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Halting Covid-19: PANDEMIC - A Predictive Model to Guide Response

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This is the second NRL Memorandum Report in a series about the new PANDEMIC model.

14. ABSTRACT
PANDEMIC is a new, time-dependent numerical model simulating the infectious spread of an epidemic in a heterogeneous, geographically dispersed region containing millions of people. Each individual can move from place to place and can interact with others while going to meetings (i.e. church or sports events), to places of work, to shop, and returning to or staying at home. The model uses an NRL-development, the Monotonic Lagrangian Grid (MLG), to track human proximity and calculate infection, viral transmission, illness and death. PANDEMIC was used to test the effects of human behavior patterns, including social distancing and quarantine strategies in the Washington DC Metropolitan region with 6.25 million people. Three 39-week scenarios from March 2020 through December 2020 are considered. These scenarios each had four stages marked by different activities to approximate what took place. Stage 1 was initially open and the covid-19 virus spread unchecked causing surge 1. Stage 2 was a 10 to 12-week lockdown down meant to blunt the first surge. Stage 3 was a limited more-or-less open period where surge 2 of the pandemic got started. Stage 4 was also a limited lockdown in all three scenarios with some school opening. Scenario 1 approximates what actually happened. Scenario 2 increases the strength of the lockdown measures, reducing the (extrapolated) national death toll from 325,000 to about 22,000. Scenario 3 further increases the strength of the mitigation measures, as was done in South Korea and Japan, showing what might have been achieved without testing or vaccines.

15. SUBJECT TERMS

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Andemic mitigation techniques	Detailed complex-environment simulation	Monotonic lagrangian grid

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Introduction

Techniques to mitigate the Covid-19 pandemic are well known.

- Personal measures that can only be enacted by the populace are:
    - Social distancing,
    - Wearing masks, and
    - Isolation including telework, virtual meetings, and remote learning
- Dedicated actions by local, state and national government are:
    - Forming, promoting, and enforcing public health mandates,
    - Testing, quarantine, and contact tracing,
    - Restrictions on and guidelines for safe gatherings and travel, and
    - Collective coordination of health care response
- Medical Science solutions still being developed and now available:
    - Vaccines, and
    - "Curative" medicines and treatments

What makes this battle both difficult to execute and complicated to predict, is that the results depend on the behavior of people who modify their actions depending on their changing perception of the situation. If people feel endangered, they tend to adhere strictly to prescribed precautionary measures, but if they feel safe, they begin to chaff at and ignore the restrictive precautions. The people generally know by now what they can and should do to reduce infections. Responsibly convincing them that these measures are necessary and effective is the collective role of the media, government, and their other leaders. Using this model on the local or state level can give decision makers scientific guidance to create effective policy. In addition, it lends scientific credibility to help convince the people they govern of the value of these precautionary actions and the importance of their vigilant adherence to them even when the situation appears to be improving.

We have developed this interaction-based simulation model PANDEMIC to test the effectiveness of the mitigation techniques listed above. Our research shows that the three personal measures – social distancing, wearing masks, and isolation - when diligently applied, could *on their own* suppress the Covid-19 pandemic. This solution is fragile, however, and small changes, either internally or externally, could have major consequences.

This is the second report on PANDEMIC. The first report (Boris, et al., 2021) includes a more complete description of the model, contains a number of references, and presents several recent, year-long simulations that show different possible outcomes of the third Covid-19 pandemic surge through February 2021. The PANDEMIC model, developed at the U.S. Naval Research Laboratory, can be adapted to any area in principal. This adaptation requires assembling the relevant information and entering it into the computer simulation initial conditions. This takes some effort and time but will be available almost without delay for other threats beyond Covid-19. Top-of-the-line laptops, desktops, and bigger parallel computers, when needed, are now powerful enough to execute simulations for large cities, entire states, or even the entire country in a couple of hours.

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The Washington DC Metropolitan Region - An Example

Using PANDEMIC, we performed detailed computer simulations of the DC Metropolitan region, taken here as a 100 kilometer by 100 kilometer square (approximately 60 x 60 miles) including Washington DC, Annapolis and Baltimore Maryland. Each of 6.25 million people in the area are represented in this model, about 2% of the United States population. The simulation advances in time for a specified number of weeks using timesteps of a few minutes duration. Listed below are the variables we included in the model:

- Each person has an age assigned demographically and a designated home location.
- Homes are placed to approximate a varying population density in the DC Metro area.
- Each person has a daily set of behaviors, statistically assigned, that includes where they go at different times - like school, shopping, work, church, etc. – and the distance traveled.
- The groups that a person works or congregates with depends on distance travelled, population density, and other factors. Personal separations while they are at gathering places are random each day so close interactions vary.
- Geographic variations in work patterns, jobs, types of housing, etc. can be modelled, including government mandates, when the appropriate databases are available.
- The probability of infection is always less than 100% and depends on exposure time and distance when two people are within the "social distance" and one of them is contagious. The social distance can be varied.
- Telework, virtual services, and remote learning are modelled by separate factors, each between 0 and 100 percent, that determine the fraction of potential participants in each activity that work from home or attend the meeting virtually.
- Mask use is modelled by reducing the probability of infection during close interactions using a "mask effectiveness" factor between 0 and 100 percent. Mask effectiveness can vary in time based on changing mandates or population response.
- A simple testing protocol is implemented with several adjustable parameters but contact tracing currently is not yet implemented.

In modeling people's daily travels, interactions are computed between pairs of people that are near enough at any time to have a significant probability of transmitting the infection. The probability of infection is finite when two people are within the "social distance" and one of them is contagious. This social distance parameter can be varied. Once infected, a person's "viral load" grows until an "immunity threshold" is reached based on the person's age and susceptibility. During the growth phase, a person passes an "isolation level" at which their condition becomes known through symptoms or testing and they self-isolate or are quarantined in the model. In the isolation/quarantine state, people can no longer participate in transmitting the virus even though they may still be contagious. If their immunity threshold is low enough, the person begins to recuperate, due either to medical care or natural immunity, and their viral load begins to dwindle. If the immunity threshold is too high, the person dies, becoming permanently inactive in the PANDEMIC model.

Three detailed computer simulations follow, presenting different scenarios of the Covid-19 epidemic now impacting the DC Metro area. These simulations illustrate the effectiveness of the three personal measures: mask wearing, social distancing and isolation (implemented through telework, virtual meetings, or withdrawal from a daily routine) to reduce the impact of the current pandemic.

Our primary conclusion is that prompt coordinated action pays big dividends in combatting such an epidemic. Whenever these three personal mitigation measures are followed diligently by the populace for a sustained duration, they are very effective in halting the epidemic. For Covid-19, the delay between initial infection and the appearance of indisputable symptoms is long enough that an infected person can cause several other people to become infected in an open society that is not adhering to these key mitigation measures. Aggressive testing, when possible at large-enough scale, is a governmental function that can solve this delay problem. Without testing, it may be too late to avoid a serious outbreak once there is compelling evidence, such as fatalities. However, implementing these mitigation measures still saves many lives and with persistent adherence ultimately halts the epidemic.

Figure 1 below shows a projection of the current situation through December 2020. Each day is marked by a vertical grey line on the figures. Explanatory labels are added across the top of the plot to aid with interpretation of the sequence of stages in modelling changing societal responses. The blue curve shows the number of infected contagious people (vertical axis) as a function of time, measured along the horizontal time axis. These are active infections at each day, not the total number of cases or the daily number of new cases as are often displayed. The orange curve is the number of people whose viral load has become large enough and their symptoms severe enough that they are quarantined (or simply self-isolate in bed) and thus they can no longer infect others. Red indicates a still higher viral load where typically hospital care is required. The black curve is the cumulative number of deaths. The green curves relate to two stages of "immunity" where the individual is on the path to recovery from Covid-19 and their viral load is reducing. The dark green curve "high viral load" immunes are potentially contagious but still isolated or in quarantine. The low viral load immunes are no longer isolated but still contagious, a threat to others, until their viral load drops below a low threshold.

This Scenario 1a (Figure 1) is our base line simulation of what has happened since March through mid-December 2020. It predicts that about 6500 people in the Washington DC Metro area will be dead by Christmas. Based solely upon population, this extrapolates to about 325,000 deaths in the nation, a number that is close to the Institute for Health Metrics and Evaluation statistics recording 332,000 deaths by December 19, 2020 (https://www.worldometers.info/coronavirus/country/us/). Fig. 1 is plotted in a logarithmic scale because of the wide range of possible values for the quantities being compared as parameters of the four scenario stages are varied.

After three months of strong pandemic mitigation measures from April to the middle of June, which were applied in the PANDEMIC Scenario 1a as 70% telework (i.e. isolation) and 20% effective mask use, the U.S. relaxed the mitigation mandates in June, July and August in an attempt to reopen. We reflected this relaxation in the simulation as 30% telework (many fewer people staying home) but slightly increased effectiveness in wearing masks (M_e). A few weeks later, now using the simulation to predict forward into the future, the mounting death toll triggers another but less universal lockdown (increasing telework to 50% while maintaining mask

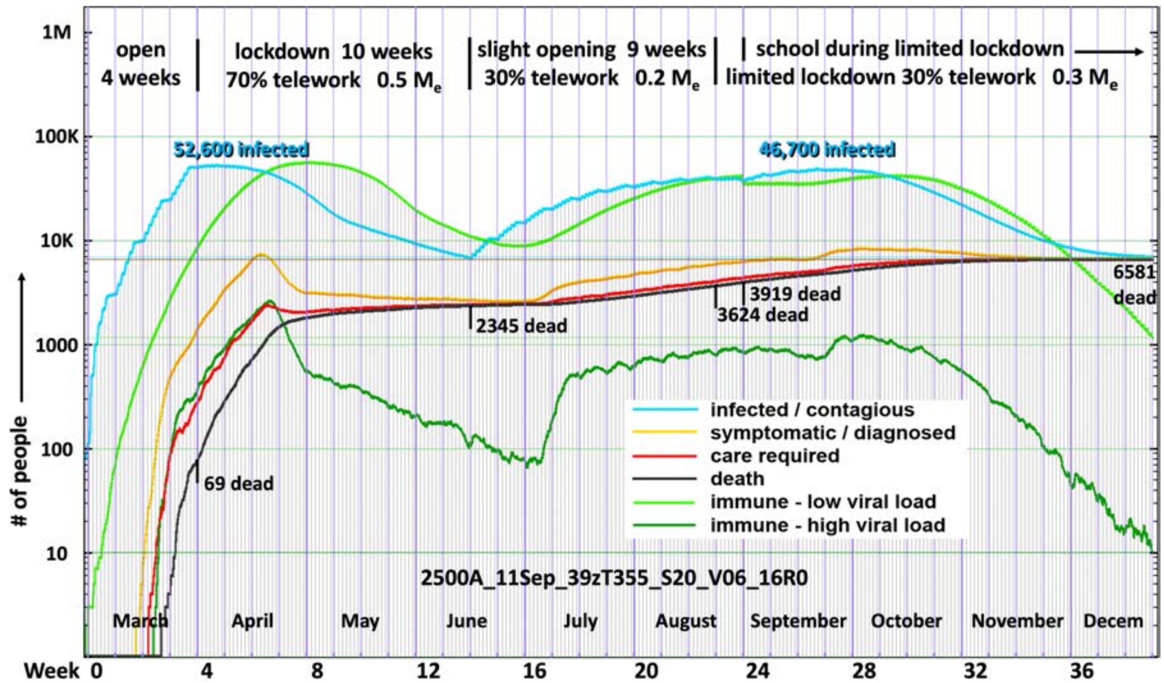

Figure 1: 39-Week simulation of the Covid-19 epidemic projected through Christmas 2020. After a 10-week lockdown from April into June, a slight 9 week re-opening requires a 2nd lockdown through December. 6581 deaths for the Metro region scales to about 325,000 deaths for the nation.

wearing at 30% effectiveness. Initially many schools reopened but many (most) shutdown again following spikes in new Covid-19 cases. As in the first peak through April and May, the several-week delay between exposures and the resulting increase in symptoms and death counts means that by the time the mitigation measures are tightened back up in September, the damage has already been done and the death toll in the DC Metro area reaches 6581 by December 20th.

A variation of this first baseline prediction, Scenario 1b, was also simulated, in which the population adheres more strictly to the personal mitigation measures moving forward into the fall by wearing masks, maintaining social distancing and isolating. This is reflected in the model by increasing mask use to 60% effectiveness and telework percentage to 80% in September (week 23) and maintaining them through the end of the simulation. The plots for Scenario 1b are not shown because they look qualitatively very similar to Figure 1 and are identical for the first 7 months. However, the death count, which grows rapidly into September and beyond in Scenario 1a (Figure 1), flatlines from October through December in Scenario 1b at about 5000 total deaths rather than continuing to grow to over 6500. This modified scenario shows that stricter adherence to the personal mitigation measures can reduce the impact of the pandemic whenever they are implemented and can avoid about 1500 additional Covid-19 deaths through the end of the year. If stricter adherence were achieved universally, the simulation predicts that the 1500 lives saved in the DC Metro region roughly extrapolates to 75,000 people saved nationwide.

The size and diversity of the DC Metro region and the number of people in it suggest that the PANDEMIC model, structured here for a limited geographic region, may be an acceptable predictor for the country as a whole even though these scenarios only contains 2% of the U.S.

population. One partial verification of this is to compare the simulated and actual percentage of infections that resulted in death. For the United States on September 12, 2020, there were 6.66 million cases resulting in 198 thousand deaths. Thus death occurs in 2.97% of the cases. In PANDEMIC's model of the DC Metro region through December, death is predicted to occur in 3.1% of the 213,000 cases. This reasonable agreement provides a measure of confidence in these projections.

The Benefits of Quick Coordinated Response

Scenarios 2 and 3, discussed below, illustrate more highly coordinated responses to the pandemic and begin earlier than actually occurred last spring. These postulated collective responses were continued through December to illustrate how much can be gained by prompt, more complete action using the three measures that people can personally execute. We show that when the personal measures are enacted promptly, the numbers of cases and deaths can be significantly reduced even without additional technological enhancement to the collective response. The total number of fatalities among the 6.25 million people simulated in the metro area could have been as low as 400 from the same starting conditions, just a small fraction of 1% of the metro area population, as shown in Figures 2 and 3. This reduced overall death toll extrapolates to onle about 20,000 deaths in the entire country.

In today's real world the death count is certainly going to be more than ten times greater than 400, as shown by Scenario 1 and other projections. The two scenarios, pictured in Figures 2 and 3 below, assume a prompt lockdown response when a dozen or so symptomatic contagious cases were first detected. These more optimal outcomes involved mandated mask use and universal telework after the 2nd and 3rd week in March respectively. In both of these simulated scenarios, on average, mask use was assumed to be 50% effective with 80% of commuters and other people isolating themselves and working virtually (80% telework). However, extra social distancing was not enforced. Whenever two people would come within 2 meters of each other, viral transmission has a probability of occurring and this probability increases with the time they are close to each other.

Figure 2 below shows a contrary-to-fact mitigation scenario in which we assume accurate information was available early in the pandemic and that the populace was urged (mandated) to act upon it decisively. By the middle of March there were about 8 or 10 symptomatic Covid-19 cases in the Washington DC Metropolitan region. But, because of the infection's up to 2-week incubation period, we had no idea how many people had already been infected. In the Scenario 2 PANDEMIC simulation, we discover that almost 4200 people were already infected and likely contagious, but they were generally not yet symptomatic. However, word actually did go out in the middle of March to many agencies and businesses, mandating full-time telework, social distancing, and mask use. This appropriate response did not spread to the entire population. Further, some groups, providing necessary food, delivery, and medical services, had to interact with people in their jobs and did so in as safe a manner as they could. Unfortunately, in today's world, some groups also feel free to ignore the recommended Covid-19 mitigation strategies, which reduces their overall effectiveness.

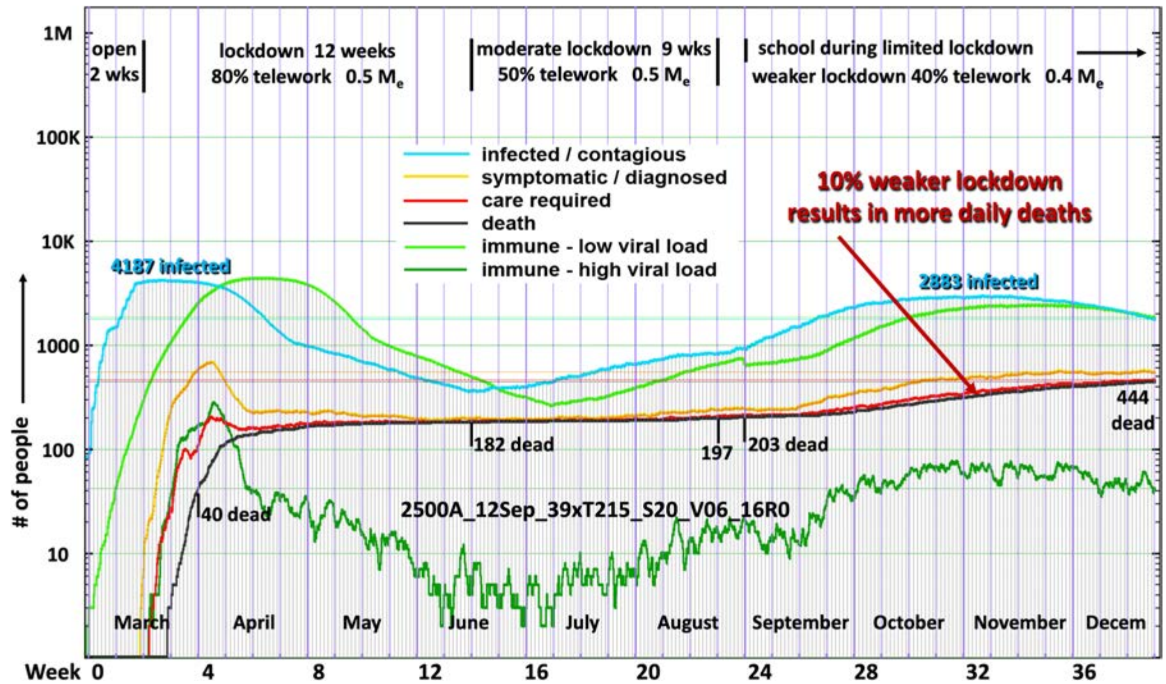

Figure 2: 39-Week simulation of the Covid-19 epidemic projected to Christmas 2020. After a strong lockdown from April into June, a weaker 9-week lockdown induces a 2nd infection peak when school is opened into December. 444 deaths for the region scales to about 22,200 deaths for the nation.

Scenario 2 in Figure 2 enacts a 12-week lockdown averaging 80% telework, after the second week of essentially unrestricted Covid-19 transmission. 80% telework is not quite universal, but it represents a populous where most of the people are taking this threat seriously by working from home while their children were trying to learn virtually from home until school closed. As Figure 2 shows, the growth in the number of active infections stopped and then dwindled until week 14, in the middle of June when the lockdown was relaxed to a moderate 50% mask effectiveness and telework.

The rush of initial infections had resolved itself with about 180 dead. In week 23 the mask effectiveness and the telework fraction were both reduced further to 40% representing an additional easing of the lockdown. As a result, the death count doubled in the last 13 weeks of the scenario. Whether an epidemic is unstable (i.e. growing) or stable (flatlined) is highly sensitive to the actions of the population as a whole. It does not take many people not wearing masks, for example, to keep the pandemic going.

Scenario 3 (Figure 3 below) enacted the initial lockdown, now only 11 weeks long, after the virus had spread freely for the first three weeks. Reacting in three weeks may be a more realistic response time for an entire population. Unfortunately, after the three weeks about 8000 people are already infected, twice the number infected a week earlier. Of these 8000, 200 were symptomatic, and a half dozen deaths had occurred by the beginning of the week 3 (the fourth week).

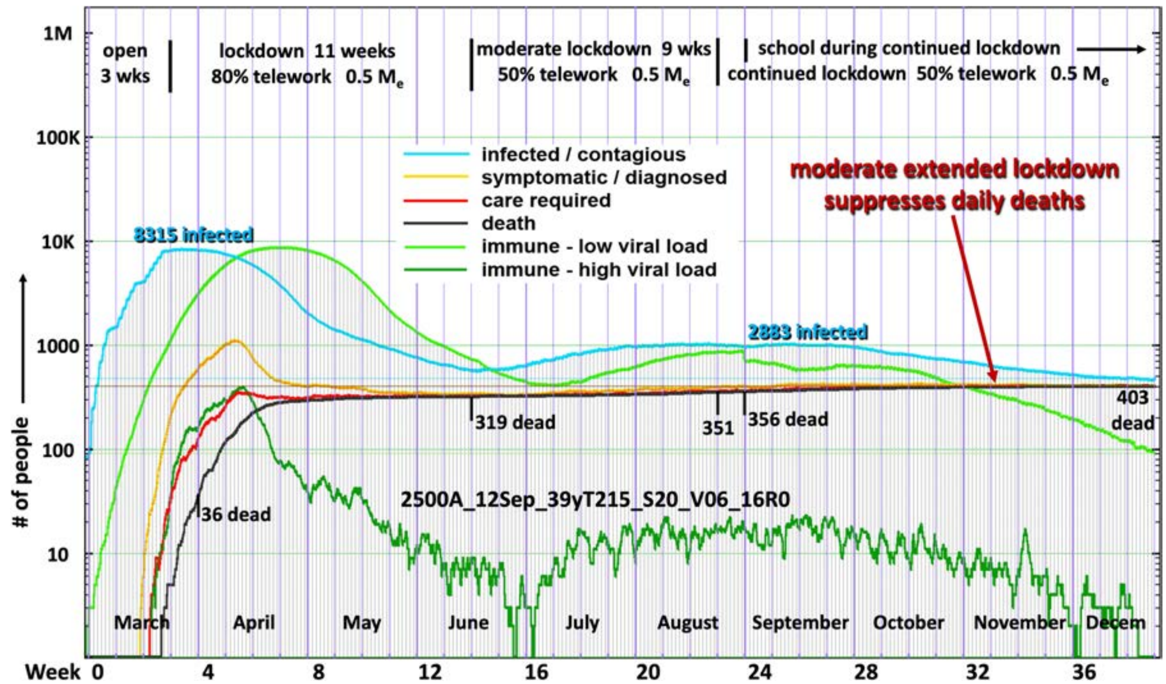

Figure 3: 39-Week simulation of the Covid-19 epidemic projected to Christmas 2020. After a strong lockdown from April into June, a weaker extended lockdown allows minimal additional infections despite school opening. 403 deaths for the region scales to about 20,000 deaths for the nation.

Through week 22 the indicators for Scenario 3 were all worse than Scenario 2. However, the mitigating safety measures were not relaxed in week 23 as in Scenario 2. As a result of this small 10% increase in mask use and telework percentage, only 403 deaths occurred by December, actually somewhat lower than in Scenario 2. In all three scenarios students went back to school on week 24 with the fraction of remote learning (i.e. telework) as specified on the figures. A noticeable increase in the infection counts can be seen after week 24 in Figures 1 and 2. This effect is much smaller in Figure 3 because both the mask use efficiency and the telework fraction are larger at the end of this third scenario.

Scenario 1 (Figure 1) implemented the initial lockdown after 5 weeks when the death toll had reached almost 100, as roughly occurred in reality. Because there is a long delay between when the virus is first transmitted and the death toll begins to mount, Figures 2 and 3 show that it is crucial to act quickly when the initial infectious transmissions first become symptomatic. It is clearly essential to have accurate information early in an epidemic about the nature and danger of the threat. For this reason, a strong testing protocol can be an important contributor to early and effective response. for example, in housing blocks and dormitories, waste or sewage water can be tested at a few locations and can give a very early indicator of infections in the building. In colleges and universities where students were tested on coming back to campus and the housing and major meeting buildings are waste-water tested, the epidemic has been effectively held in check and the schools are remaining open.

A testing protocol is a government capability that can initiate and control effective, prompt responses and adjustments to an epidemic. When a new threat comes along, however, a useful test for the presence of the infection when it precedes the obvious medical symptoms, is usually not available and must be developed. In the three main scenarios considered here, some testing was implemented beginning in week 24 as testing was being implemented for the DC Metro region in real life. In PANDEMIC a fraction of the people can be tested each week and any active Covid-19 infections found by testing were placed in isolation/quarantine after a 5-day processing delay. The PANDEMIC model has no contact tracing capability yet, but does keep data, recording who infected whom and when it happened. In the future software could be imported to allow contact tracing and quarantine capability in the simulation and to simulate aspects of local, regional, and global government travel restrictions.

Conclusion

Our model supports the core conclusion that prompt coordinated action pays big dividends in combatting an epidemic. The delay between initial infection and the appearance of indisputable symptoms is long enough in Covid-19 that an infected person can cause several other people to become infected in an open society that is not adopting these key mitigation techniques. The benefit of a person-to-person, interaction-based model such as PANDEMIC, based on real world variables and behaviors, is that the population and its governing officials can better see the results of their actions. They can see how long it will take to halt the epidemic if they take strong actions and the importance of small increases in compliance in stopping the unstable growth of the pandemic. They can test how to relax restrictions while maintaining an acceptable risk level.

Three 39-week scenarios from March 2020 through December 2020 are considered. These scenarios each had four stages marked by different activities to approximate what took place. Stage 1 was initially open and the Covid-19 virus spread unchecked causing surge 1. Stage 2 was a 10 to 12-week lockdown down meant to blunt the first surge. Stage 3 was a limited more-or-less open period where surge 2 of the pandemic got started. Stage 4 was also a limited lockdown in all three scenarios with some school opening. Nevertheless, the third surge was initiated. Scenario 1 approximates what actually happened. Scenario 2 increases the strength of the lockdown measures, reducing the (extrapolated) national death toll from 325,000 to about 22,000. Scenario 3 further increases the strength of the mitigation measures, as was done in South Korea and Japan, showing what might have been achieved without vaccines by near universal and responsible mask use.

Scenario 1 is certainly not a worst case, which would be doing nothing or not “shutting down” in any way. The model was also used to predict such a worst case. For example, when 0% telework and 0% mask wearing was implemented in PANDEMIC from March through December throughout the DC Metro area, nearly one half of the population became inflected quickly and 3% of these died, about 90,000 people. Social distancing was not enforced beyond the 2-meter maximum distance allowed for infection to occur, an integral part of the viral-transmission calculation. PANDEMIC showed that doing nothing could have cost 4.5 million deaths nation-wide.

However, we note, this time in the people’s favor, such a dire outcome probably would not happen with Covid-19. Unlike fast killers like Ebola, this virus has a long incubation time and spreads slowly enough that people would change their behavior defensively, even without being told to do so, if the death toll continued to rise. They would surely “hunker down” rather than ignore what was happening to so many of those around them. As a result with no otherwise mandated action, the casualties would certainly have been less than 90,000 in just the metro region.

Table 1 below summarizes some of the Covid-19 case counts from the four scenarios considered: Scenario 1a (red), Scenario 1b (red to blue), Scenario 2 (yellow), and Scenario 3 (green) to compare what the current pandemic has done or could have done in the Washington DC Metropolitan region through mid-December. The Scenario 1 simulations agree reasonably closely through the first four months of the pandemic with what has transpired. Figures 2 and 3, as captured in the table, also present the corresponding results had the personal mitigation techniques been employed systematically much earlier. These results, specifically intended to apply to a representative but limited area, home to about 2% of the United States population of 330 million people, were extrapolated to the entire U.S. and agree reasonable closely with other projections for Scenario 1.

Table 1. Numbers of Contagious, Symptomatic, and Deceased People in 3 Scenarios

Approx. Date	1 April	1 May	1 June	1 July	1 Aug	1 Sept	1 Oct	1 Nov	1 Dec
1A. # contagious	50798	30082	9529	14833	33098	38446	47196	22764	8607
# symptomatic	1432	3193	2744	2604	4632	6183	8133	7649	6685
# deaths	78	1784	2246	2416	2890	3919	5103	6244	6547
1B. # contagious	50798	30082	9529	14833	33098	38446	10928	5084	5012
# symptomatic	1432	3193	2744	2604	4632	6183	5160	4946	4946
# deaths	78	1784	2246	2416	2890	3919	4898	4936	4939
2. # contagious	3997	989	489	396	657	927	2293	2881	2579
# symptomatic	598	228	197	193	212	249	341	482	550
# deaths	40	163	180	185	189	203	226	311	444
3. # contagious	8142	2157	768	628	966	967	961	692	522
# symptomatic	609	402	344	336	370	402	418	415	408
# deaths	36	292	318	324	335	356	380	394	400

Table 1: Results of 39-Week simulations of the Covid-19 epidemic projected to Christmas 2020. After a strong lockdown from April into June, a weaker extended lockdown allows minimal additional infections despite school opening. 400 deaths for the region scales to about 20,000 deaths for the nation. Nationwide statistics are about 50 times larger than in Table 1.

The new model used here, PANDEMIC, can run on high-performance parallel computers, desktops, and laptops, and will be described in an upcoming publication. The few pages here are offered to demonstrate the use of this model for understanding the current pandemic. They show what could have happened as best and worst case scenarios, what appears to be happening now, and what can possibly be done to reduce the undesired consequences moving forward. Hopefully this capability can provide guidance for the future, to urge a continued collective vigilant response today, and so that prompt appropriate action is taken should we face another pandemic.

In light of recent developments, a number of extensions and modifications of PANDEMIC are required to implement new information. Fast testing protocols, contact tracing, new Personal Protective Equipment (PPE), new information about the reduced transmission of Covid-19 outdoors, and about the performance of the several vaccines available can all be implemented.

A version of PANDEMIC, adapted to your city or region, could be developed. Only 17 of the 50 states contain more people than the DC Metropolitan area and thus might require a more powerful computer than a laptop. For more information, contact Dr. Jay P. Boris at jay.boris@nrl.navy.mil.

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