19 pandemic. It is possible that some of the inputs may not reflect actual conditions on Election Day on November 3, 2020. For example, we do not consider a change in voter arrival pattern compared to previous elections. With more voters working from home, this pattern may change. If the pattern becomes more evenly distributed throughout the day, various metrics associated with wait times and line lengths will improve. A large number of voters are expected to vote early prior to the 2020 General Election, and as a result, the demographics of in-person Election Day voting may change. This may change the times to complete each step of the voting process. The number of individuals who self-identify as high-risk is also unknown before an election and likely will vary between polling locations due to socioeconomic status and health of the community. With more individuals self-identifying as high-risk, the less equitable the voting process becomes when measuring wait time. Additionally, when the lines are very long, some dedicated poll workers may be needed to ensure high-risk voters are aware of the priority queue. Finally, the simulation model does not consider ballot machine or check-in booth downtime. A system with more polling locations will experience a larger impact from resource downtime. When resource downtime is experienced, this introduces additional delays that lead to longer wait times and line lengths.

Planning for an election is a topic of national concern, with elections considered to be part of our nation’s critical infrastructure. This paper presents a detailed analysis of a discrete event simulation model that supports planning for elections. The results can be used to inform election planning decisions and help election officials operate elections that are efficient and safe.

Acknowledgments

The authors would like to thank Professor Barry Burden at the University of Wisconsin-Madison for his expertise, the voting information he provided, andthe feedback he provided on a draft of this manuscript.

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A Tables of Results

Table 11: Average (standard deviation) of voter metrics for a full factorial design on factors V, E, Q, and P. We find that early voting is critical to acceptable performance of the voting system. Implementing a priority queue (Q+) does not substantially impact the average (std. dev.) of any metric. Assuming the same number of resources, fewer polling locations lead to better metrics.

Voter Metrics

Factor Level							Average (Std. Dev.) of Average of Statistic				
V	E	Q	C	B	T	P	Wait Time	Time Inside	Sojourn Time	15 min wait	30 min wait
-	-	-	-	+	+	-	77.4 (18.2)	8.2 (0.0)	85.6 (18.2)	0.93 (0.05)	0.86 (0.07)
-	-	-	-	+	+	+	119.4 (19.4)	8.6 (0.0)	127.9 (19.4)	0.94 (0.02)	0.9 (0.03)
-	-	+	-	+	+	-	77.4 (18.2)	8.2 (0.0)	85.6 (18.2)	0.81 (0.04)	0.76 (0.06)
-	-	+	-	+	+	+	119.4 (19.4)	8.6 (0.0)	128.0 (19.4)	0.82 (0.02)	0.79 (0.03)
-	0	-	-	+	+	-	5.5 (3.7)	8.2 (0.0)	13.7 (3.7)	0.16 (0.14)	0.03 (0.06)
-	0	-	-	+	+	+	13.6 (5.8)	8.5 (0.0)	22.1 (5.8)	0.33 (0.11)	0.19 (0.11)
-	0	+	-	+	+	-	5.5 (3.7)	8.2 (0.0)	13.7 (3.7)	0.16 (0.12)	0.05 (0.08)
-	0	+	-	+	+	+	13.6 (5.8)	8.5 (0.0)	22.1 (5.8)	0.31 (0.1)	0.19 (0.1)
-	+	-	-	+	+	-	0.0 (0.1)	8.2 (0.0)	8.3 (0.1)	0.0 (0.0)	0.0 (0.0)
-	+	-	-	+	+	+	0.5 (0.3)	8.3 (0.0)	8.9 (0.3)	0.0 (0.0)	0.0 (0.0)
-	+	+	-	+	+	-	0.0 (0.1)	8.2 (0.0)	8.3 (0.1)	0.0 (0.0)	0.0 (0.0)
-	+	+	-	+	+	+	0.5 (0.3)	8.3 (0.0)	8.9 (0.3)	0.0 (0.0)	0.0 (0.0)
+	-	-	-	+	+	-	177.9 (19.8)	8.2 (0.0)	186.1 (19.8)	0.97 (0.0)	0.95 (0.01)
+	-	-	-	+	+	+	230.0 (21.2)	8.6 (0.0)	238.6 (21.2)	0.98 (0.0)	0.95 (0.01)
+	-	+	-	+	+	-	177.9 (19.8)	8.2 (0.0)	186.1 (19.8)	0.85 (0.0)	0.83 (0.01)
+	-	+	-	+	+	+	230.0 (21.2)	8.6 (0.0)	238.6 (21.2)	0.85 (0.0)	0.83 (0.0)
+	0	-	-	+	+	-	24.8 (8.9)	8.2 (0.0)	33.0 (8.9)	0.54 (0.09)	0.41 (0.13)
+	0	-	-	+	+	+	49.3 (13.8)	8.5 (0.0)	57.9 (13.8)	0.72 (0.09)	0.62 (0.11)
+	0	+	-	+	+	-	24.8 (8.9)	8.2 (0.0)	33.0 (8.9)	0.48 (0.08)	0.39 (0.1)
+	0	+	-	+	+	+	49.3 (13.9)	8.5 (0.0)	57.9 (13.9)	0.64 (0.07)	0.56 (0.09)
+	+	-	-	+	+	-	0.2 (0.3)	8.2 (0.0)	8.4 (0.3)	0.0 (0.0)	0.0 (0.0)
+	+	-	-	+	+	+	1.4 (0.9)	8.4 (0.0)	9.7 (0.9)	0.02 (0.02)	0.0 (0.0)
+	+	+	-	+	+	-	0.2 (0.3)	8.2 (0.0)	8.4 (0.3)	0.0 (0.0)	0.0 (0.0)
+	+	+	-	+	+	+	1.4 (0.9)	8.4 (0.0)	9.7 (0.9)	0.02 (0.03)	0.0 (0.0)

Table 12: Average (standard deviation) of maximum voter metrics for a full factorial design on factors V, E, Q, and P. We find that early voting is critical to good performance of the voting system. Implementing a priority queue (Q+) will increase maximum of metrics in most scenarios. Assuming the same number of resources, fewer polling locations lead to better metrics.

Voter Metrics

Factor Level							Average (Std. Dev.) of Maximum of Statistic		
V	E	Q	C	B	T	P	Wait Time	Time Inside	Sojourn Time
-	-	-	-	+	+	-	139.6 (20.9)	45.0 (6.9)	167.1 (21.8)
-	-	-	-	+	+	+	330.6 (43.8)	45.3 (6.9)	343.5 (44.6)
-	-	+	-	+	+	-	158.5 (24.4)	45.0 (6.9)	185.1 (24.9)
-	-	+	-	+	+	+	353.1 (42.0)	45.3 (6.8)	366.3 (41.2)
-	0	-	-	+	+	-	27.2 (10.4)	43.2 (6.3)	57.4 (10.6)
-	0	-	-	+	+	+	100.1 (23.6)	43.5 (6.3)	114.5 (23.3)
-	0	+	-	+	+	-	30.9 (11.9)	43.2 (6.3)	60.2 (12.0)
-	0	+	-	+	+	+	112.6 (26.7)	43.4 (6.3)	125.5 (26.4)
-	+	-	-	+	+	-	1.0 (1.3)	40.6 (5.4)	40.6 (5.4)
-	+	-	-	+	+	+	24.1 (7.8)	40.6 (5.4)	43.4 (6.7)
-	+	+	-	+	+	-	1.1 (1.5)	40.6 (5.4)	40.6 (5.4)
-	+	+	-	+	+	+	27.2 (8.6)	40.6 (5.4)	44.1 (7.0)
+	-	-	-	+	+	-	278.8 (31.9)	45.7 (6.6)	309.6 (32.8)
+	-	-	-	+	+	+	583.2 (53.0)	46.1 (6.6)	595.3 (52.1)
+	-	+	-	+	+	-	300.8 (31.1)	45.7 (6.6)	331.5 (31.4)
+	-	+	-	+	+	+	589.0 (51.3)	46.0 (6.7)	601.8 (50.0)
+	0	-	-	+	+	-	67.8 (17.0)	44.4 (6.7)	98.2 (17.9)
+	0	-	-	+	+	+	186.0 (32.0)	44.8 (6.7)	200.0 (31.8)
+	0	+	-	+	+	-	76.3 (18.6)	44.4 (6.7)	106.3 (19.9)
+	0	+	-	+	+	+	211.7 (37.5)	44.7 (6.6)	225.5 (36.5)
+	+	-	-	+	+	-	2.9 (2.9)	41.5 (5.4)	41.8 (5.4)
+	+	-	-	+	+	+	36.1 (11.5)	41.6 (5.4)	51.6 (9.7)
+	+	+	-	+	+	-	3.3 (3.4)	41.5 (5.4)	41.8 (5.5)
+	+	+	-	+	+	+	40.4 (12.7)	41.6 (5.5)	54.7 (10.8)

Table 13: Average (standard deviation) of polling location metrics for a full factorial design on factors V, E, Q, and P. We find that early voting is critical to good performance of the voting system. Implementing a priority queue (Q+) does not substantially impact the average (std. dev.) of any metric. Assuming the same number of resources, fewer polling locations lead to better wait time and sojourn time but worse line length and voters inside.

Polling Location Metrics

Factor Level							Average (Std. Dev.) of Average of Statistic			
V	E	Q	C	B	T	P	Line Length	Voters Inside	Wait Time	Sojourn Time
-	-	-	-	+	+	-	3376.0 (815.0)	360.2 (3.4)	77.1 (18.2)	85.3 (18.2)
-	-	-	-	+	+	+	128.8 (21.8)	9.5 (0.1)	111.2 (19.6)	119.7 (19.6)
-	-	+	-	+	+	-	3376.1 (815.2)	360.2 (3.4)	77.1 (18.3)	85.3 (18.3)
-	-	+	-	+	+	+	128.9 (21.8)	9.5 (0.1)	111.2 (19.6)	119.7 (19.6)
-	0	-	-	+	+	-	168.2 (119.4)	248.0 (11.6)	5.4 (3.7)	13.7 (3.7)
-	0	-	-	+	+	+	11.5 (5.4)	7.1 (0.3)	12.7 (5.5)	21.1 (5.5)
-	0	+	-	+	+	-	168.3 (119.3)	248.0 (11.6)	5.5 (3.7)	13.7 (3.7)
-	0	+	-	+	+	+	11.6 (5.4)	7.1 (0.3)	12.7 (5.5)	21.2 (5.5)
-	+	-	-	+	+	-	0.4 (0.9)	135.6 (7.9)	0.0 (0.1)	8.3 (0.1)
-	+	-	-	+	+	+	0.2 (0.1)	3.8 (0.2)	0.6 (0.3)	8.9 (0.3)
-	+	+	-	+	+	-	0.4 (0.9)	135.6 (7.9)	0.0 (0.1)	8.3 (0.1)
-	+	+	-	+	+	+	0.2 (0.1)	3.8 (0.2)	0.6 (0.3)	8.9 (0.3)
+	-	-	-	+	+	-	7839.1 (880.9)	364.0 (0.7)	177.5 (19.8)	185.8 (19.8)
+	-	-	-	+	+	+	252.1 (23.9)	9.6 (0.0)	219.2 (22.0)	227.7 (22.0)
+	-	+	-	+	+	-	7839.8 (880.8)	364.0 (0.7)	177.5 (19.8)	185.8 (19.8)
+	-	+	-	+	+	+	252.2 (23.9)	9.6 (0.0)	219.3 (22.0)	227.8 (22.0)
+	0	-	-	+	+	-	942.9 (372.1)	309.4 (13.1)	24.7 (8.9)	32.9 (8.9)
+	0	-	-	+	+	+	50.4 (15.3)	8.8 (0.3)	45.4 (13.2)	53.9 (13.2)
+	0	+	-	+	+	-	942.9 (372.0)	309.4 (13.1)	24.7 (8.9)	33.0 (8.9)
+	0	+	-	+	+	+	50.4 (15.3)	8.8 (0.3)	45.5 (13.2)	53.9 (13.2)
+	+	-	-	+	+	-	3.9 (7.1)	169.0 (9.2)	0.2 (0.3)	8.4 (0.3)
+	+	-	-	+	+	+	0.8 (0.5)	4.8 (0.3)	1.5 (0.8)	9.8 (0.9)
+	+	+	-	+	+	-	3.9 (7.1)	169.0 (9.2)	0.2 (0.3)	8.4 (0.3)
+	+	+	-	+	+	+	0.8 (0.5)	4.8 (0.3)	1.5 (0.8)	9.8 (0.9)

Table 14: Average (standard deviation) of the maximum of polling location metrics for a full factorial design on factors V, E, Q, and P. We find that early voting is critical to good performance of the voting system. Implementing a priority queue (Q+) does not substantially impact the average (std. dev.) of any metric. Assuming the same number of resources, fewer polling locations lead to better wait time and sojourn time but worse line length and voters inside.

Polling Location Metrics

Factor Level							Average (Std. Dev.) of Maximum of Statistic			
V	E	Q	C	B	T	P	Line Length	Voters Inside	Wait Time	Sojourn Time
-	-	-	-	+	+	-	6200.5 (921.5)	392.8 (4.9)	94.0 (18.5)	102.3 (18.5)
-	-	-	-	+	+	+	615.1 (87.1)	24.3 (0.3)	219.6 (26.2)	228.0 (26.2)
-	-	+	-	+	+	-	6199.9 (925.7)	392.8 (4.9)	94.1 (18.5)	102.3 (18.5)
-	-	+	-	+	+	+	617.6 (88.0)	24.3 (0.3)	220.0 (26.4)	228.4 (26.4)
-	0	-	-	+	+	-	1214.9 (467.1)	266.8 (12.4)	7.4 (4.5)	15.6 (4.5)
-	0	-	-	+	+	+	161.1 (38.8)	18.5 (0.6)	45.8 (16.6)	54.2 (16.7)
-	0	+	-	+	+	-	1215.2 (466.8)	266.8 (12.4)	7.4 (4.5)	15.6 (4.5)
-	0	+	-	+	+	+	161.7 (39.9)	18.5 (0.6)	45.8 (16.5)	54.2 (16.6)
-	+	-	-	+	+	-	42.3 (56.9)	145.9 (8.6)	0.0 (0.1)	8.3 (0.1)
-	+	-	-	+	+	+	20.7 (9.9)	10.0 (0.5)	3.6 (2.1)	12.0 (2.1)
-	+	+	-	+	+	-	42.4 (57.9)	145.9 (8.6)	0.0 (0.1)	8.3 (0.1)
-	+	+	-	+	+	+	20.7 (10.0)	10.0 (0.5)	3.6 (2.1)	12.0 (2.1)
+	-	-	-	+	+	-	12407.3 (1399.7)	396.5 (1.6)	199.0 (19.7)	207.2 (19.7)
+	-	-	-	+	+	+	1188.3 (106.8)	24.4 (0.3)	352.8 (28.7)	361.2 (28.7)
+	-	+	-	+	+	-	12403.9 (1398.6)	396.5 (1.6)	199.0 (19.7)	207.2 (19.7)
+	-	+	-	+	+	+	1190.4 (105.3)	24.4 (0.3)	352.2 (28.5)	360.6 (28.5)
+	0	-	-	+	+	-	3014.7 (754.6)	332.7 (14.0)	31.3 (10.5)	39.5 (10.5)
+	0	-	-	+	+	+	340.1 (55.1)	23.2 (0.6)	124.7 (25.3)	133.1 (25.3)
+	0	+	-	+	+	-	3013.1 (751.8)	332.7 (14.0)	31.3 (10.5)	39.5 (10.5)
+	0	+	-	+	+	+	340.9 (56.2)	23.2 (0.6)	125.0 (25.8)	133.4 (25.8)
+	+	-	-	+	+	-	126.3 (128.4)	181.9 (9.7)	0.3 (0.4)	8.5 (0.4)
+	+	-	-	+	+	+	41.1 (19.1)	12.5 (0.5)	7.8 (4.2)	16.2 (4.2)
+	+	+	-	+	+	-	126.6 (129.2)	181.9 (9.7)	0.3 (0.4)	8.5 (0.4)
+	+	+	-	+	+	+	40.8 (19.0)	12.5 (0.5)	7.8 (4.3)	16.2 (4.4)

Table 15: Average (standard deviation) of voter metrics for full factorial design on factors C, B, T, and P. We find that PPE and associated health precautions (T) will significantly worsen key metrics. Less then the recommended number of check-in booths (B) will significantly worsen metrics. Capacity (C) has relatively little impact compared to other factors but increases wait time and sojourn time while reducing the time inside in some cases. Assuming the same number of resources, consolidating polling locations is beneficial.

Voter Metrics

Factor Level							Average (Std. Dev.) of Average of Statistic				
V	E	Q	C	B	T	P	Wait Time	Time Inside	Sojourn Time	15 min wait	30 min wait
+	0	+	-	-	-	-	110.4 (21.2)	5.9 (0.0)	116.3 (21.2)	0.83 (0.02)	0.8 (0.03)
+	0	+	-	-	-	+	157.4 (20.0)	6.1 (0.0)	163.5 (20.0)	0.75 (0.03)	0.71 (0.03)
+	0	+	-	-	+	-	218.2 (25.9)	8.2 (0.0)	226.4 (25.9)	0.85 (0.0)	0.83 (0.01)
+	0	+	-	-	+	+	270.4 (26.3)	8.4 (0.0)	278.8 (26.3)	0.82 (0.01)	0.81 (0.01)
+	0	+	-	+	-	-	5.1 (3.2)	5.9 (0.0)	11.0 (3.2)	0.15 (0.11)	0.04 (0.06)
+	0	+	-	+	-	+	13.6 (5.2)	6.5 (0.0)	20.1 (5.2)	0.3 (0.08)	0.19 (0.08)
+	0	+	-	+	+	-	24.8 (8.9)	8.2 (0.0)	33.0 (8.9)	0.48 (0.08)	0.39 (0.1)
+	0	+	-	+	+	+	49.3 (13.9)	8.5 (0.0)	57.9 (13.9)	0.64 (0.07)	0.56 (0.09)
+	0	+	+	-	-	-	110.4 (21.2)	5.9 (0.0)	116.3 (21.2)	0.83 (0.02)	0.8 (0.03)
+	0	+	+	-	-	+	156.9 (19.9)	6.1 (0.0)	163.0 (19.9)	0.74 (0.03)	0.7 (0.03)
+	0	+	+	-	+	-	218.2 (25.9)	8.2 (0.0)	226.4 (25.9)	0.85 (0.0)	0.83 (0.01)
+	0	+	+	-	+	+	267.8 (25.8)	8.4 (0.0)	276.1 (25.8)	0.81 (0.01)	0.79 (0.01)
+	0	+	+	+	-	-	5.1 (3.2)	5.9 (0.0)	11.0 (3.2)	0.15 (0.11)	0.04 (0.06)
+	0	+	+	+	-	+	11.2 (4.4)	7.4 (0.2)	18.6 (4.6)	0.25 (0.08)	0.15 (0.07)
+	0	+	+	+	+	-	24.1 (8.7)	8.2 (0.0)	32.3 (8.7)	0.47 (0.08)	0.38 (0.1)
+	0	+	+	+	+	+	37.4 (10.7)	8.7 (0.0)	46.1 (10.7)	0.52 (0.07)	0.44 (0.08)

Table 16: Average (standard deviation) of the maximum of voter metrics for full factorial design on factors C, B, T, and P. We find that PPE and associated health precautions (T) will significantly worsen key metrics. Less then the recommended number of check-in booths (B) will significantly worsen metrics. Capacity (C) has relatively little impact compared to other factors but increases wait time and sojourn time while reducing the time inside in some cases. Assuming the same number of resources, consolidating polling locations is beneficial.

Voter Metrics

Factor Level							Average (Std. Dev.) of Maximum of Statistic		
V	E	Q	C	B	T	P	Wait Time	Time Inside	Sojourn Time
+	0	+	-	-	-	-	208.4 (30.7)	43.6 (11.4)	231.3 (31.8)
+	0	+	-	-	-	+	620.9 (57.0)	43.8 (11.4)	630.1 (57.2)
+	0	+	-	-	+	-	388.8 (43.5)	44.4 (6.7)	417.5 (43.1)
+	0	+	-	-	+	+	942.5 (69.9)	44.6 (6.7)	955.8 (70.2)
+	0	+	-	+	-	-	30.6 (10.6)	43.6 (11.4)	59.4 (14.3)
+	0	+	-	+	-	+	111.5 (24.4)	43.9 (11.3)	121.1 (24.0)
+	0	+	-	+	+	-	76.3 (18.6)	44.4 (6.7)	106.3 (19.9)
+	0	+	-	+	+	+	211.7 (37.5)	44.7 (6.6)	225.5 (36.5)
+	0	+	+	-	-	-	208.4 (30.7)	43.6 (11.4)	231.3 (31.8)
+	0	+	+	-	-	+	620.9 (57.0)	43.7 (11.4)	630.1 (57.2)
+	0	+	+	-	+	-	388.8 (43.5)	44.4 (6.7)	417.5 (43.1)
+	0	+	+	-	+	+	942.5 (69.9)	44.6 (6.7)	955.8 (70.2)
+	0	+	+	+	-	-	30.6 (10.6)	43.6 (11.4)	59.4 (14.3)
+	0	+	+	+	-	+	106.9 (22.8)	45.1 (10.9)	116.4 (22.9)
+	0	+	+	+	+	-	76.3 (18.6)	44.4 (6.7)	106.1 (19.7)
+	0	+	+	+	+	+	193.6 (33.4)	44.9 (6.8)	207.5 (32.1)

Table 17: Average (standard deviation) of polling location metrics for a full factorial design on factors C, B, T, and P. We find that PPE and associated health precautions (T) and less then the recommended number of check-in booths (B) will significantly worsen key metrics. Capacity (C) has relatively little impact compared to other factors but increases wait time and sojourn time while reducing the number of voters inside in some cases. Assuming the same number of resources, consolidating polling locations is beneficial.

Polling Location Metrics

Factor Level							Average (Std. Dev.) of Average of Statistic			
V	E	Q	C	B	T	P	Line Length	Voters Inside	Wait Time	Sojourn Time
+	0	+	-	-	-	-	3679.6 (725.2)	198.2 (1.2)	109.5 (21.3)	115.4 (21.3)
+	0	+	-	-	-	+	118.8 (17.0)	5.3 (0.1)	130.3 (17.8)	136.4 (17.8)
+	0	+	-	-	+	-	5859.4 (706.5)	223.1 (0.5)	217.0 (25.9)	225.3 (25.9)
+	0	+	-	-	+	+	170.9 (18.6)	6.0 (0.0)	229.9 (24.8)	238.3 (24.8)
+	0	+	-	+	-	-	195.7 (130.6)	222.7 (9.4)	5.1 (3.2)	10.9 (3.2)
+	0	+	-	+	-	+	14.5 (6.0)	6.8 (0.3)	12.0 (4.6)	18.3 (4.7)
+	0	+	-	+	+	-	942.9 (372.0)	309.4 (13.1)	24.7 (8.9)	33.0 (8.9)
+	0	+	-	+	+	+	50.4 (15.3)	8.8 (0.3)	45.5 (13.2)	53.9 (13.2)
+	0	+	+	-	-	-	3679.6 (725.2)	198.2 (1.2)	109.5 (21.3)	115.4 (21.3)
+	0	+	+	-	-	+	118.3 (16.8)	5.3 (0.1)	129.5 (17.5)	135.6 (17.5)
+	0	+	+	-	+	-	5859.4 (706.5)	223.1 (0.5)	217.0 (25.9)	225.3 (25.9)
+	0	+	+	-	+	+	168.6 (18.1)	6.0 (0.0)	224.9 (23.6)	233.3 (23.6)
+	0	+	+	+	-	-	195.7 (130.6)	222.7 (9.4)	5.1 (3.2)	10.9 (3.2)
+	0	+	+	+	-	+	11.9 (5.1)	7.7 (0.6)	9.7 (3.8)	16.7 (3.9)
+	0	+	+	+	+	-	915.3 (363.6)	309.4 (13.1)	23.9 (8.7)	32.2 (8.7)
+	0	+	+	+	+	+	38.4 (12.0)	9.0 (0.3)	32.4 (9.6)	41.0 (9.6)

Table 18: Average (standard deviation) of the maximum polling location metrics for a full factorial design on factors C, B, T, and P. We find that PPE and associated health precautions (T) and less then the recommended number of check-in booths (B) will significantly worsen key metrics. Capacity (C) has relatively little impact compared to other factors but increases wait time and sojourn time while reducing the number of voters inside in some cases. Assuming the same number of resources, consolidating polling locations is beneficial.

Polling Location Metrics

Factor Level							Average (Std. Dev.) of Average of Statistic			
V	E	Q	C	B	T	P	Line Length	Voters Inside	Wait Time	Sojourn Time
+	0	+	-	-	-	-	136.0 (21.9)	141.9 (21.9)	6079.9 (877.9)	210.0 (1.6)
+	0	+	-	-	-	+	370.6 (34.8)	376.6 (34.8)	853.8 (84.0)	13.2 (0.2)
+	0	+	-	-	+	-	250.2 (26.4)	258.5 (26.4)	10083.5 (1239.2)	235.7 (1.3)
+	0	+	-	-	+	+	535.1 (40.2)	543.4 (40.2)	1075.2 (81.2)	14.6 (0.2)
+	0	+	-	+	-	-	7.2 (4.1)	13.1 (4.1)	1500.8 (518.3)	239.3 (10.1)
+	0	+	-	+	-	+	44.3 (15.3)	50.6 (15.2)	199.5 (48.3)	17.6 (0.6)
+	0	+	-	+	+	-	31.3 (10.5)	39.5 (10.5)	3013.1 (751.8)	332.7 (14.0)
+	0	+	-	+	+	+	125.0 (25.8)	133.4 (25.8)	340.9 (56.2)	23.2 (0.6)
+	0	+	+	-	-	-	136.0 (21.9)	141.9 (21.9)	6079.9 (877.9)	210.0 (1.6)
+	0	+	+	-	-	+	370.6 (34.8)	376.6 (34.8)	853.8 (84.0)	13.2 (0.2)
+	0	+	+	-	+	-	250.2 (26.4)	258.5 (26.4)	10083.5 (1239.2)	235.7 (1.3)
+	0	+	+	-	+	+	535.1 (40.2)	543.4 (40.2)	1075.2 (81.2)	14.6 (0.2)
+	0	+	+	+	-	-	7.2 (4.1)	13.1 (4.1)	1500.8 (518.3)	239.3 (10.1)
+	0	+	+	+	-	+	41.0 (14.0)	47.3 (13.9)	199.2 (48.3)	24.2 (3.2)
+	0	+	+	+	+	-	31.2 (10.5)	39.5 (10.5)	3012.1 (751.8)	332.7 (14.0)
+	0	+	+	+	+	+	111.0 (23.8)	119.4 (23.8)	338.4 (56.1)	23.3 (0.7)