Member's Paper

The Future of COVID-19 in Ontario: Variants, Vaccines, and Avoiding Future Waves

COVID-19 Risk Factors in the Province of Ontario

By
The CIA Pandemic Modelling Project Team

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Executive Summary

Throughout the COVID-19 pandemic, the one consistent theme has been the constantly changing environment, making it difficult to predict future outcomes. These changes have included new variants that are more infectious, the impact of vaccines, seasonality, and dynamic government intervention measures. On top of the introduction of new variables over time, there has also been new information on the known factors.

Further, with each of these factors, we do not have a comprehensive understanding of their impact: we do not know exactly how infectious each variant is, nor do we know the level of vaccination required for herd immunity or how that level changes from summer through the fall.

To understand the COVID-19 pandemic in the face of these uncertain factors, this paper explores a variety of scenarios for Ontario where key assumptions are varied and the outcomes of the pandemic are presented. These scenarios show a range of possible future outcomes that may be realized over the coming year.

Analyzing the scenarios collectively provides a different perspective than looking only at the most likely scenario. Most notably, our findings indicate that vaccination rates nearing 90% of total population may be required to prevent a fourth wave in late 2021 – driven by seasonality – depending on how infectious variants are and actual vaccine effectiveness against those variants. This implies that in order to mitigate a fourth wave, everyone who is currently eligible would need to get fully vaccinated. The knowledge that this potential future wave can be mitigated highlights the importance of setting higher targets for vaccination and continuing to ensure the public follows through on second doses through the summer and fall.

Résumé

Tout au long de la pandémie de COVID-19, la seule cohérence a été l’évolution constante de l’environnement, ce qui rend difficile de prévoir la suite des choses. Ces changements comprennent notamment l’apparition de nouveaux variants plus infectieux, l’impact des vaccins, la saisonnalité et les mesures dynamiques d’intervention gouvernementale. Outre l’introduction de nouvelles variables au fil du temps, de nouvelles informations ont été publiées sur les facteurs connus.

Par ailleurs, pour chacun de ces facteurs, nous ne comprenons pas tout à fait leur impact : nous ne savons pas exactement à quel point chaque variant est infectieux et nous ne connaissons pas non plus le taux de vaccination nécessaire à l’immunité collective ni comment ce taux change de l’été à l’automne.

Pour comprendre la pandémie de COVID-19 face à cette incertitude, nous explorerons dans le présent document plusieurs scénarios valables pour l’Ontario et selon lesquels les hypothèses clés varient, puis nous présenterons les résultats de la pandémie. Ces scénarios font ressortir divers résultats qui pourraient se concrétiser au cours de la prochaine année.

Plus particulièrement, nous avons constaté que des taux de vaccination de près de 90 % de la population totale pourraient être nécessaires pour prévenir une quatrième vague en fin d’année 2021 en raison de la saisonnalité. Cela dépendra de l’intensité de l’infectiosité des variants et de l’efficacité réelle des vaccins contre ces derniers. Cela implique que pour atténuer une quatrième vague, toutes les personnes actuellement admissibles devraient se faire vacciner complètement. Le fait que cette éventuelle vague puisse être atténuée souligne l’importance d’établir des cibles de vaccination plus élevées et de continuer à veiller à ce que la population reçoive une deuxième dose pendant l’été et l’automne.

L’objectif de la modélisation est d’aider les autorités de santé publique à mieux gérer la pandémie en identifiant les principales variables de risque :

The objective of the modelling is to help public health authorities better manage the pandemic by identifying the key risk variables:

- Vaccines are the only reasonable approach to end the pandemic in the near-term:
    - Reaching herd immunity without vaccines would be very difficult and would have large impacts on public health.
    - Global vaccine rollouts would help suppress the emergence of new variants by reducing the number of infections.
- Public willingness to vaccinate is currently the most important factor in Ontario:
    - Vaccine supply levels are projected to be sufficient, even with significant decreases in shipments.
    - To reach herd immunity in the near term, a high percentage of the population must be vaccinated.
    - Willingness to vaccinate can be influenced through government action.
- Government interventions provide short-term relief and can prevent health-care system overrun:
    - It is very difficult to eliminate disease with interventions alone.
    - When interventions are lifted, infections will continue to spread at an exponential rate.
- Unvaccinated individuals will be at increased risk in future waves:
    - Variants are more dangerous than the original “wild type” strain.
    - Intervention levels are expected to be lower because the vaccination rollout will reduce stress on the health-care system.

- Les vaccins sont le seul moyen raisonnable de mettre fin à la pandémie à court terme :
    - Il serait très difficile d’atteindre l’immunité collective sans vaccin, ce qui entraînerait des répercussions importantes sur la santé publique.
    - La vaccination à l’échelle mondiale aiderait à supprimer l’apparition de nouveaux variants en réduisant le nombre d’infections.
- La volonté de la population de se faire vacciner est actuellement le facteur le plus important en Ontario :
    - Les stocks de vaccins devraient suffire, malgré la baisse importante des livraisons.
    - Pour atteindre l’immunité collective à court terme, un pourcentage élevé de la population doit être vaccinée.
    - La volonté de se faire vacciner peut être influencée par des mesures gouvernementales.
- Les interventions gouvernementales offrent un répit à court terme et peuvent prévenir le débordement du système de santé :
    - Il est très difficile d’éliminer la maladie au moyen d’interventions seulement.
    - Lorsque les interventions seront levées, les infections continueront de se propager à un taux exponentiel.
- Les personnes non vaccinées courront un risque accru au cours des prochaines vagues :
    - Les variants sont plus dangereux que la souche originale « de type sauvage ».
    - Les niveaux d’intervention devraient être moindres, car la mise en œuvre de la vaccination réduira le stress sur le système de santé.

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Note to reader

Given that the biology of the COVID-19 virus was evolving more quickly than the authors of this paper could update their model and capture and analyze the results, the authors decided to limit the scope of this research paper to phase 1, which ended on April 1, 2021. Although important, the emergence of the Delta and other variants are not part of the scope of this research paper but should be considered for future research on this topic. Despite the timeframe, the authors strongly believe that the insights, findings, and recommendations conveyed in this research remain highly relevant and useful to actuaries, decision-makers, and the public.

Introduction

Throughout the COVID-19 pandemic, there have been many models and research projects predicting COVID-19 outcomes. Almost every province and the federal government have released projection figures with regards to testing, new cases, hospitalization, ICU occupancy, deaths, vaccinations, and recoveries. For the most part, these projections have been developed by experts in health ministries, provincial public health bodies, and researchers at various universities across Canada. Given the actuarial expertise in predictive analytics and risk modelling, the Canadian Institute of Actuaries (CIA) called for volunteers to explore how actuaries could also contribute to the research. Recognizing that many models had already been developed by the subject matter experts, the scope of our analysis was to leverage an existing model to provide additional insights into risk assessment and mitigation to this pandemic.

We reached out to researchers and governments in Alberta, British Columbia, Ontario, and Québec to see if they would be interested to collaborate. Ontario responded to our call in the form of a research team from the University of Toronto comprised of Drs. Ashleigh Tuite, David Fisman, and Amy Greer. Their model, "Mathematical modelling of COVID-19 transmission and mitigation strategies in the population of Ontario, Canada," is the foundation of our research paper and analysis.

Given that our starting model was for Ontario, our research paper and the analyses also pertain to COVID-19 risks specifically in the context of Ontario. Nevertheless, we believe that several of our findings and conclusions apply to other jurisdictions as well. We studied the starting model to assess and understand its strengths and shortcomings. Assumptions were updated based on the actual experience data and variables were added to reflect newly available information since the development of the original model. We hope our research paper will provide the public and governments with an enhanced understanding of the interaction and relative impact of various COVID-19 risks.

Part A: Model explanation

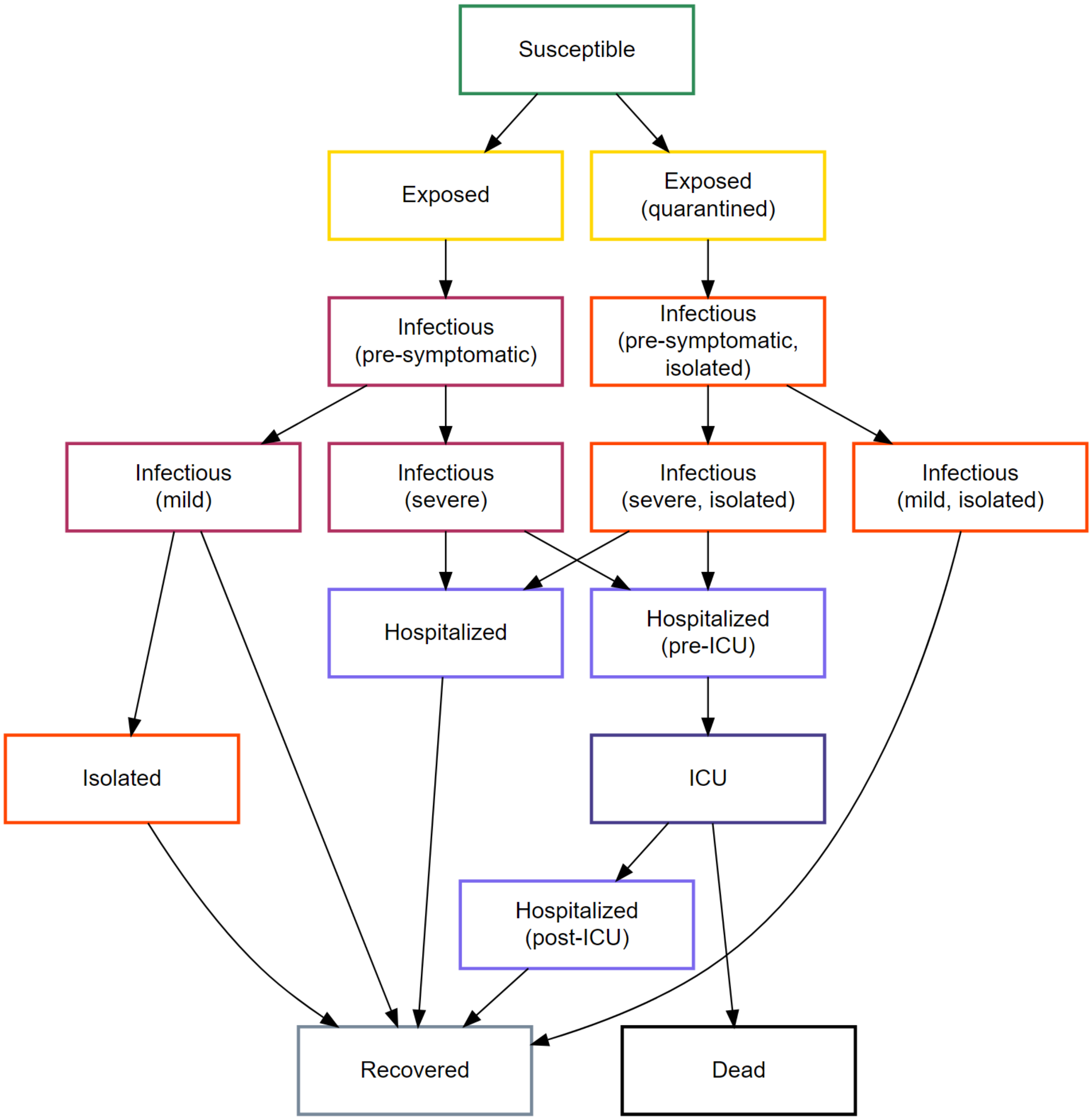
Original model

The analyses included in this paper used a model[1] for the spread of COVID-19 in Ontario – originally developed by Drs. Ashleigh Tuite, David Fisman, and Amy Greer – and was revised as required to meet the needs of this paper. The qualifications and credentials of the original model developers gave us confidence that the underlying framework is based on sound epidemiological principles while enabling us to make modifications to the model to analyze risks effectively.

The model, "Mathematical modelling of COVID-19 transmission and mitigation strategies in the population of Ontario, Canada," is developed in R using a modified "susceptible-exposed-infectious-recovered" framework with additional compartments to incorporate public health interventions, varying severities of clinical symptoms, and the risk of hospital admission. While the back-testing against the experience in Ontario showed the need for model calibration, the model provided the foundation for assessing the importance of physical distancing and enhanced case findings. It also allowed for fixed-duration and dynamic interventions based on projected occupancy of intensive care units, with a random walk to capture super-spreader events.

[1] https://www.cmaj.ca/content/192/19/E497

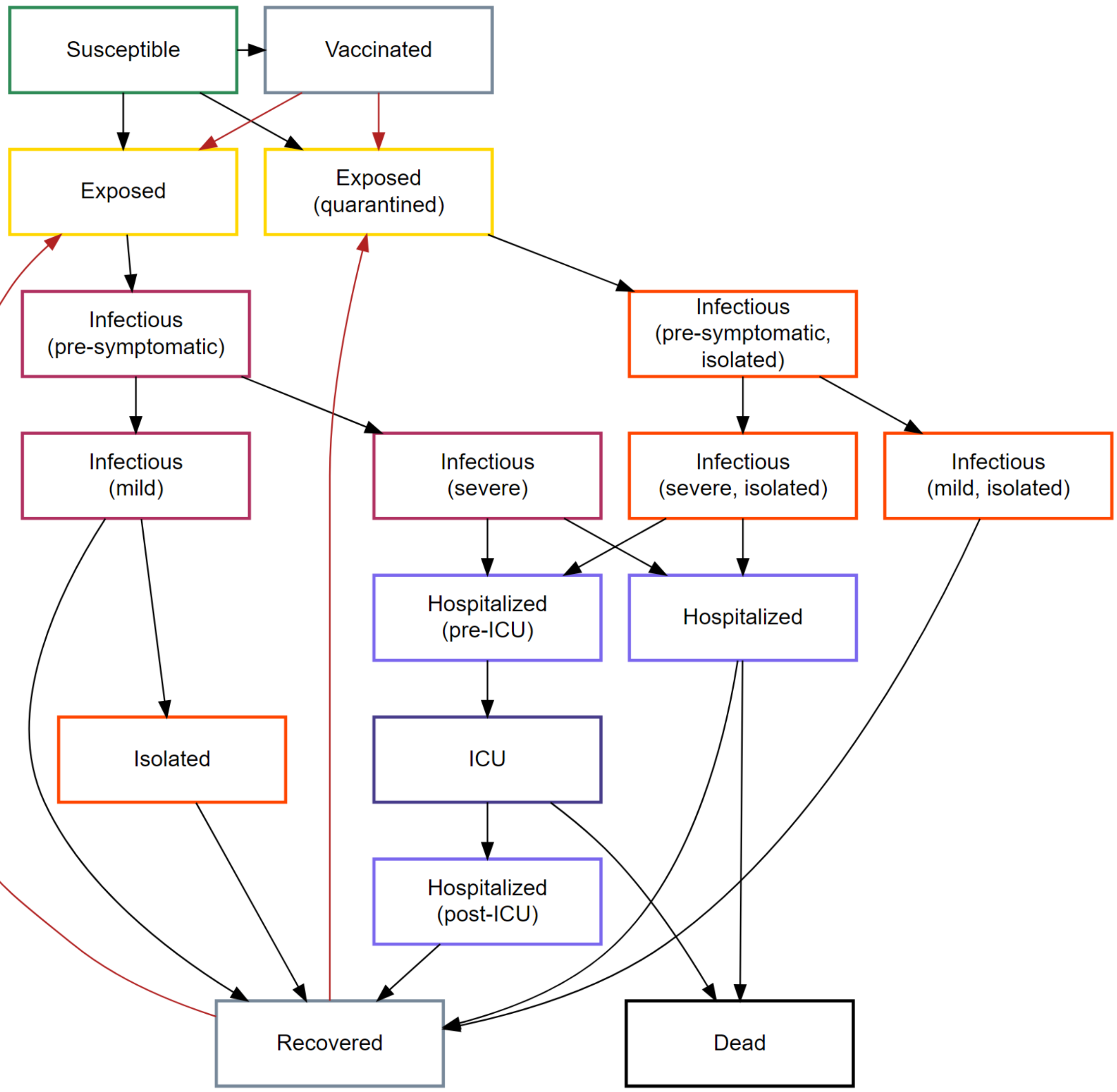
Figure 1: Original model framework



Model updates

The model was enhanced by the authors to incorporate additional factors that influence the spread of COVID-19. The enhancements were determined based on preliminary analyses and judgment was also required in qualitatively assessing their significance. Figure 2 shows the revised model framework.

Figure 2: Revised model framework



Seasonality

Given the timing of the second wave, and seasonality being a key factor in modelling spread of viruses in general, we felt it was appropriate to add seasonality[2] to the model. We observed increased cases during the colder months and decreases in the warmer months. With this, it was necessary to apply seasonality to the infection rate to fit the experience data. While there could be many possible reasons

[2] https://www.pnas.org/content/117/44/27456

for the seasonality experience observed, our analysis focused on the observed impact of seasonality, not the cause. As such, the seasonality effect is modelled as a sinusoidal function dependent on the date in the year, not other factors such as temperature, humidity, etc.

Deaths from the non-ICU hospitalization compartments

The original model assumed that all deaths only occurred from ICU. In our analysis, we found that a significant number of deaths occur outside of the ICU. To better fit the experience, the model was revised to allow for deaths in the two hospitalization compartments: "Hospitalized" and "ICU."

Calibration against experience in Ontario

The original model was built at the beginning of the pandemic and therefore did not include an approach to populate the various compartments in the model. For our analysis, we calibrated the model to use the reported Ontario figures from April 2020 to February 2021 with an adjustment to account for underreporting of active cases. To reasonably allocate the infection statistics across age and health demographics, we used the population, probability of infection, and probability of severe infection.

Updated assumptions

Given the quickly evolving COVID-19 data due to its novel nature, we noted some of the original assumptions were out of date. Using available Canadian[3] and Ontario data,[4] we updated the probability of severe infection, ICU admittance, and death, as well as the average length of stay in the ICU and post-ICU compartments.

Vaccinations

The vaccine rollout in 2021 quickly became a critical component in managing the virus spread. Ontario's vaccine rollout plan was added to the model, incorporating the vaccine effectiveness, dose requirements, susceptibility period, willingness to vaccinate, and the priority order in which populations would be vaccinated. The vaccine effectiveness was further split into protection against mild and severe cases, to better capture variant situations. Studies conducted during our research found that vaccines remained highly effective at preventing severe infections from variant strains,[5] despite lower effectiveness against mild infections.

Higher death rate during ICU overcapacity

It is important to recognize that when the health-care system is overrun, death rate will increase with limited medical resources. This was captured in the model by increasing the probability of death for cases above the ICU capacity.

The degree to which mortality will increase in a situation where the health-care system is overrun is unclear. After looking at global situations where ICU overcapacity occurred, we believed a 500% multiplier on the probability of death was reasonable. This multiplier is illustrative and is only relevant in adverse scenarios. The dynamic intervention strategy was designed to prevent this situation from arising in reasonable scenarios.

[3] https://health-infobase.canada.ca/covid-19/epidemiological-summary-covid-19-cases.html?stat=num&measure=total_last7&map=pt#a2

[4] https://covid-19.ontario.ca/data; https://data.ontario.ca/dataset/status-of-covid-19-cases-in-ontario

[5] https://www.nejm.org/doi/full/10.1056/NEJMc2104974

Susceptibility after vaccination/recovery

The model previously assumed the recovered population was no longer susceptible. As new variants emerged, it became important to recognize that vaccinated and recovered people remain susceptible to infection.[6] The model was updated, accordingly, to allow for reinfection.

Interventions

Public interventions play a critical role in the spread of COVID-19. The intervention framework of the original model was based on ICU count and was limited to a single lockdown level. This means that the population is either in a locked-down situation or living a normal life. As we have experienced and supported by the data, the rules enforced by the government have been more complex than this binomial approach. The dynamic intervention method in the original model was expanded to have three government intervention levels based on ICU count and new infections. This revision does not directly map to Ontario's approach but fits the data better and provides reasonable projections. The three levels were fit to the observed data after the "no intervention" parameters were established. These factors linearly scale the rates of transmission. The parameters for each level vary by age but can be summarized into the following groups at a high level:

Table 1: Relative social contact rate by intervention level

Intervention level	Relative social contact rate
No intervention	100%
Low	50%
Moderate	40%
Strict	30%

Variants

The rise of variants in 2021 shifted our focus from vaccines and other risks to variants. The original model was designed for shorter-term projections at the beginning of the pandemic and could not capture multiple strains of the virus.

To accommodate the variants in our projections, we introduced additional compartments to track variants. For our analysis, we seeded variants into the model with an assumption that 1 in 1000 infections on March 1, 2021, were from a variant. The variant infections have separate transmissibility and vaccine effectiveness assumptions and would grow in prevalence over time.

Note that, for simplicity, the variant compartments have not been reflected in the revised model framework diagram.

[6] https://www.statnews.com/2021/05/13/vaccines-work-variants-complicated/

Part B: Model risk and uncertainty

With pandemic risk modelling, further to the uncertainty in the factors within our awareness, we need to be mindful of other factors that are unknown to us when we forecast future outcomes. This stems from the novel nature of the virus, with experts researching the virus as the situation unfolds and evolves in parallel. This naturally means there is limited reliable data available for modelling. While we may be able to use historical data from similar pandemics and apply a general pandemic modelling framework, significant judgment needs to be applied to capture the uniqueness of each pandemic.

We have highlighted below the key risks that could contribute to large differences between our COVID-19 model's projections and the actual outcomes observed in Ontario. Overall, with many uncertainties still looming over the COVID-19 situation in Ontario, we recommend that the model be primarily used for qualitative assessment of the virus spread and its impact on the health-care system over a time horizon of one year or less.

Assumptions

Given that this is a novel coronavirus, we have limited data and research on its epidemiology. For the epidemiology-related assumptions, reliance was given on the original model's assumptions where limited information exists or when expert judgment is required. For other aspects where empirical data were available, we exercised judgment to assess reasonability and revised the original assumptions. We have primarily relied on the Canadian and Ontario data without any modifications in developing the hospitalization rate, ICU admission rate, and mortality rate.

With vaccines now being widely available, it has become a critical aspect in managing the virus. With the vaccine rollout in the current environment of emerging variants, we exercised judgment to set the vaccine parameters as well as its effectiveness against variants. It is important to note that the information on the vaccines is constantly being updated and logistical issues such as vaccine availability, administration capacity, and the public's willingness to be vaccinated are all key components to the model that we cannot predict with certainty.

Another key assumption is the public health intervention. Due to its inherently adaptive nature to the evolving situation, it is not practical to consider all possibilities and capture them in our model. Our modelling leverages the original model's use of the ICU capacity as the limiting factor in triggering the intervention measures. Even though our model does not consider all key metrics studied by the government in their decision-making, we believe using the ICU occupancy level provides a reasonable fit to the past experience with reasonable predictive power.

Calibration and validation

To achieve a reasonable model output in comparison to the actual experience, we have used the Ontario data (non-ICU hospitalization, ICU, death count) from April 1, 2020, to January 31, 2021, for calibration. In this exercise, we did not attempt to bifurcate the observations into the data directly resulting from the course of the pandemic itself versus any unusual or isolated observations resulting from one-off external forces. We have taken the data at face value and adjusted the intervention levels to fit the model output to the data observed.

Due to the limited data availability and the sensitivity to intervention levels, it was not practical to partition Ontario's experience data into a training versus testing set, thus, out-of-sample validation was not feasible. Also, in order to capture the seasonality aspect observed in the data, it was necessary to use the full data. With all of the available data used in the calibration exercise, the risk of model overfitting is very high and the model's predictive power is limited. It is also very difficult to assess and obtain relevant sample data from outside of Ontario due to the dynamic pandemic responses observed regionally and globally. Other variables such as cultural, geographical, political, and health-care system differences also limit the data relevance, inhibiting its applicability in our model validation. Figures 3 to 5 show the comparison of the actual data and the model output following the calibration exercise.

Figure 3: Number of patients in hospital

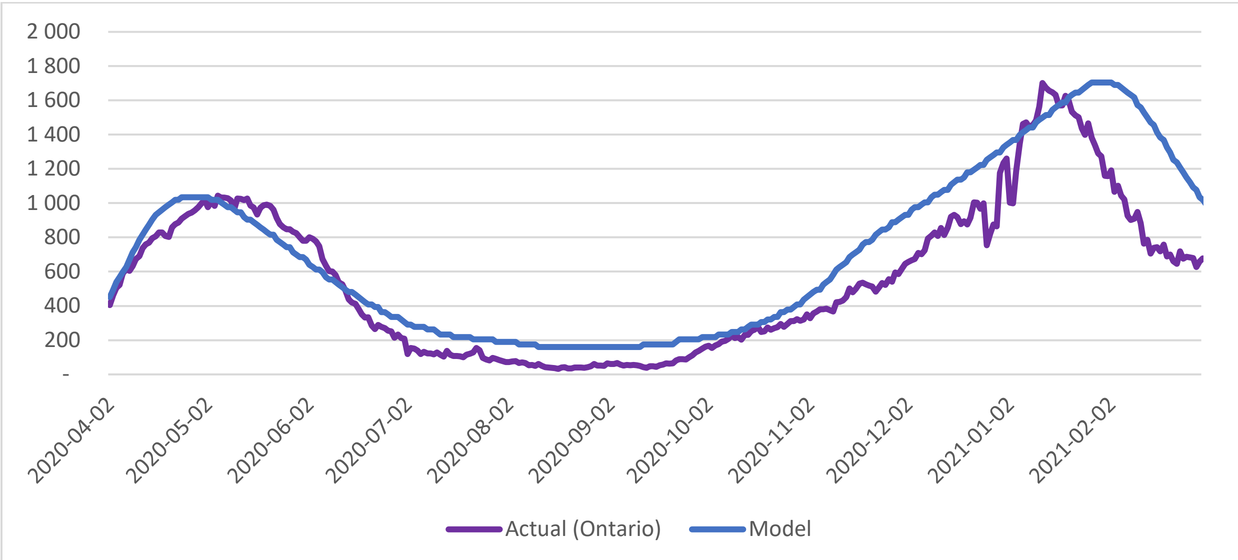


Figure 4: Number of patients in ICU

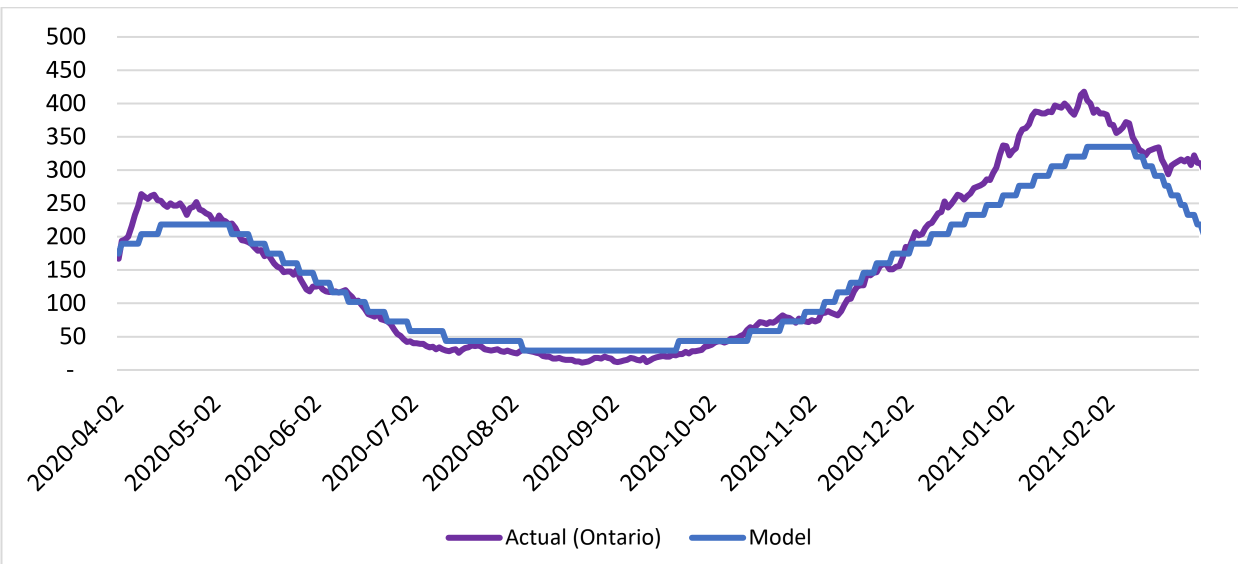
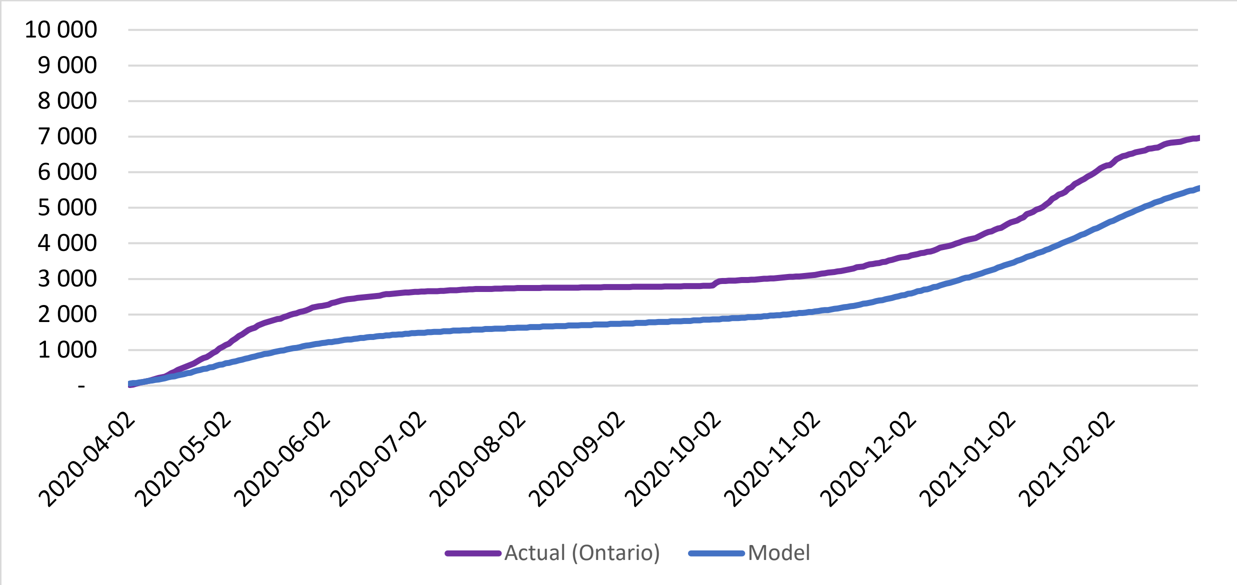


Figure 5: Cumulative deaths



Interpretation of results

In this paper you will see many specific results, which can vary significantly depending on the parameters used. Ranges of uncertainty have not been presented for the forecasted values in any projection as we did not have meaningful estimates for the level of uncertainty of the model inputs. Instead, the approach taken by the authors has been to present a number of scenarios that when taken as a whole capture the uncertainty and interaction of COVID-19 risks. The specific values presented in this paper should not be interpreted as best estimate predictions. They are the specifics of a potential scenario that is presented to provide the reader with an understanding of the outcomes that various levels of risk factors may lead to.

With many concurrently moving pieces, it is very difficult to capture all aspects comprehensively for a robust model. It is vital to monitor the emerging experience against the model's projection to modify and recalibrate as new information becomes available. With higher uncertainties on model parameters, the long-term reliability diminishes, thus, it is important to use the model for short-term horizon projections only to aid with immediate risk assessment and decision making.

Considerations for future improvement

Below are some potential factors that could impact the COVID-19 spread which were not considered in our model. These include:

- population density
- community gatherings (e.g., religious gatherings, organized social events)
- centralized location transmissions (e.g., grocery stores, hospitals, pharmacies)
- post-vaccination/recovery transmissions
- travel and border control
- vaccine efficacy wear-off over time, booster requirements, and impact of delayed second doses in a roll-out strategy
- impact of some segments of the population being eligible or ineligible at different times

- changes to the impact of different intervention levels over time as the relative strictness and public adherence to interventions changes

The model is deterministic with a defined base scenario. While it was out of scope for this project, as more research develops with new data, using stochastic modelling of the parameters may better capture the uncertainties of the model. Additionally, correlations between the parameters could be explored to better understand and capture the tail risk of COVID-19 spread quantitatively.

Part C: Understanding COVID-19 risks

To understand the relative risk of COVID-19 factors and identify the key assumptions, we analyzed each of the risks associated with COVID-19 individually. While variants stood out as the most material risk factor, the other factors were also explored to understand their relative impact. The interaction of these risks is analyzed in Part D.

Variants

As the world entered year two of the COVID-19 pandemic, the virus started to evolve, and variants have emerged in multiple countries. At the beginning of 2021, vaccines were expected to slow down the spread of COVID-19 in Ontario. However, the emergence of variants appears to have changed the expectation. The most common variant initially was the Alpha variant, which was first detected in the United Kingdom in September 2020. The Alpha variant is about 40% to 70% more transmissible[7] and has 60% higher death rates than the original "wild type" strain.[8]

In addition to the Alpha variant, there are three other variants detected in Ontario, including Delta variant first detected in India, the Beta variant first detected in South Africa, and the Gamma variant first detected in Brazil. Based on the recent studies,[9] the Gamma variant is very similar to the Alpha variant. However, the Beta variant is known to be more transmissible than the Alpha and Gamma variants. The Delta variant has been identified as the new greatest threat to eliminating the COVID-19 pandemic. Research shows that the Delta variant is 40% to 60% more transmissible than the Alpha variant. It is also more virulent, infecting people who have been partially vaccinated and shows a higher risk of hospitalization.

To understand the impact of variants, optimistic and pessimistic scenarios were modelled with varying transmissibility relative to the original strain. We assumed the vaccine effectiveness against the variants to be 70% of the 94% effectiveness assumed for the original strain (i.e., 66% effectiveness). Table 2 summarizes the scenarios tested. For this analysis, we assumed the population willingness to vaccinate is 80%[10] and that Ontario's vaccine roll-out plan[11] from January 1, 2021, would materialize as planned.

Table 2: New variant transmissibility by variant scenario

Variant scenario	Transmissibility relative to the original strain
No variants	100%
Optimistic	150%
Baseline	170%
Pessimistic	190%

[7] https://www.reuters.com/article/us-health-coronavirus-pfizer-moderna/pfizer-moderna-testing-their-vaccines-against-uk-coronavirus-variant-cnn-idUSKBN28W145
[8] https://www.ctvnews.ca/health/coronavirus/death-rate-from-COVID-19-variants-60-per-cent-higher-epidemiologist-1.5363953
[9] https://www.publichealthontario.ca/-/media/documents/ncov/voc/2021/02/sars-cov-2-variants-point-prevalence.pdf?la=en
[10] https://www150.statcan.gc.ca/n1/pub/45-28-0001/2021001/article/00011-eng.htm
[11] https://www.rcinet.ca/en/2021/01/11/more-canadians-ready-and-willing-to-get-COVID-19-vaccines-survey/

Figures 6 to 8 show the actual experience in Ontario from April 2, 2020, to February 28, 2021, followed by the model projection thereafter for one year. As shown, there is a slight disconnect between the endpoint of the actual experience and the beginning point of the model projection. It was not practical to calibrate the model to perfectly match. This impact is deemed immaterial in the model projection.

The data available for actual experience reflects reported cases only. Thus, to account for the unreported cases, we have assumed a reporting rate of 20%. The actual case count graphed is five times the reported case count as a reasonable proxy of the reality.

Figure 6: Daily active infection cases of COVID-19

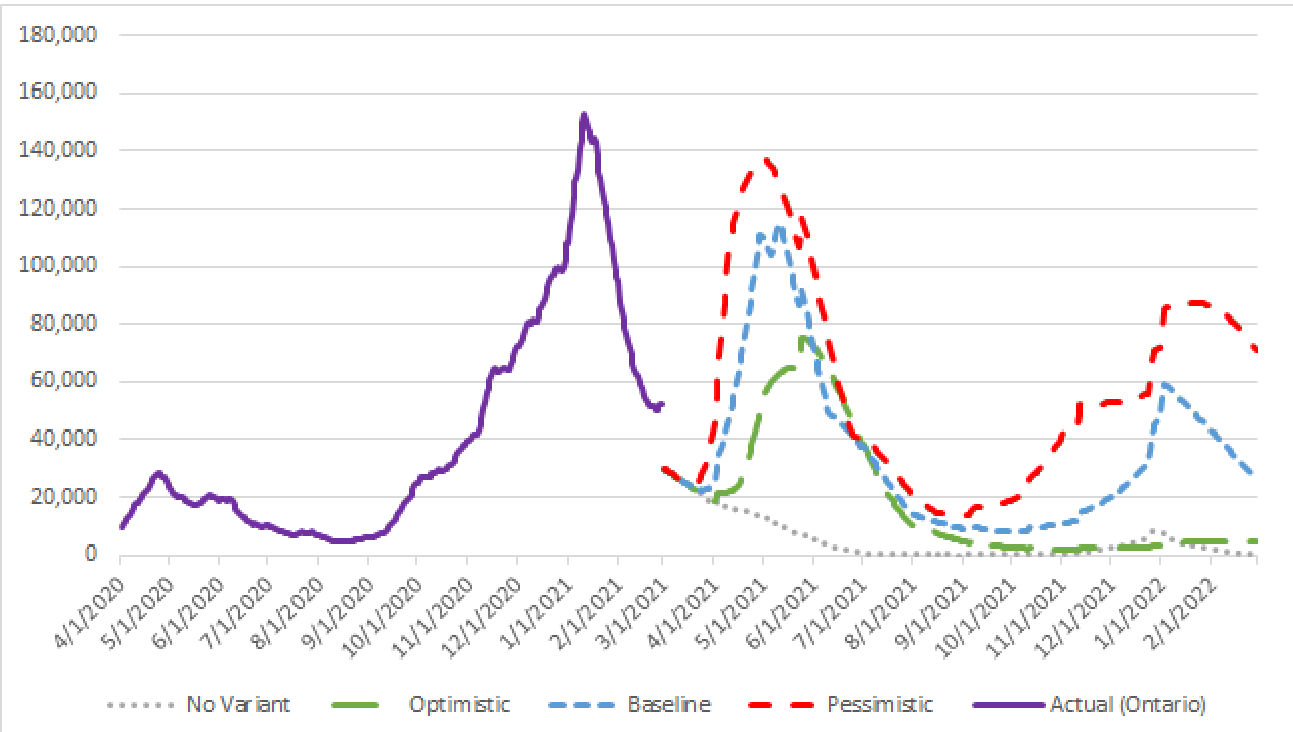


Figure 7: Daily ICU cases of COVID-19

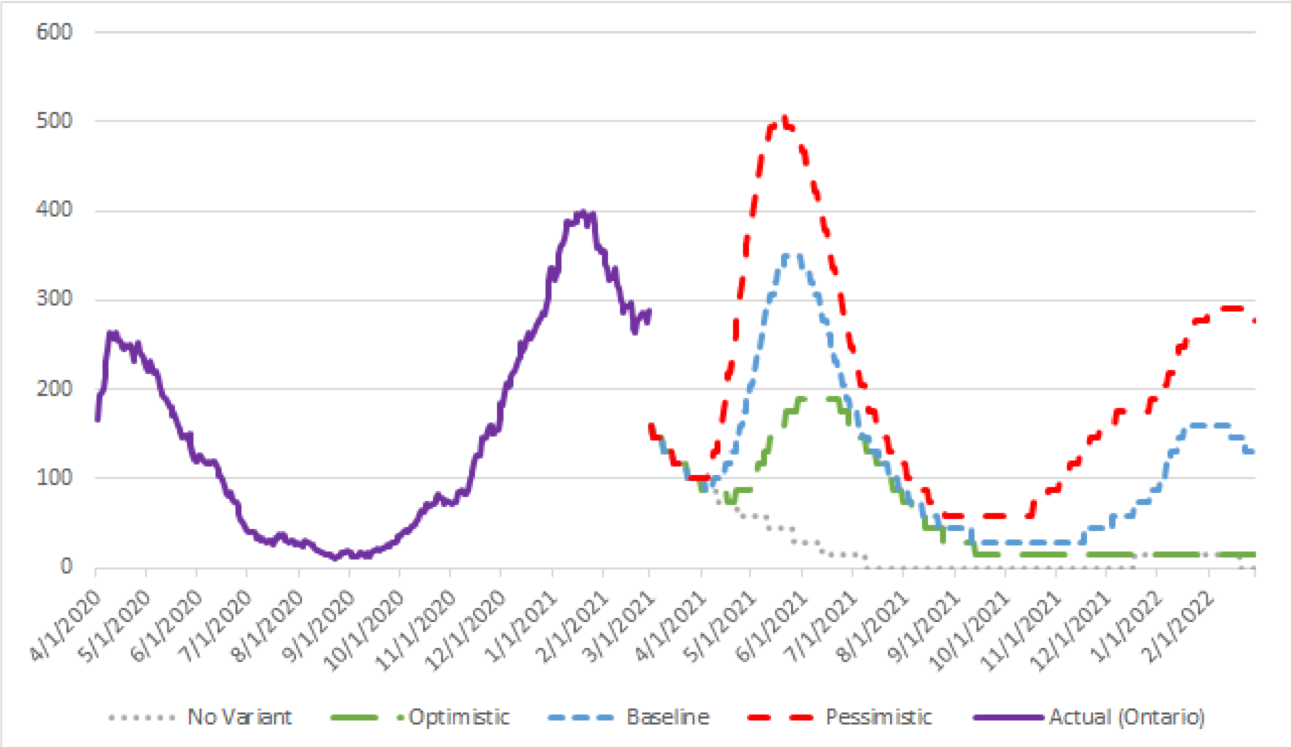
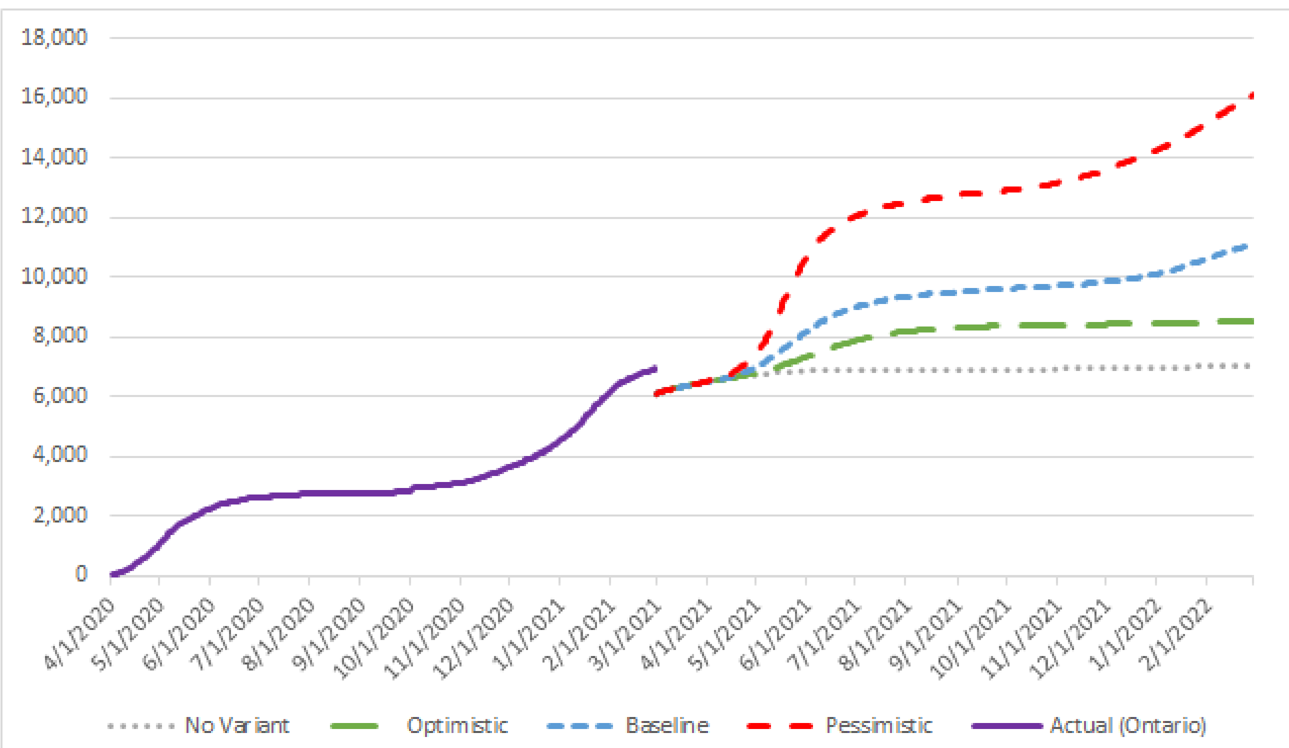


Figure 8: Cumulative deaths from COVID-19



While the scenario with no variants seems unrealistic given the observed emergence of variants, the model output indicating the elimination of COVID-19 in the summer of 2021 is noteworthy. This emphasizes the significance of a successful rollout of a highly effective vaccine while taking advantage of the positive seasonality effects to manage this pandemic.

All variant scenarios analyzed show a third wave in the spring of 2021 (which we now know happened) as well as a potential fourth wave in late 2021. However, we do note from our model that the COVID-19 impact subsides in the summer months, primarily due to the seasonality effects.

Other COVID-19 risk factors

Outside of variants, we have also identified and studied other risk factors as summarized in Table 3, including a qualitative risk assessment. Consistent with the variant analysis, the vaccine rollout combined with the positive seasonality effects during the summer months mitigated much of the adverse outcomes. See the Appendix for detailed analyses.

Table 3: COVID-19 risk factors

Factor	Description	Risk assessment	Notes
Early loosening of interventions	Government loosens restrictions more aggressively	Moderate	Loosening interventions too early can lead to moderately higher infections and deaths, and ultimately resulting in increased government interventions again in the long term.
Social distancing	Decrease in overall public adherence to social distancing	Moderate	Similar to the loosening of interventions scenario, this scenario can lead to increased spread and the need to increase interventions long-term.
Super spreading events	Events that lead to increased spread relative to usual day-to-day	Moderate	The data shows an increase in infections after major holidays, especially in the winter, indicating that these events contribute to COVID-19 spread.
Vaccination rate	Impact of lower willingness to vaccinate by the public	Moderate	This can lead to an increase in severe infections and the adverse outcome will be more significant with variants. Lower willingness for at-risk demographics is the key driver in the increase of severe infections. In scenarios where herd immunity is not reached in the near term, the willingness to vaccinate at-risk populations is increasingly important.
Vaccine supply	Impact of a slower rollout due to limited vaccine supply	Low	This has a lower impact than the lower vaccination willingness scenario as the at-risk demographics are still able to be effectively vaccinated. Seasonality also helps to limit spread as we are modelling a rollout over the summer.
Vaccinated return to normal	Having vaccinated people return to normal life	Low	Given that our modelling of vaccination assumed fully vaccinated individuals are expected to have significantly lower transmission rates for the original COVID-19 virus, having them return to normal practices should not significantly impact spread. This scenario assumes unvaccinated individuals still take precautions.

Part D: Scenario testing of variants and vaccines

Variants present the highest risk, and vaccines are the best long-term defense to mitigate future spread according to the results presented in Part C. In Part C, we explored the impact of variants while keeping the vaccine effectiveness and the population's willingness to vaccinate constant at 66% and 80%, respectively. This section explores a variety of variant scenarios to better understand the interaction of key risk factors. The projections of COVID-19 infections and ICU cases have been assessed on optimistic, baseline, and pessimistic scenarios.

Table 4: New variant transmissibility by variant scenario

Variant scenario	Transmissibility relative to the original strain
Optimistic	150%
Baseline	170%
Pessimistic	190%

Recognizing the uncertainty around vaccine effectiveness as well as the population's willingness to be vaccinated, we have assessed three vaccine success rate scenarios (low, medium, and high) against each of the variant scenarios. The "medium" scenario represents our baseline assumption.

Our model assumes that vaccines are 94% effective against the original "wild type" strain of COVID-19.[12] This assumption was based on studies conducted during a pre-variant period using vaccines rolled-out in Ontario. The effectiveness of vaccines against variant strain is evolving and not as well understood. We tested 60%, 70%, and 90% relative effectiveness of the vaccines against variants. This equates to 56%, 66%, and 85% effectiveness against variant infection. This is important as over time nearly all new infections will be from variants.

At the onset of our research, the willingness to vaccinate was found to be close to 70% of those surveyed. In more recent surveys, this number increased to approximately 80%. We tested plausible rates of 70%, 80%, and 90% willingness rates in the low, medium, and high scenarios, respectively.

Table 5: Vaccine parameters by vaccine success rate

Vaccine success rate	Variant vaccine effectiveness[13]	Willingness to vaccinate
Low	56%	70%
Medium	66%	80%
High	85%	90%

We observe the high vaccine success rate to be the most important factor in eradicating COVID-19. Even under the pessimistic variant scenario, the high vaccine success rate scenario manages to keep the virus under control with a low level of government intervention needed after September 1, 2021. However,

[12] Moderna 94.5% efficacy: https://www.fda.gov/media/144673/download, Pfizer 95.0% efficacy: https://www.fda.gov/media/144416/download, other vaccines were studied/approved with variant cases.
[13] Applicable to variants only; 94% is used for the original "wild type" strain.

with a low vaccine success rate, we could see a fourth wave along with the need for moderate to strict government intervention until early 2022.

Baseline scenario with varied vaccine success rates

Figures 9 and 10 highlight forecasted infections over time with fixed expected variant infectiousness and varying vaccine scenarios. Under the medium success vaccine scenario, we see decreasing infections over the summer but the risk of a fourth wave in late 2021. The low success vaccine scenario shows a high level of infections maintained throughout the summer of 2021 and resulting in a dual peak in the late 2021 and early 2022. The high success vaccine scenario highlights the potential to mitigate the risk of a fourth wave this fall.

Figure 9: Baseline variant scenario's daily active infection cases of COVID-19

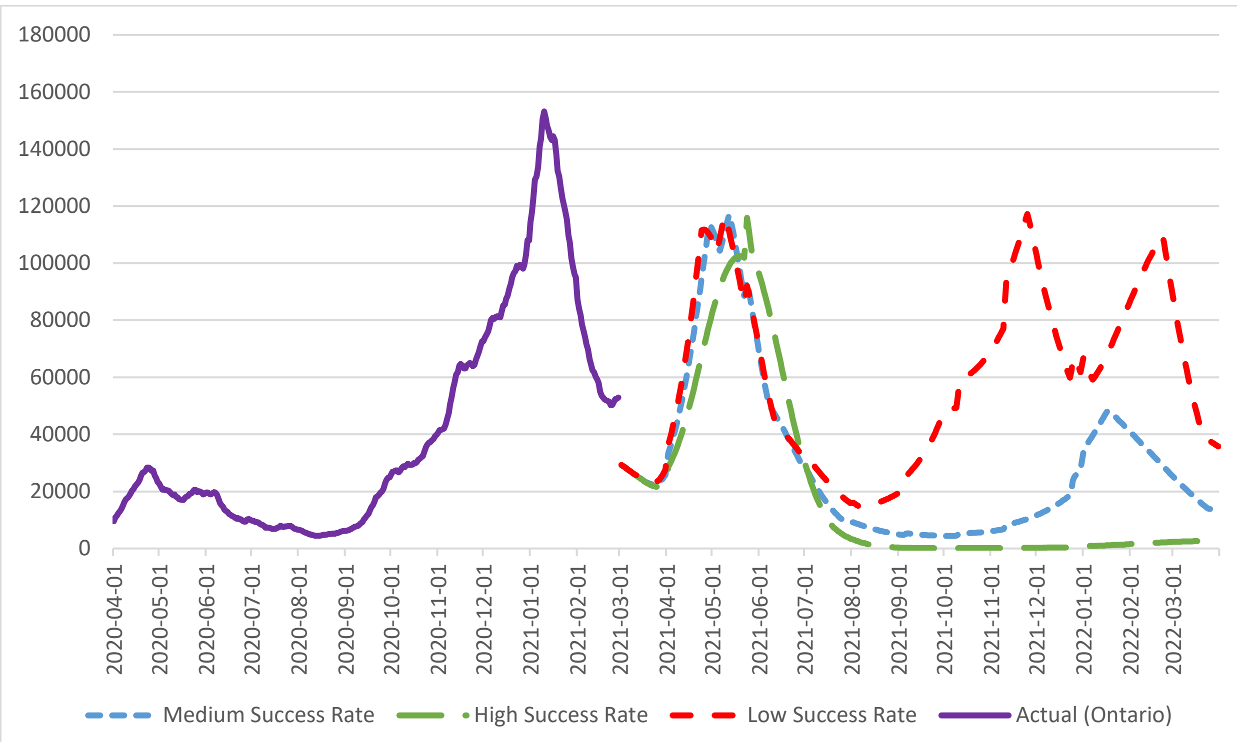
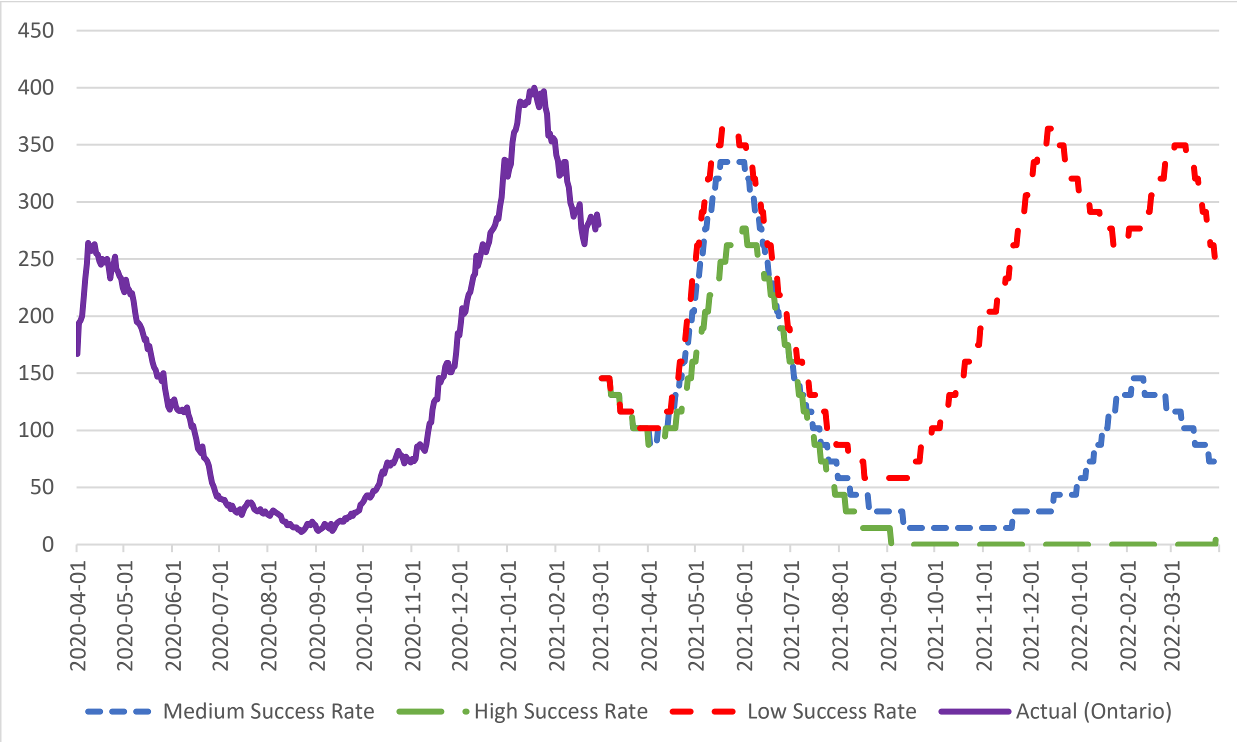


Figure 10: Baseline variant scenario's daily ICU cases of COVID-19



To further analyze the above scenarios, the days in each lockdown level (low, moderate, and strict) were assessed for each scenario after September 1, 2021. As presented, only the low success rate scenario results in a strict lockdown after September 1. A medium and high success rate will result in no strict government lockdown, even avoiding a moderate lockdown in the latter scenario.

Table 6: Baseline time in lockdown

Approximate time in lockdown based on vaccine success rate	Low success rate	Medium success rate	High success rate
Low	1 month	4 months	<1 month
Moderate	3–4 months	2 months	0
Strict	2 months	0	0

Optimistic scenario with varied vaccine success rates

Similar to the base variant scenario, even with an optimistic assumption for variant transmissibility there is still the risk of a fourth wave in the fall under both the low and medium success rate vaccine scenarios – although the fourth waves in these scenarios are less pronounced than the baseline. Again, a strong vaccine rollout can mitigate a fourth wave.

Figure 11: Optimistic variant scenario's daily active infection cases of COVID-19

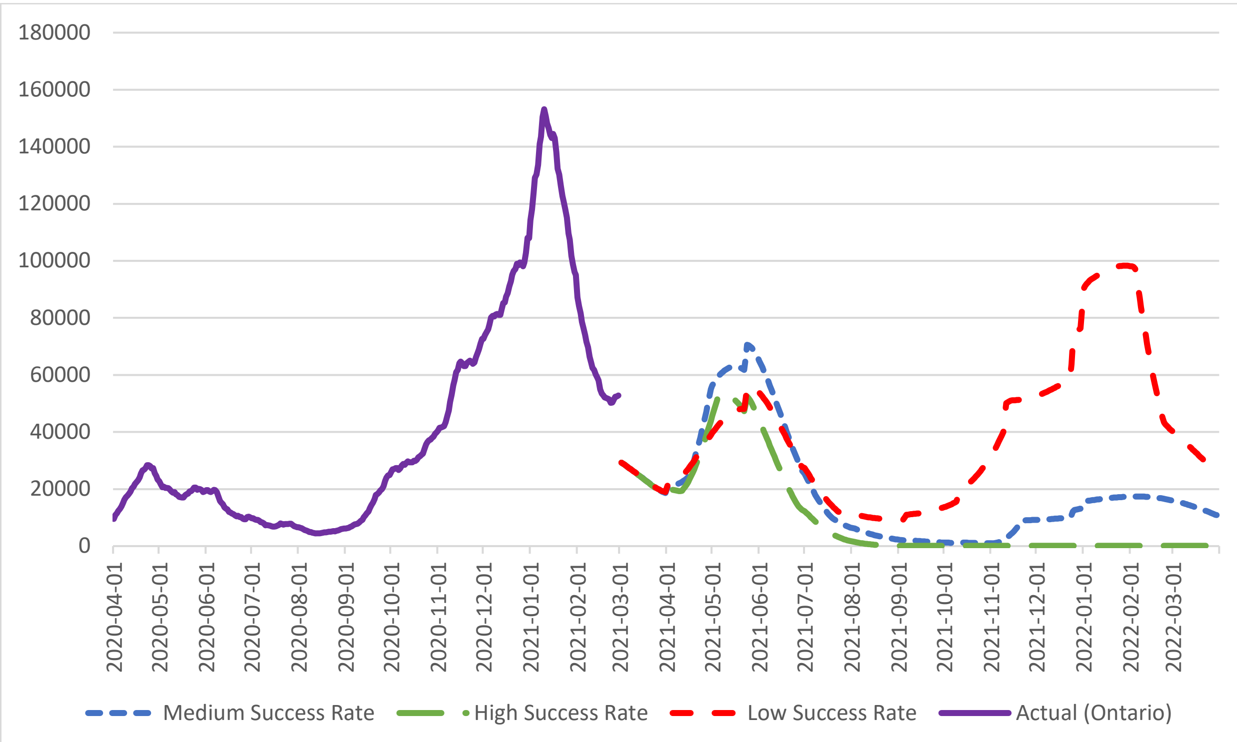


Figure 12: Optimistic variant scenario's daily ICU cases of COVID-19

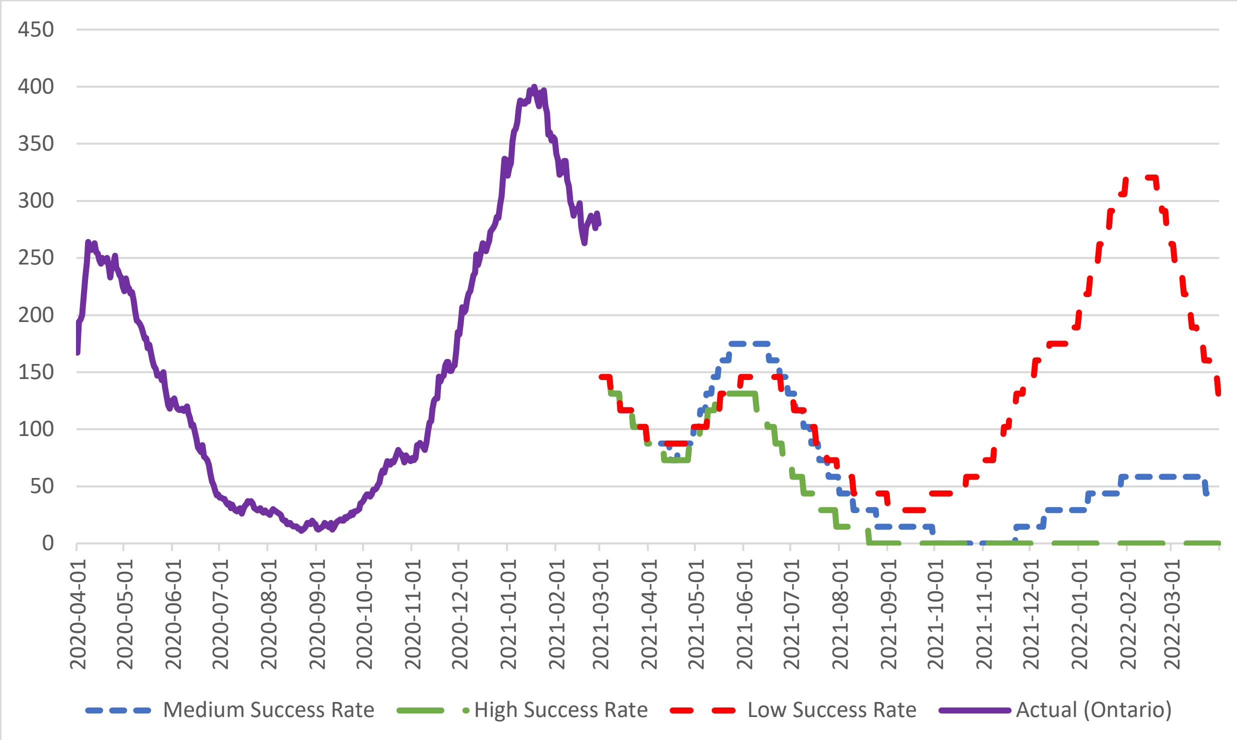


Table 7 presents the days in each form of lockdown for the optimistic scenario. Comparing to the baseline scenario, the worst-case vaccine outcome results in a 72% decrease in the number of days in a strict lockdown. A notable finding is that Ontario can also potentially avoid any form of lockdown altogether given the highest success rate vaccine outcome. Additionally, the medium success rate results in a low intervention level only.

Table 7: Optimistic time in lockdown

Approximate time in lockdown based on vaccine success rate	Low success rate	Medium success rate	High success rate
Low	2 months	7 months	0
Moderate	4 months	0	0
Strict	<1 month	0	0

Pessimistic scenario with varied vaccine success rates

In the scenario with a pessimistic assumption for both COVID-19 transmissibility and vaccine outlook, we see the risk of an extreme fourth wave in the fall. However, even with pessimistic transmissibility assumptions, there is still potential to limit infections in the fall and winter through vaccine response.

Figure 13: Pessimistic variant scenario's daily active infection cases of COVID-19

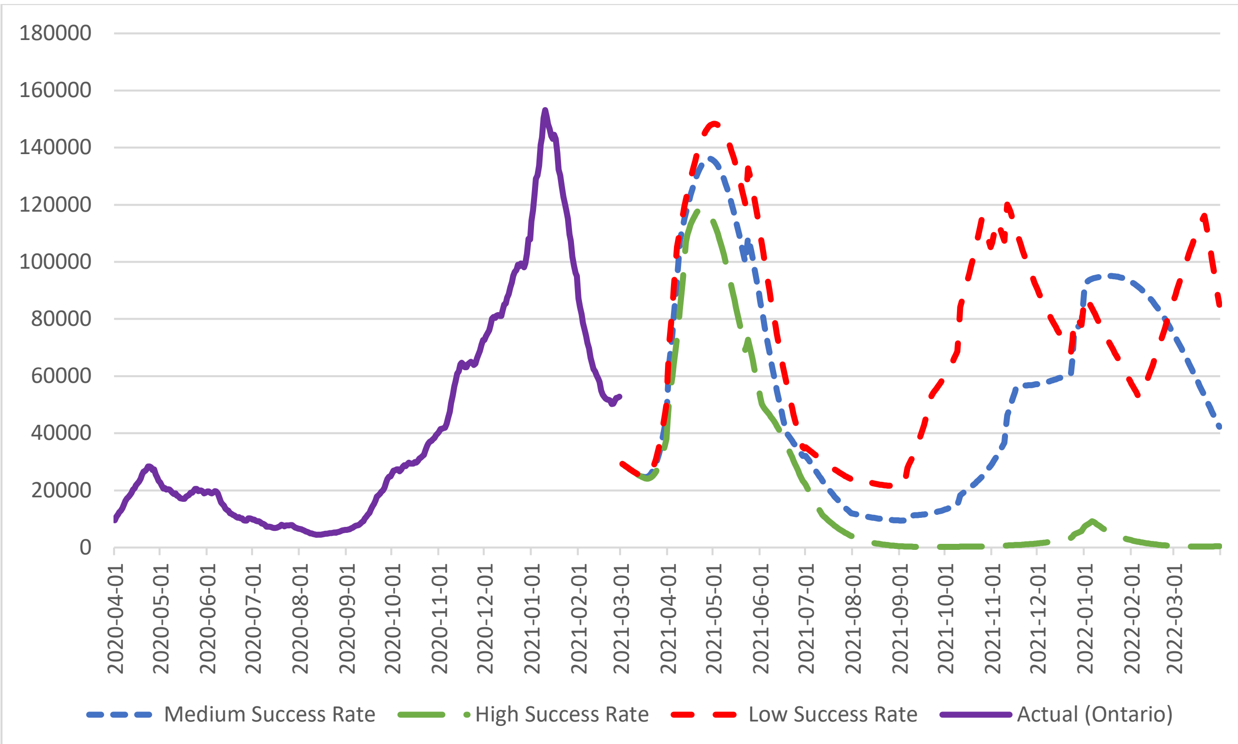


Figure 14: Pessimistic variant scenario's daily ICU cases of COVID-19

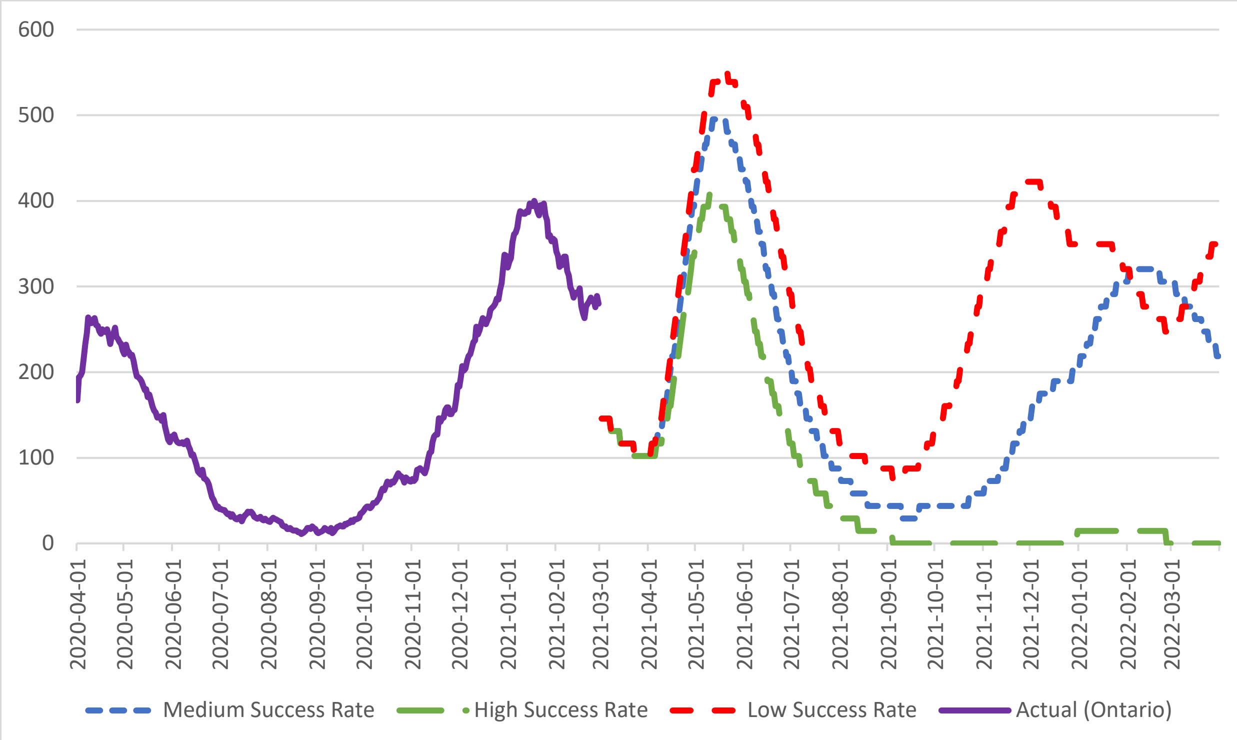


Table 8 presents the days in each form of lockdown for the pessimistic scenario. Even with a pessimistic expectation of a variant 90% more transmissible than the original strain, a high vaccine success rate can potentially result in about two weeks of low lockdown, which is similar to the baseline high success scenario of 11 days in low lockdown. This is a notable finding as it shows that there is potential for Ontario to largely avoid going into an extended lockdown if sufficient vaccine success is achieved, mitigating social duress. There is still potential, however, to have a strict lockdown spanning over three months if the lowest vaccine success rate occurs.

Table 8: Pessimistic time in lockdown

Approximate time in lockdown based on vaccine success rate	**Low success rate**	**Medium success rate**	**High success rate**
Low	<1 month	2 months	<1 month
Moderate	3 months	4 months	0
Strict	3–4 months	0	0

Impact of willingness to vaccinate

Our analysis above demonstrated that a high vaccine success rate (i.e., 85% vaccine effectiveness against variants and 90% willingness to vaccinate) in a variant emerging environment is key to eradicating COVID-19. However, we recognize vaccine effectiveness is a factor with many considerations beyond human control. Thus, in this section, we further explore the impact of the public's willingness to vaccinate against variants.

The willingness to vaccinate impacts the ultimate percentage of the population that receives a vaccination. In our testing, we found that this was the most important factor in terms of vaccination rate. In particular, we found that a high willingness to vaccinate is critical for at-risk populations. The vaccination rollout will reduce the strain on the health-care system, which will likely result in a loosening of interventions, and increase the potential for reducing severe infections. Loosening restrictions broadly due to positive overall experience exposes the remaining unvaccinated at-risk populations to a more transmissible and deadlier variant. The willingness to vaccinate will also determine when and if herd immunity is reached. If the willingness to vaccinate is high, the potential for future waves is greatly diminished.

To assess the required level of willingness to vaccinate in preventing future waves, we have further tested 80%, 90%, and 100% willingness to vaccinate for the baseline variant scenario (i.e., 170% transmissibility of the original strain) with the baseline assumption of 66% vaccine effectiveness against variants.

As shown in figures 15 and 16, we note a significant improvement in the magnitude of the fourth wave when the willingness to vaccinate improves from 80% to 90%. At the peak of the fourth wave, a population 80% willing to vaccinate results in infections and ICU cases that are respectively five- and ten-times worse than a population 90% willing to vaccinate.

Table 9: Willingness to vaccinate scenarios

Scenario	Variant vaccine effectiveness[14]	Willingness to vaccinate
Baseline willingness	66%	80%
+10% willingness	66%	90%
+20% willingness	66%	100%

[14] Applicable to variants only; 94% is used for the original "wild type" strain.

Figure 15: Baseline variant scenario's daily active infection cases of COVID-19 assuming 66% variant vaccine effectiveness

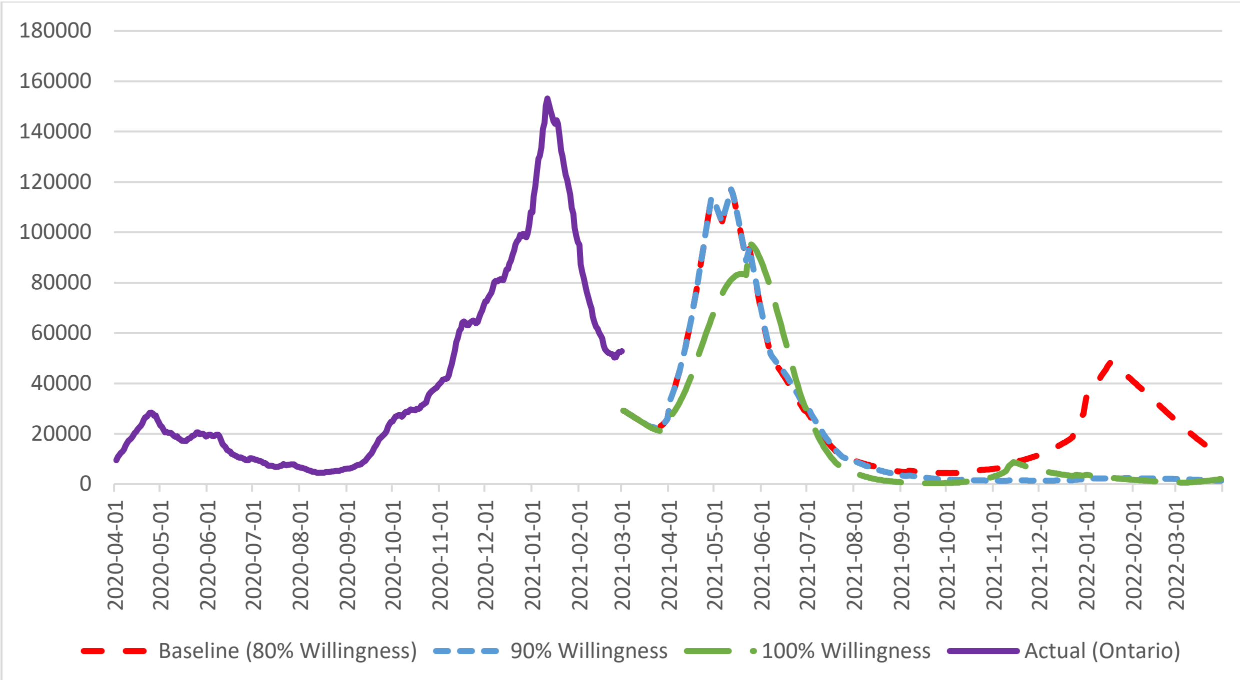
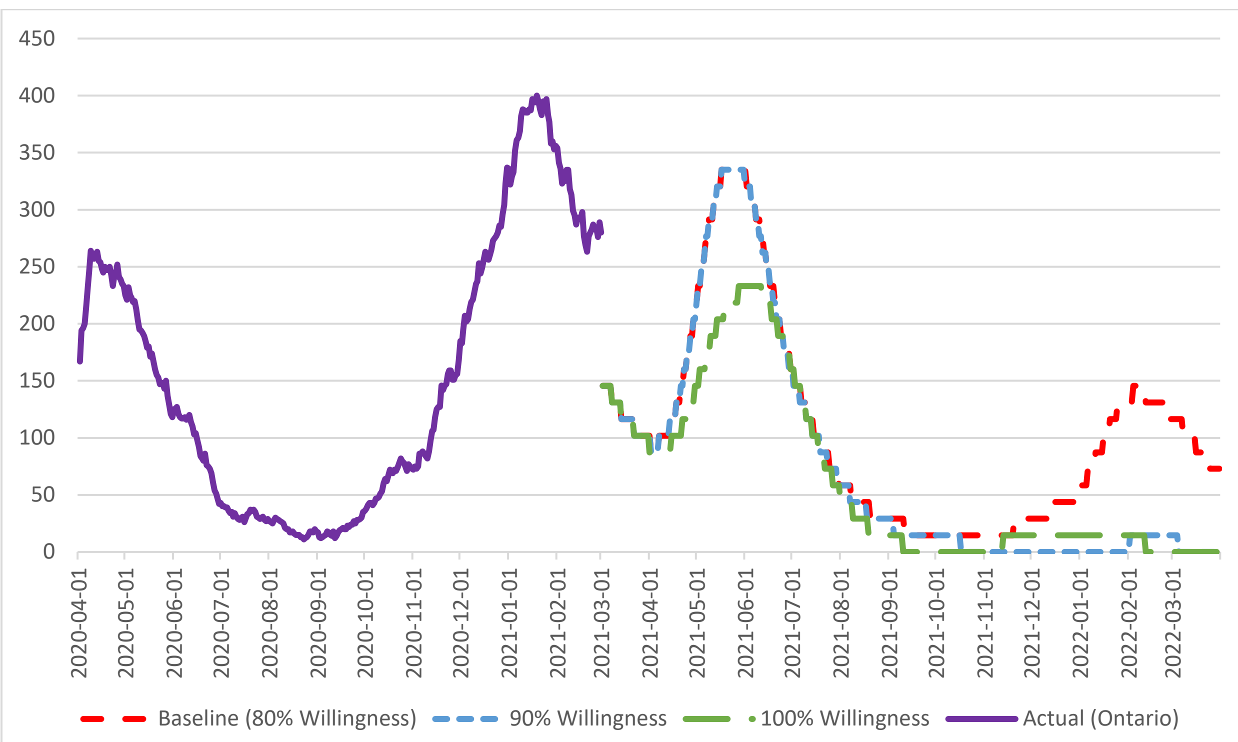


Figure 16: Baseline variant scenario's daily ICU cases of COVID-19 assuming 66% variant vaccine effectiveness



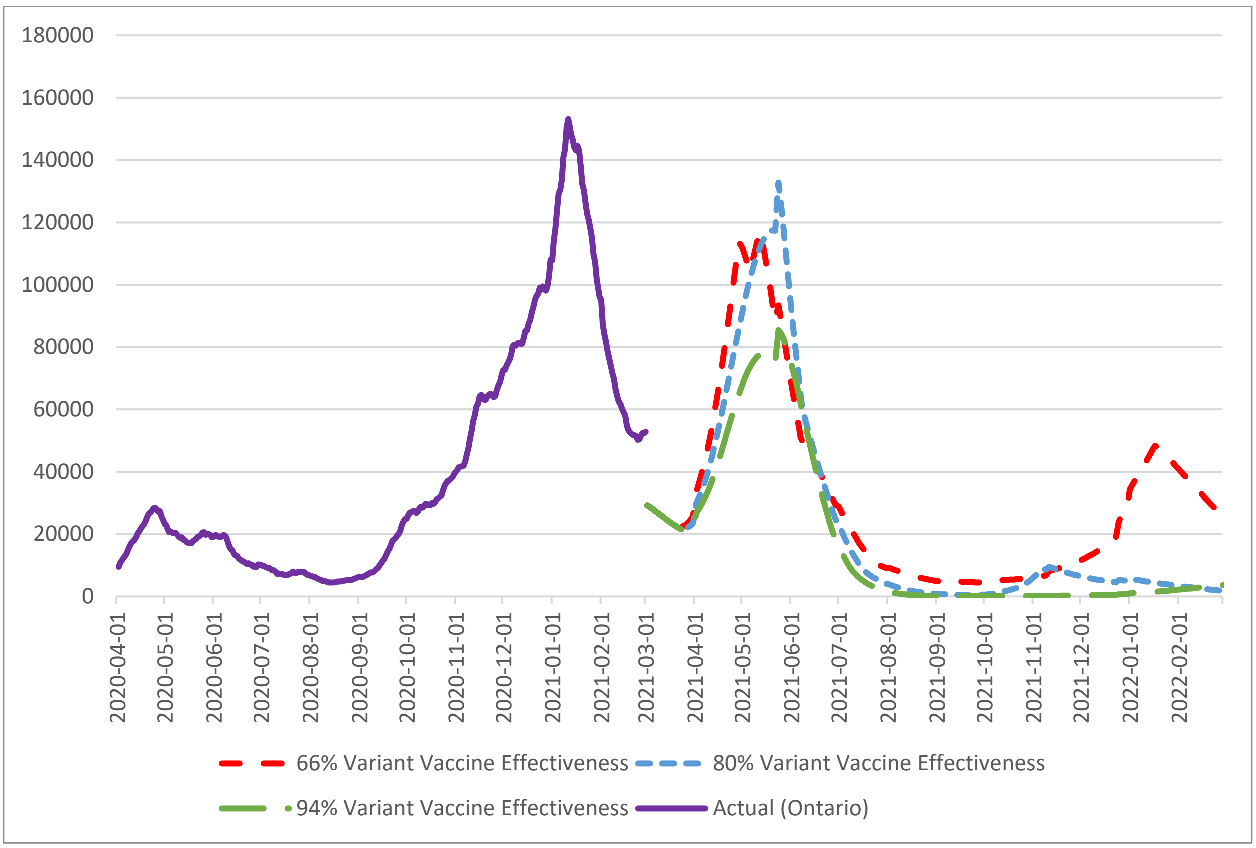
Impact of vaccine effectiveness

Figures 17 and 18 aim to outline the sensitivity of Ontario's COVID-19 infections and ICU cases at varying levels of vaccine effectiveness against new strains of coronavirus, and at a fixed level of population willingness to vaccinate. The baseline scenario assumed that 80% of Ontario's population is willing to vaccinate and that the vaccine has a 66% effectiveness against preventing new variant spread and severe cases of new strains.

Table 10: Vaccine effectiveness scenarios

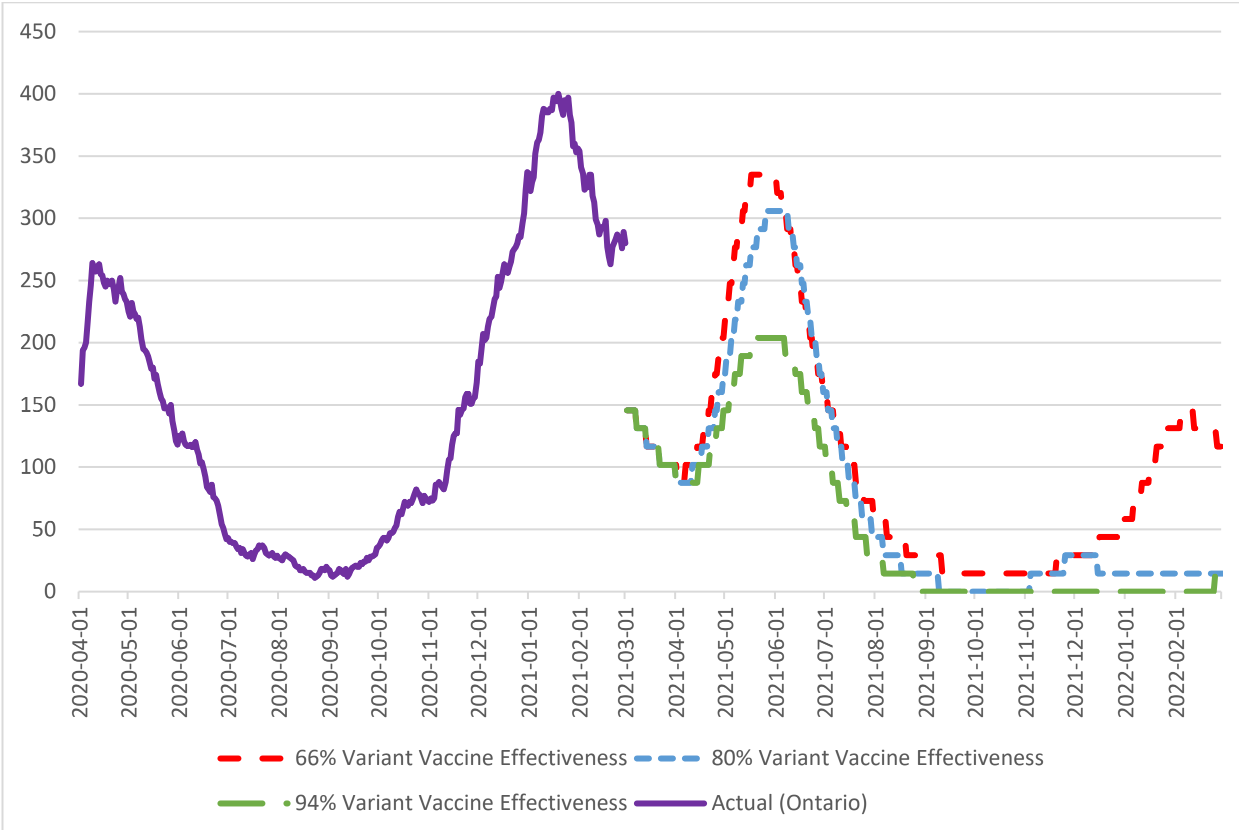
Scenario	Variant vaccine effectiveness[15]	Willingness to vaccinate
Baseline effectiveness	66%	80%
+14% effectiveness	80%	80%
+28% effectiveness (same vaccine effectiveness to variants as original strain)	94%	80%

Figure 17: Baseline variant scenario's daily active infection cases of COVID-19 assuming 80% willingness



[15] Applicable to variants only; 94% is used for the original "wild type" strain.

Figure 18: Baseline variant scenario's ICU cases of COVID-19 assuming 80% willingness



As expected, vaccines with higher effectiveness against the new strains of coronavirus result in better projections. Under the 80% effectiveness scenario, the fourth wave is kept largely in control but not eliminated. However, it is unrealistic to assume a high vaccine effectiveness rate against variants until cases come down globally.

Until COVID-19 is controlled globally, mutations and variants of concern will continue to emerge. As a result, vaccine efficacy remains largely unknown and difficult to project. Vaccine manufacturers are in a reactionary state and modifications will be needed to address new mutations.

In summary, we found that results were more sensitive to population willingness to vaccinate than to vaccine effectiveness. At 80% willingness and 80% effectiveness, the fourth wave ICU cases peak at about 120 cases in the winter of 2022. In comparison, at 90% willingness and 66% effectiveness, fourth wave ICU cases peak at about 50 cases in the spring of 2022. This is driven by two factors: higher willingness provides better protection for at-risk populations and vaccines are assumed to be highly effective against severe cases despite lower effectiveness against mild infections. In addition, willingness to vaccinate is easier to project and influence than vaccine effectiveness.

Part E: Mitigating COVID-19 transmission through heightened government intervention

The government of Ontario had adopted a COVID-19 response framework that used colour codes based on numerous indicators, with each colour code having its corresponding intervention measures. This framework allowed for interventions to be phased-in, in response to the changing level of the indicators. An alternative approach to mitigating future waves is to have increased government interventions for a prolonged fixed period. At the onset of the COVID-19 pandemic, some countries were able to nearly eliminate COVID-19 through an immediate high level of interventions that persisted until the virus was under control. A similar approach today would be able to drive down COVID-19 cases to a low enough level where contact tracing and self-isolation may be effective in mitigating future waves.

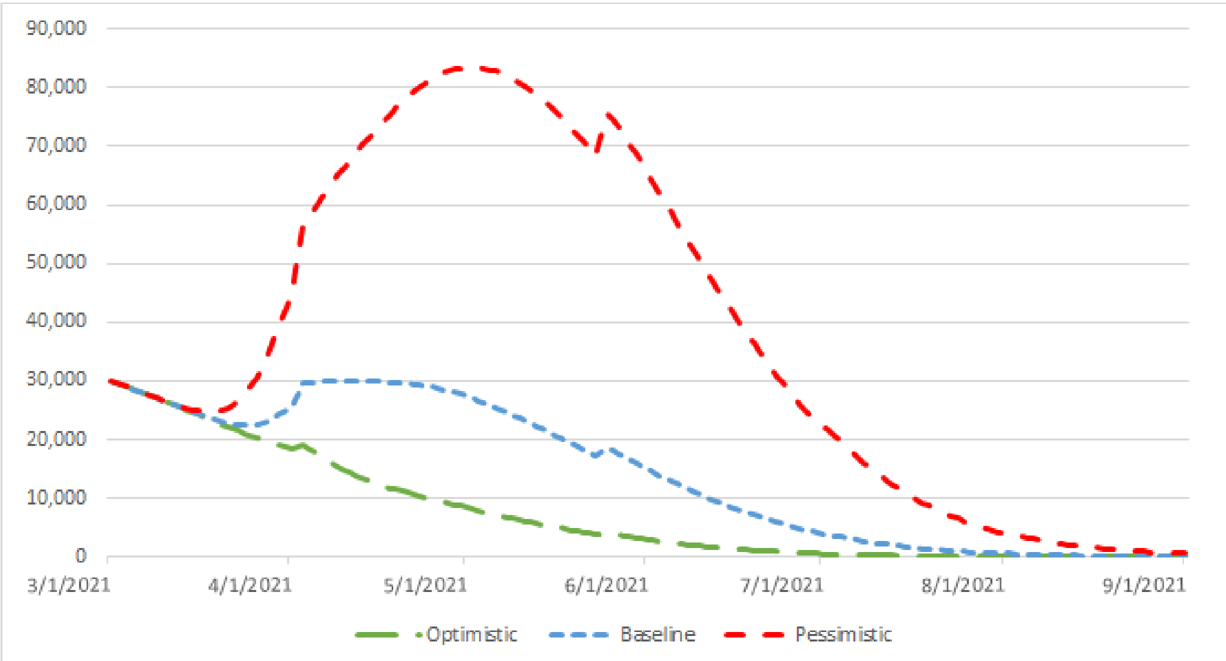
For this analysis, the model ignores spread from travel into Ontario. Any intervention strategy based on this analysis would need to address travel from other regions – for example by coordinating the restriction period with other regions, banning travel, or implementing strict quarantine conditions.

Also, it is worth noting that the analysis studies the prolonged strict intervention's impact on epidemiological aspects of COVID-19 only. The possible social and economic impact as well any other potential adverse effects of such intervention measures have not been analyzed.

Assessment of required strict intervention period

To assess the impact of increased intervention measures, we used April 1, 2021, as the start date of strict intervention measures. This effectively allows us to understand how long of a prolonged intervention would have been required for Ontario to avoid a third wave and reduce the active case to 1 per 100,000 people which is deemed to be manageable by government to prevent future waves. Ontario has approximately 14 million of population and 140 cases of active infections are identified as the manageable level in this analysis to avoid future waves.

Figure 19: Optimistic, Baseline, and Pessimistic variant scenarios' daily active infection cases of COVID-19 assuming the strict intervention from April 1, 2021, and baseline assumptions for willingness to vaccinate and vaccine effectiveness



If we assume an optimistic level of variant transmissibility, the model predicts 111 days until COVID-19 active infections fall below 140. This suggests that even with an optimistic assumption for variant transmissibility, over three months of strict level interventions may be required to mitigate the future spread of the virus. At the baseline transmission estimate for variants, the forecast shows 144 days of strict level interventions required to get below 140 active cases – more than a month longer than the optimistic scenario. In the pessimistic variant transmissibility scenario, 180 days – over six months – of strict level government intervention are forecasted to be required to reduce active infections to less than 140.

Table 11 summarizes the sensitivity test results for the relative transmission rate of the variants.

Table 11: Strict intervention length by variant scenario

Variant scenario	Approximate time in strict intervention period to achieve 1 case per 100K in Ontario
Optimistic	3–4 months
Baseline	4–5 months
Pessimistic	6 months

In summary, it could take three to six months of continued strict government interventions to bring the COVID-19 pandemic to the manageable level that would eliminate future waves of COVID-19.

Impact of stricter intervention levels

Given that most of the Ontario population was under the highest intervention levels for the first half of 2021 (with significant economic and mental health impacts), it is worth exploring whether stricter interventions could significantly reduce the required time of the restrictions.

The analysis in this section assumes that the relative transmission rate of the variants is 70% higher than the original strain, the vaccines are 70% effective to the variants, and baseline willingness to vaccinate. Further sensitivity testing is performed to understand the impact of relative contact frequency rates on the number of active infections. As with the previous section, the interventions are modelled to begin on April 1, 2021.

To model an even stricter level of government intervention, the strict level of intervention was further tightened by 30% and 60% relative to the base contact frequency rate for all age groups. Figure 20 shows the projection of active COVID-19 infections assuming the stricter intervention levels from April 1, 2021, and thereafter.

Figure 20: Daily active infection cases of COVID-19 under stricter intervention levels from April 1, 2021

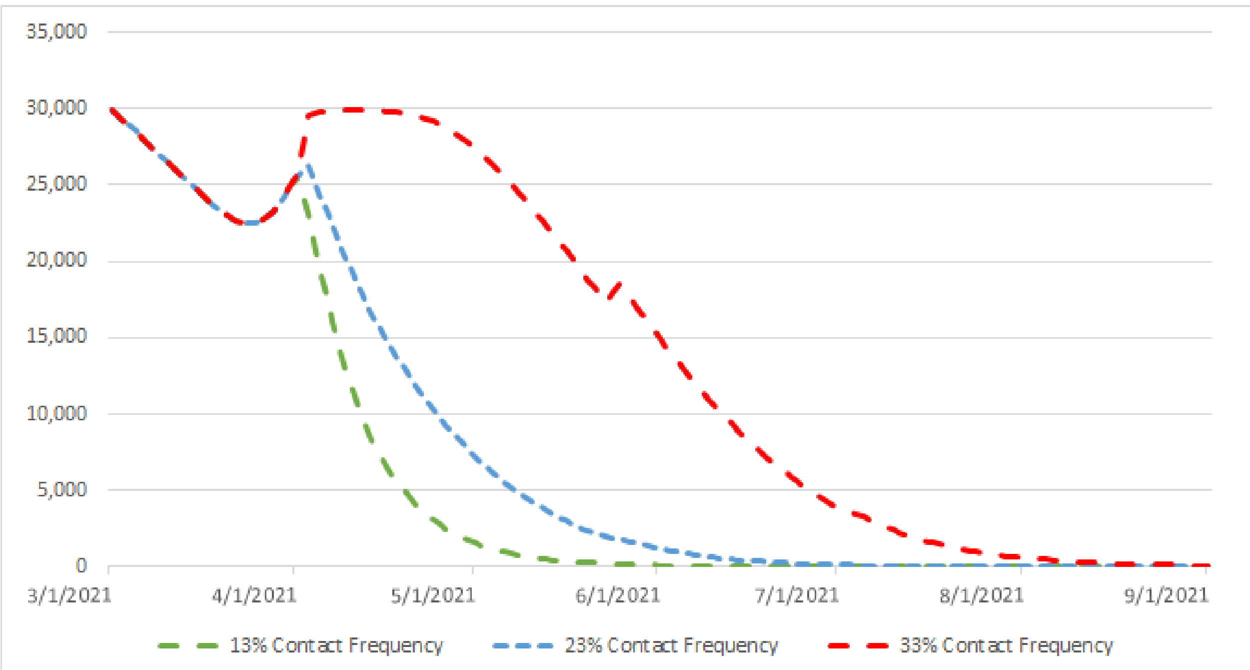


Table 12 shows the number of days of government intervention required to get to 140 active infections for each of the scenarios. Even in a stricter intervention scenario, 56–89 days of continuous interventions would be required as of April 1 to get down to 140 active cases. Also note that this figure could vary significantly depending on other variables including the number of active infections on the date the interventions begin, and the proportion of the population who is vaccinated.

Table 12: Strict intervention length by intervention scenario

Intervention scenario	Approximate time in strict intervention period to achieve 1 case per 100K in Ontario (days)
Base	4–5 months
Scenario 1 (-30% shock on relative contact frequency rate)	3 months
Scenario 2 (-60% shock on relative contact frequency rate)	2 months

In summary, while interventions are a useful method to limit COVID-19 spread when infections and hospitalizations get too high, a significant level of intervention would be required for months at a time to bring down COVID-19 cases through strict intervention alone. The exact length of time could vary significantly depending on how transmissible variants are, the number of existing infections, and public adherence to the interventions. Further, a strategy to prevent cases from travel would also need to be implemented for an intervention-only strategy to work. Finally, it is worth noting that these scenario tests took place at the outset of the third wave where there were relatively fewer variants. Implementing a government intervention strategy with a higher proportion of cases being variants of concern would likely increase the amount of time required to reach 140 active cases.

While it does not appear that an intervention strategy to significantly limit future waves is feasible today, a shortened high-level intervention may be plausible in the future depending on the active level of infections and vaccination rate at that time.

Conclusion

The purpose of this research paper is to provide decision-makers within government as well as actuaries and the general public an understanding of the interactions and relative impact of various COVID-19 risks. To effectively navigate this pandemic and any future pandemics, it is crucial to understand which risks could have the most potential impact, and how other factors can influence these risks. In this research, we have highlighted that COVID-19 variants present the largest risk.

Through this analysis, we have identified the following:

- The risk of a fourth wave in the fall of 2021 is a plausible scenario given the seasonality of this virus (Part A: Model explanation – model updates).
- The emergence of variants is a risk and a potential driver of future pandemic waves (Part C: Understanding COVID-19 risks – variants).
- The importance of vaccination of the population to prevent the fourth wave (Part D: Scenario testing of variants and vaccines).
- Governments should pursue the vaccination plan to mitigate infections, hospitalizations, and deaths despite the lower effectiveness of the vaccines against new variants (Part C: Understanding COVID-19 waves – variants).
- Our modelling shows that increasing the population's willingness to vaccinate and the vaccine effectiveness to 90% against variants should effectively eliminate a fourth wave (Part D: Scenario testing of variants and vaccines).
- Our modelling shows that increasing the population's willingness to vaccinate (90%) with lower vaccine effectiveness (66%) reduces the magnitude of future waves versus a lower willingness to vaccinate (80%) and higher vaccine efficacy (80%). The population's willingness to vaccinate is the key to mitigating future waves (Part D: Scenario testing of variants and vaccines).
- We have shown that an increased vaccination strategy by the government is a more effective way to prevent the future spread of COVID-19 than one that relies solely on a government-led intervention strategy.

Throughout this paper, we have presented a variety of plausible future scenarios to explore the tradeoffs of various risks related to COVID-19. We believe that exploration of various scenarios – more than just focusing on the best estimate forecast – is crucial to understanding the pandemic and understanding how our decisions today might play out in an unknown future. It is important to include scenario testing in model analysis when making public policy decisions in the future. It is equally important to use dynamic models whenever possible to predict pandemic outcomes. Models developed by epidemiologists and actuaries together will provide reliable information to the decision-makers in mitigating risks associated with a pandemic.

Key insights

1. The population's willingness to vaccinate is the key to managing the current pandemic. Vaccines can be developed but if left unadministered or administered to a low level, future waves of the pandemic cannot be mitigated. In the face of complacency towards vaccines, governments must educate the public about the potential negative results of this inaction.
2. Even if vaccine effectiveness is lower than originally expected, safe vaccines with lower efficacy may be sufficient to combat a pandemic as long as the population has a high degree of willingness to vaccinate.
3. Set high targets for vaccinations of the population and follow through on the roll-out plan. Ensure the population gets the required number of doses.
4. In the absence of vaccines, government interventions are an effective way to manage the spread of COVID-19. However, once there has been significant spread in the population, a strategy to drastically reduce active cases that relies solely on government intervention would likely not be feasible. This is due both to the length of time required for the intervention and difficulties managing inter-border travel. While early, strict lockdowns have been effective in some jurisdictions at virtually eliminating COVID-19, this strategy has become much less practical as the pandemic has progressed. Atlantic Canada has experienced good results by controlling and limiting access to their border.
5. There is benefit to the approaches of scenario-testing and risk assessment provided in this paper to increase understanding of pandemics. Applying these actuarial principles to future work can provide additional insight beyond forecasting that is focused on predicting outcomes.

Appendix: Analysis of other COVID-19 risk factors in a non-variant scenario

This appendix provides more details on the risks analyzed in Part B.

Early loosening of interventions and social distancing

Ontario had a COVID-19 response framework with five colour codes, dictating the level of intervention measures based on numerous indicators and thresholds. While the decision-making is in principle evidence-informed, we have explored the risk of loosening of interventions too soon and reacting to implement interventions too late due to the potential lagging nature of observed indicators.

We tested the impact of loosening the intervention level to the lowest level during the downward trend in cases in February 2021. The early loosening combined with a potential lag to implement restrictions again could put us in a worse situation with increased active cases compared to the pre-loosening state. In isolation, this risk did not result in a significant impact on our projection because the loosening was temporary, and interventions were not fully turned off. However, loosening restrictions temporarily exacerbates other risks, such as variants that can spread quickly under loosening rules.

Further, while the loosening of interventions may provide the public with some immediate gratitude as well as an economic relief, it may be rather short-lived with potentially more adverse long-term outcomes. The on and off interventions may be perceived as indecisiveness with the government losing credibility, resulting in less compliance of the interventions from the public which in turn could drive worse waves of infections than we have experienced so far.

While the investigation of more strict interventions observed in other countries such as China or New Zealand was out of the scope of this paper, it is noteworthy that they appear to have eliminated COVID-19 much more effectively.

Super spreading events

The original model captured the risk of super spreading events in the random walk function applied to the transmission rate. In our analysis, we took a deeper look at the data and performed sensitivity tests on super spreader events.

When looking at the daily effective reproduction number (R_e) in Ontario, we observed unstable results and large spikes following major holidays. As a result, we tested by shocking the contact frequency rates on major public holidays in the projection.

Our testing did not identify a need to incorporate super spreading events in the model. Super-spreading events are difficult to predict and are influenced by interventions. In addition, super spreading events are implicitly included in the seasonality term introduced to the model.

Vaccination rate

Several factors are impacting the vaccination rate, such as the public's willingness to be vaccinated, vaccine supply, and the rollout strategy.

The willingness to vaccinate impacts which populations receive the vaccine given a specified supply, as well as the ultimate percentage of the population that receives a vaccination. In our testing, we found that this was the most important factor in terms of vaccination rate. In particular, we found that a high willingness to vaccinate is critical for at-risk populations. The vaccination rollout will reduce the strain on the health-care system, which will likely result in a loosening of interventions, and increase the potential for reducing severe infections. This exposes the remaining unvaccinated at-risk populations to a more transmissible and deadlier variant. The willingness to vaccinate will also determine when and if herd immunity is reached. If the willingness to vaccinate is high, the potential for future waves is greatly diminished.

The vaccine supply impacts how quickly willing populations are vaccinated. In our initial testing, we did not find results that were sensitive to the vaccine supply projection in our model. This was because supply was not projected to be significant before the summer when the seasonality term drives transmission down. By the time the colder weather arrives, it was projected that supply would be high enough to combat a new wave, even with large decreases to the supply. However, the emergence of variants has increased the importance of the supply.

Similar to the willingness to vaccinate, the rollout strategy impacts who receives the vaccine given a specified supply. However, the rollout strategy does not impact the ultimate percentage of the population vaccinated. In our testing, we did not find there to be a material impact from different rollout strategies. We tested several different strategies, including prioritizing based on the risk of severe infections and prioritizing based on contact frequency. Results were not found to be sensitive to the strategy because of the dynamic interventions applied in the model. The intervention level is based on infections and ICU cases, which naturally reduces the sensitivity to other factors.

Vaccinated return to normal

We analyzed the impact of vaccinated people returning to normal activities. In this scenario, public intervention measures that limit contact frequency are not applied to the recovered and the vaccinated populations.

In our testing, we did not find that this had a material impact on the results. However, our model does not accurately capture the potential transfer between a vaccinated carrier of the disease and a susceptible individual.

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