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Examining the effects of voluntary avoidance behaviour and policy-mediated behaviour change on the dynamics of SARS-CoV-2: A mathematical model

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A R T I C L E I N F O

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A B S T R A C T

Background: Throughout the SARS-CoV-2 pandemic, policymakers have had to navigate between recommending voluntary behaviour change and policy-driven behaviour change to mitigate the impact of the virus. While individuals will voluntarily engage in self-protective behaviour when there is an increasing infectious disease risk, the extent to which this occurs and its impact on an epidemic is not known.

Methods: This paper describes a deterministic disease transmission model exploring the impact of individual avoidance behaviour and policy-mediated avoidance behaviour on epidemic outcomes during the second wave of SARS-CoV-2 infections in Ontario, Canada (September 1, 2020 to February 28, 2021). The model incorporates an information feedback function based on empirically derived behaviour data describing the degree to which avoidance behaviour changed in response to the number of new daily cases COVID-19.

Results: Voluntary avoidance behaviour alone was estimated to reduce the final attack rate by 23.1%, the total number of hospitalizations by 26.2%, and cumulative deaths by 27.5% over 6 months compared to a counterfactual scenario in which there were no interventions or avoidance behaviour. A provincial shutdown order issued on December 26, 2020 was estimated to reduce the final attack rate by 66.7%, the total number of hospitalizations by 66.8%, and the total number of deaths by 67.2% compared to the counterfactual scenario.

Conclusion: Given the dynamics of SARS-CoV-2 in a pre-vaccine era, individual avoidance behaviour in the absence of government action would have resulted in a moderate reduction in disease however, it would not have been sufficient to entirely mitigate transmission and the associated risk to the population in Ontario. Government action during the second wave of the COVID-19 pandemic in Ontario reduced infections, protected hospital capacity, and saved lives.

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1. Introduction

Managing the impact of the SARS-CoV-2 pandemic has been an enormous challenge for public health policymakers. As with all respiratory infectious diseases, transmission is driven by human contact behaviour and regardless of the availability of vaccines, mitigation has continued to focus on non-pharmaceutical interventions (NPIs). Behaviour modification in the context of respiratory infectious diseases includes, among other measures, physical distancing strategies such as reducing contact with others, maintaining a certain distance from others when in contact, and avoiding crowded indoor spaces (Public Health Agency of Canada, 2022a). While the relative contribution of physical distancing to epidemic control is high (Haug et al., 2020), policymakers have had to navigate between recommending voluntary behaviour change and implementing policy-driven behaviour change to mitigate the impact of SARS-CoV-2 at a population level.

Psychological theory postulates that individuals will voluntarily engage in self-protective or avoidance behaviour when there is an increasing disease risk (Rogers, 1975; Rosenstock et al., 1988). Evidence from the 2009 H1N1 influenza pandemic and the 2003 SARS epidemic suggest that individuals voluntarily reduced their contacts (Rubin et al., 2009), reduced their time in public places (Bayham et al., 2015), avoided air travel (Beutels et al., 2009; Fenichel et al., 2013), and avoided public transit (Beutels et al., 2009) out of concern for disease transmission. Emerging evidence from the SARS-CoV-2 pandemic also supports the theory that individuals voluntarily modify their behaviour in response to infectious disease risk by increasing the amount of time spent at home (Yan et al., 2021) and avoiding crowded places (Gao et al., 2021). Furthermore, engagement in precautionary behaviour in response to SARS-CoV-2 varies by sociodemographic characteristics such as age, gender, and household income, suggesting heterogeneity in the type and degree of behaviour change in which individuals are willing and able to participate (Brankston et al., 2021a, 2022).

Assessing the extent to which individuals engage in voluntary avoidance behaviour with increased disease risk and incorporating this feedback into disease transmission models is challenging. Past efforts have been based on a variety of theories such as prevalence-based behaviour change, social referencing, and cost-utility payoff (Verelst et al., 2016; Weston et al., 2018). The vast majority of authors did not have the opportunity to include empirically-derived behaviour data from ongoing epidemics to parameterize their models (Weston et al., 2018). Those that included empirically-derived behaviour data used a single parameter to describe avoidance behaviour which may not adequately predict the impact of heterogeneity in avoidance behaviours that likely exists due to age or other characteristics on epidemic outcomes (Bayham et al., 2015).

The SARS-CoV-2 pandemic has provided a unique opportunity to investigate the way in which voluntary avoidance behaviour interacts with government issued public health policy during public health emergencies. Our previous work demonstrated that Canadians changed their physical distancing behaviour in response to evolving epidemic growth and stringency of public health measures (Brankston et al., 2022). However, it is challenging to disentangle the relative contribution of voluntary versus policy-mediated behaviour change on the mitigation of disease transmission. The importance of doing so lies in the theory that public policy may displace or combine with voluntary avoidance behaviour that would have happened regardless of government intervention (Yan et al., 2021). If voluntary avoidance behaviour and policy-mediated avoidance behaviour would lead to a similar outcome, then government issued public health policy would be unnecessary to achieve the same goal.

We used a deterministic disease transmission model to explore the potential impact of individual avoidance behaviour and policy-mediated avoidance behaviour on epidemic outcomes during the second wave of SARS-CoV-2 infections in Ontario, Canada (September 1, 2020 to February 28, 2021) during which time, the original wild-type virus was predominantly circulating. The model incorporates empirically-derived behaviour data collected during the second wave of the SARS-CoV-2 pandemic in Ontario to account for two different levels of risk-taking behaviour and the degree to which behaviour changed as a function of the number of new daily cases of COVID-19. The model was developed to describe the epidemic prior to widespread vaccine distribution during a time period in which non-essential businesses had reopened with capacity limitations, private indoor social gatherings were limited to 10 individuals, and daycares and schools had reopened with the associated high contact occupations, such as teachers and bus drivers, returning to work (Canadian Institute for Health Information, 2021). Public health restrictions remained reasonably consistent across the province between September and December 2020 with some local increases in restrictions until a provincial "shutdown" order was implemented on December 26, 2020 (Canadian Institute for Health Information, 2021).

The temporary "shutdown" policy prohibited indoor gatherings, in-person shopping in non-essential businesses, and indoor/outdoor dining (Office of the Premier: Government of Ontario, 2020). This order was ultimately expanded to include a "stay-at-home" order which required individuals to remain at home with some exceptions (i.e., grocery shopping, health care, exercise) and was extended until mid-February 2021 for most health regions (Office of the Premier: Government of Ontario, 2021a) and to March 8 for two of the largest health regions in Ontario (Office of the Premier: Government of Ontario, 2021b). During the time period in which these policies were in effect, schools were closed to in-person learning with a graduated reopening based on public health indicators by region (Office of the Premier: Government of Ontario, 2021a; 2021c). Consequently, the provincial policy was in effect from December 26, 2020 until the end of the second wave of COVID-19 in Ontario.

2. Methods

The study protocol covering the collection of the data used to parameterize the model was approved by the University of Guelph Research Ethics Board (protocol #20-04-011) and the University of Toronto Research Ethics Board (protocol #38251). The remainder of the data used were publicly available and, as such, approval by a research ethics board was not required. A detailed description of the full methodology is included in the Appendix.

2.1. Model overview

Using a modified 'Susceptible-Exposed-Infectious-Recovered' framework, we developed an age- and risk-structured compartmental model describing SARS-CoV-2 transmission during the second pandemic wave in Ontario, Canada (September 1, 2020 to February 28, 2021). Both the detection of SARS-CoV-2 variants of concern (VOC) and the introduction of vaccines beginning in late December 2020 had the potential to create a complex impact on the second wave of infections in Ontario and projected model outcomes. However, by March 1, 2021 fewer than 35% of isolates were VOCs (Ontario Agency for Health Protection and Promotion (Public Health Ontario), 2021a) and less than 5% of the Ontario population had completed a two dose vaccine regimen (Ontario Agency for Health Protection and Promotion (Public Health Ontario), 2022). Thus, these developments likely had minimal impact on disease dynamics during this time period and as such no vaccine or VOC effects were included in the model (details in Appendix Section 1 Epidemic Context). The model was run for 209 days beginning September 1, 2020 to capture all projected epidemic outcomes, including lagged outcomes such as deaths. Accordingly, outcomes were projected at 180, 195, and 209 days for infections, hospitalizations, and deaths, respectively.

Fig. 1 represents the model compartments and transitions between them. Residents of long term care (LTC) facilities were excluded from the model based on the total number of LTC residents in Ontario ($n = 133{,}470$). It was assumed that all LTC residents were over the age of 60 years (Statistics Canada, 2016). Case data were retrieved for Sept 1, 2020 to the official end of wave 2, February 28, 2021 and COVID-19 mortality data, excluding LTC deaths, were obtained for Sept 7, 2020 to March 29, 2021 using the dataset entitled Status of COVID-19 cases in Ontario (Government of Public Health Ontario, 2022). Hospitalization data were obtained for Sept 1, 2020 to March 15, 2021 from the COVID-19 Data Tool (Public Health Ontario, 2022). Deaths and hospitalization data were obtained for a wider range of dates to allow for lags in outcome data that would follow infections during the second pandemic wave. The model assumes that individuals remained infectious until they recovered or were admitted to hospital, recovered individuals remained immune from reinfection for the duration of the model run, and all deaths occurred in identified cases that were hospitalized. As the objective was to explore the epidemic over a short time period, the model assumed a closed population with no births or non-COVID-19 deaths. The model was constructed using R (R Core Team, 2019). Model equations can be found in the Appendix (Section 2 Model Equations).

Model state variables and their definitions are given in Table 1.

Table 2 describes the parameter symbols and definitions.

2.2. Model structure and parameters

The model was stratified by four age groups: <18, 18 to 39, 40 to 59 and 60 years and older using 2021 census data for Ontario (Statistics Canada, 2022). The model was further stratified by two levels of risk-taking behaviour to represent heterogeneity in precautionary behaviour within the population and its effect on SARS-CoV-2 transmission dynamics. Details of the stratification process and assumptions for population mixing between age and risk groups are shown in the Appendix (Section 4 Mixing).

Parameters describing the biological and clinical course of infection were derived from published studies and data from Public Health Ontario (Table 3, full details in Appendix Section 3 Model Parameters). The probability of transmission given contact between an infectious and susceptible individual was estimated using maximum likelihood estimation to approximate the observed cumulative number of deaths reported during the second wave of COVID-19 in Ontario. (Government of Public Health Ontario, 2022).

A parameter describing individual avoidance behaviour in response to increasing epidemic growth was estimated based on longitudinal survey data collected between September 2020 and November 2020. Survey data collection methods are described fully elsewhere (Brankston et al., 2022). Briefly, the survey instrument was administered online to a convenience sample of Ontario adults in each of 3 cycles over a period of 3 months and included questions about risk-modifying behaviours. A physical distancing index was calculated describing respondents' engagement in distancing behaviours during each of the three time periods and scaled from 0 to 1 with a higher score indicating a greater degree of distancing behaviour (details are in the Appendix Section 3 Model Parameters) (Merkley & Loewen, 2021).

Survey respondents were categorized into two levels of risk-taking behaviour. Risk taking was defined as a mean physical distancing index of 0.5 or lower over the 3 survey waves and a physical distancing index score of less than 0.75 for the final survey wave, assessed at a time during which the second wave of SARS-CoV-2 was underway. This accounts for individuals who changed their behaviour very little regardless of population infection risk. All other respondents were categorized as exhibiting risk averse behaviour.

A mixed effects linear regression model was developed to assess changes in the physical distancing index with changes in the number of daily new cases of COVID-19 (details are in the Appendix Section 3 Model Parameters). The regression

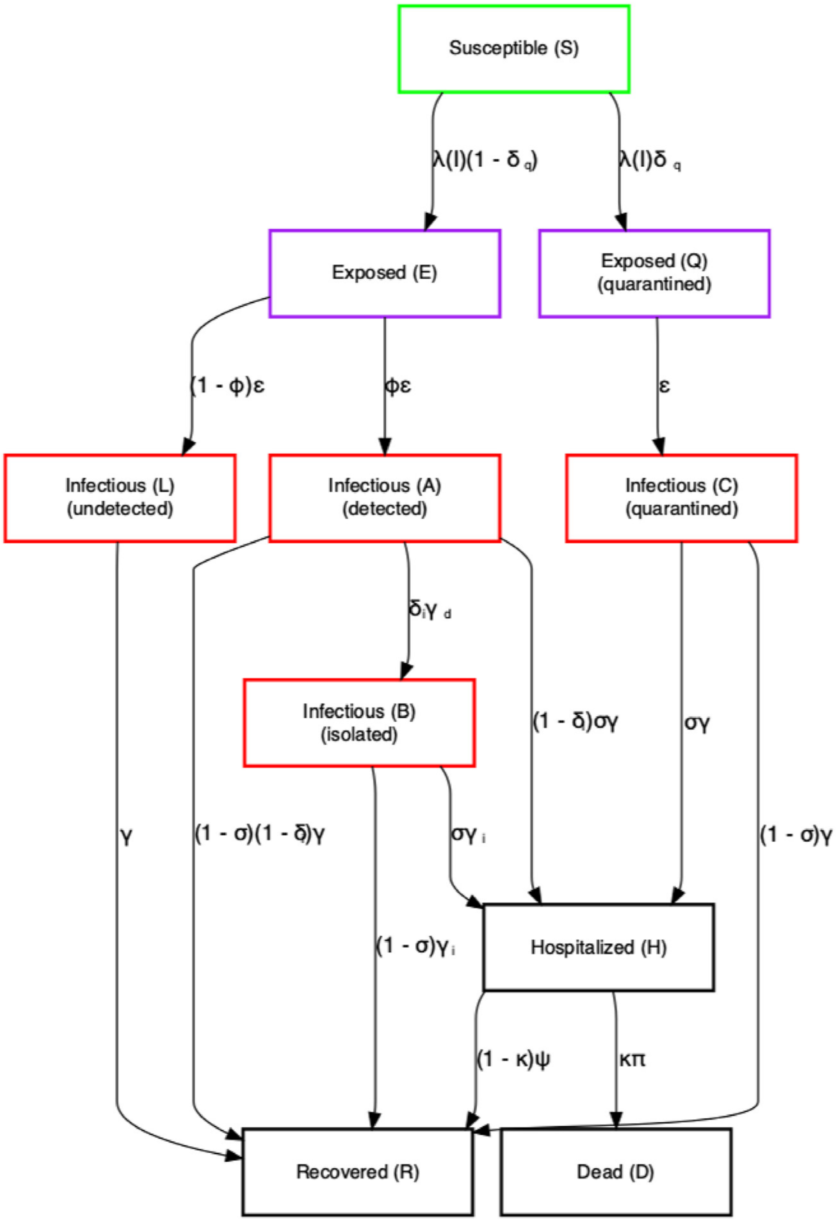

Fig. 1. Flow diagram of the model state variables and transitions between them. Individuals in the Exposed compartments (purple) were distributed between quarantined and not quarantined where quarantined cases represent those identified during contact tracing. The model is stratified by age group and level of risk-taking behaviour as assigned based on data from a behaviour survey collected between September and December 2020. All those hospitalized were assumed to be no longer infectious and all deaths were assumed to occur in those who were hospitalized. All recovered individuals were assumed to remain immune to reinfection for the duration of the model.

coefficients for a given age group and risk level represent the change in the physical distancing index for each additional case of COVID-19 reported in Ontario and serve as the avoidance behaviour parameter.

2.3. Model scenarios

Model scenarios are outlined in Table 4. The "counterfactual" scenario represents the projected epidemic outcomes had individuals not responded to increasing epidemic growth with avoidance behaviour and no policy was implemented to control the epidemic, apart from measures that were already in place in September 2020. Scenario 2 reflects the projected epidemic outcomes had no additional policy been implemented but individuals engaged in avoidance behaviour in response to epidemic growth (i.e., new daily cases). Scenario 3 represents the projected epidemic outcomes when individuals engaged

Table 1
Model state variables and definitions.

Variable	Description
S	Number of susceptible individuals
E	Number of exposed individuals
Q	Number of exposed individuals (quarantined)
A	Number of infectious individuals
B	Number of infectious individuals (isolated)
C	Number of infectious individuals (quarantined)
K	Number of infectious individuals (undetected)
H	Number of hospitalized individuals
D	Cumulative number of COVID deaths
R	Number of recovered individuals
Y	Cumulative number of hospitalizations
Z	Cumulative number of infections
I	Number of newly reported infectious cases
J	Number of newly reported infectious cases (in quarantine)

Table 2
Parameter symbols and definitions.

Parameter	Definition
m	Age group
i	Risk level (i.e., risk averseness)
δ_q	Probability of being detected and quarantined
δ_i	Probability of being isolated
λ	Force of infection
β	Transmission probability
θ	Number of contacts
ε	1/Latent period (rate of becoming infectious)
σ	Probability of hospitalization
γ	1/Infectious period (rate of recovery from infection)
γ_d	1/Average time to case detection (symptom onset to case report)
γ_i	1/Average time in isolation once detected
κ	Probability of death among hospitalized cases
π	1/Average time to death once hospitalized
ψ	1/Average time in hospital
rr_i	Relative risk of transmission with isolation
φ	Probability of being detected (i.e., fraction detected)
α	Avoidance behaviour parameter in response to cumulative deaths (increase in the physical distancing index per death)
$interv$	Reduction in contacts with stay-at-home order
ρ	1/Duration of being a new case

in avoidance behaviour and a province-wide “shutdown” order was issued on December 26, 2020 resulting in an estimated 40% reduction in contacts (Yuan et al., 2022).

2.4. Outcomes

Key model outputs include the final epidemic attack rate (the proportion of the Ontario population that was infected, including symptomatic and asymptomatic individuals), the total number of hospitalizations, and the total number of deaths for each model scenario during the second wave of SARS-CoV-2 in Ontario. The total number of infections averted, number of hospitalizations averted, and number of deaths averted under each different scenario relative to the counterfactual model were also evaluated. The impact of each model scenario was assessed by comparing the scenario-specific age and risk distributions for each of the outcomes.

2.5. Sensitivity and uncertainty analyses

Uncertainty with respect to the avoidance behaviour parameter was assessed by varying the value of the parameter within the 95% confidence intervals of the regression coefficients using Latin Hypercube Sampling (Blower & Dowlatabadi, 1994) for scenarios in which this parameter was used (scenarios 2 and 3). For each scenario that included the avoidance behaviour parameter, we ran 100 simulations of the model using a different set of avoidance behaviour parameters for each iteration. Where applicable, for each outcome, the median value and range capturing 95% of values are reported.

A univariate analysis of sensitivity of each outcome to an increase or decrease of the avoidance behaviour parameter using the lower and upper 95% confidence bounds of the regression coefficient was performed according to established procedures

Table 3
Model parameters and values.

Parameter Type	Age group	Risk group	Value	Source
Natural History				
Transmission probability per contact	<18	All	0.1401498	Model fitting
	18–39		0.1643579	
	40–59		0.1615146	
	60+		0.5519466	
Latent period, days	All	All	3.3	Zhao et al. (2021)
Infectious period, days	<18	All	8	(Ontario Agency for Health Protection and Promotion (Public Health Ontario)., 2021), (Ontario Agency for Health Protection and Promotion (Public Health Ontario), 2021b), (Cevik et al., 2021)
	18–39		11	
	40–59		13	
	60+		13	
Probability of hospitalization	<18	All	0.004	(Ontario Agency for Health Protection and Promotion (Public Health Ontario), 2021c)
	18–39		0.008	
	40–59		0.027	
	60+		0.152	
Probability of death given hospitalization	<18	All	0.0000	Papst et al. (2021)
	18–39		0.0163	
	40–59		0.0686	
	60+		0.3026	
Average time to death once hospitalized, days	<18	All	10.1	Xia et al. (2022)
	18–39		10.1	
	40–59		11.85	
	60+		16.3	
Average time in hospital among survivors, days	<18	All	10.1	Xia et al. (2022)
	18–39		10.1	
	40–59		11.85	
	60+		16.3	
Intervention-related				
Proportion of normal number of contacts estimated to occur during stay-at-home order	All	All	0.6	Yuan et al. (2022)
Probability case quarantines after notification by contact tracing	<18	All	0.0762	(Hamadeh et al., 2021; Wu et al., 2021)
	18–39		0.0762	
	40–59		0.0855	
	60+		0.0942	
Probability case isolates after detection	All	All	0.45	Wu et al. (2021)
Average time to case detection (symptom onset to case report and management), days	All	All	6.25	(Office of the Auditor General of Ontario, 2020), (Ontario Agency for Health Protection and Promotion (Public Health Ontario)., 2020)
Average time in isolation once detected, days	All	All	7.75	Ontario policy in 2020 (Government of Ontario: Ministry of Health, 2020)
Probability of being detected if infected (i.e., fraction detected)	<18	All	0.254	Hamadeh et al. (2021)
	18–39		0.254	
	40–59		0.285	
	60+		0.314	
Relative risk of transmission with isolation	All	All	0.1	Assumed as per (Tuite et al., 2020)
Behaviour-related				
Number of contacts			Matrix (see Appendix Section 4)	(Prem et al., 2021) and empirical data (Brankston et al., 2021b)
Avoidance behaviour parameter in response to cumulative deaths	<18	Risk taking	0	Derived from empirical data (Brankston et al., 2022)
	18–39	Risk taking	0	
	40–59	Risk taking	0	
	60+	Risk taking	0	
	<18	Risk averse	0.0001227243	
	18–39	Risk averse	0.0001220000	
	40–59	Risk averse	0.0001209000	
	60+	Risk averse	0.0001463000	
Proportion of the population	<18	Risk taking	0.06981928	Empirical data (Brankston et al., 2022) and Canadian census (Statistics Canada, 2022)
	18–39	Risk taking	0.11353965	
	40–59	Risk taking	0.07160641	
	60+	Risk taking	0.03284745	
	<18	Risk averse	0.12218379	
	18–39	Risk averse	0.1762853	
	40–59	Risk averse	0.19317068	
	60+	Risk averse	0.22054744	

Table 4
Model scenarios.

Scenario	Condition	Date of implementation of shutdown order
1	Counterfactual	Not implemented
2	Individual avoidance only	Not implemented
3	Individual avoidance + policy	Dec 26, 2020

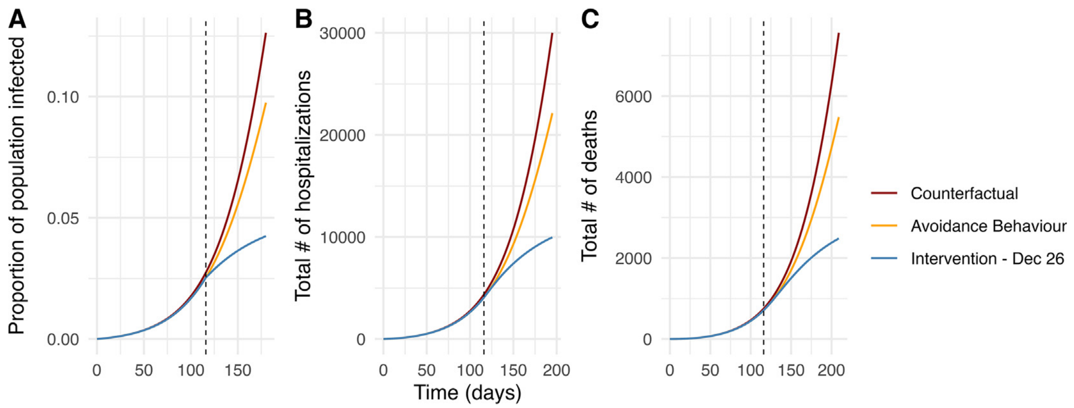

Fig. 2. Model projected outcomes by scenario for the second SARS-CoV-2 pandemic wave in Ontario. Fig. 2A represents the proportion of the Ontario population infected, 2B represents the cumulative number of hospitalizations, and 2C represents the cumulative number of deaths during the second SARS-CoV-2 pandemic wave in Ontario for scenarios 1 to 3. The vertical dashed line represents the initiation of the December 26 intervention.

(Okaïs et al., 2010). The deviation of the attack rate, total number of hospitalizations, and total number of deaths from the original model outputs to the upper and lower limits were calculated.

3. Results

Model fitting results demonstrate that the model trajectory for cumulative deaths closely matched the observed values (Appendix Fig. A1). Early in the epidemic, while cumulative deaths were low, deviations from observed values were unstable. However, once the cumulative number of observed deaths was greater than 100 at day 58, the median deviation of model projections from observed values was 2.9% (range 0–14.3%). A plot of the residuals shows systematic deviation of the model to the data when comparing the model trajectory for cumulative deaths (Appendix Fig. A2A). This is indicative of a poor fit however, when plotting the residuals for daily reported deaths, the random pattern of the residuals as a function of time suggest that the model provides a good fit to the observed data (Appendix Fig. A2B).

Fig. 2 and Table 5 show the model outcomes by scenario. In the counterfactual scenario with no individual avoidance behaviour and no new policy interventions beyond the measures that were in place in September 2020 (scenario 1), the second wave of the pandemic in Ontario was projected to have resulted in 12.6% of the population becoming infected, 30,021 hospitalizations, and 7565 deaths. Individual avoidance behaviour alone (scenario 2) was estimated to reduce the final attack rate by 23.1%, the number of hospitalizations by 26.2%, and the number of deaths by 27.5% compared to the counterfactual scenario (Tables 5 and 6).

The provincial policy issued on December 26, 2020, combined with individual avoidance behaviour (scenario 3), resulted in a projected epidemic attack rate of 4.2% with a total of 9978 hospitalizations, and 2484 deaths. By comparison, the model scenario in which no additional policy was implemented resulted in more than twice the projected epidemic attack rate (9.7%), number of hospitalizations (22,137), and deaths (5,481). The model closely approximated the cumulative number of deaths and underestimated the number of hospitalizations compared with observed data from the second wave of COVID-19 in Ontario (Table 5).

Table 5
Model outcomes by scenario. Observed data from Ontario is included for comparison.

Scenario	Final epidemic size (#)	Final attack rate (%)	Cumulative hospitalizations (#)	Cumulative deaths (#)
1	1,780,504	12.6	30,021	7565
2	1,373,727	9.7	22,137	5481
3	598,217	4.2	9978	2484
Observed			11,939	2448

Table 6
Outcomes averted from the counterfactual scenario to behaviour avoidance only, from the counterfactual scenario to the December 26 intervention, and from behaviour avoidance only to the December 26 intervention, 2.5%–97.5% range (varying the avoidance behaviour parameter within the 95% confidence interval of each estimate).

Scenario comparison	Median total infections averted (2.5%–97.5% range)	Median total hospitalizations averted (2.5%–97.5% range)	Median cumulative deaths averted (2.5%–97.5% range)
Scenario 1 to 2	401,452 (318,576–481,422)	7818 (6250–9149)	2081 (1652–2406)
Scenario 1 to 3	1,181,140 (1,163,331–1,199,586)	20,026 (19,679–20,349)	5078 (4990–5159)
Scenario 2 to 3	774,363 (756,555–792,809)	12,142 (11,795–12,465)	2993 (2905–3075)

Table 7
Rate of projected infections, hospitalizations, and deaths per 1000 population by age and risk stratifications for scenarios 1 to 3. Stratifications are grouped according to age group, risk level, and age group and risk level combined.

Scenario	Number of infections per 1000 population			Number of hospitalizations per 1000 population			Number of deaths per 1000 population		
	1	2	3	1	2	3	1	2	3
Age									
<18	124.7	97.2	41.2	0.16	0.12	0.05	0.000	0.000	0.000
18–39	147.5	116.5	50.6	0.37	0.29	0.13	0.007	0.005	0.002
40–59	107.2	83.8	36.2	0.99	0.77	0.34	0.072	0.056	0.023
60+	123.4	89.9	40.5	7.01	5.10	2.32	2.094	1.513	0.688
Risk level									
Risk taking	156.4	132.7	55.7	1.92	1.62	0.70	0.436	0.366	0.159
Risk averse	114.1	83.1	37.0	2.22	1.55	0.71	0.578	0.398	0.183
Age and risk									
<18 risk taking	112.8	94.5	38.5	0.15	0.12	0.05	0.000	0.000	0.000
18-39 risk taking	168.6	144.1	60.6	0.42	0.36	0.15	0.007	0.006	0.002
40-59 risk taking	152.3	129.4	54.4	1.41	1.19	0.51	0.102	0.086	0.035
60 + risk taking	218.4	184.0	79.2	12.40	10.45	4.56	3.690	3.100	1.353
<18 risk averse	131.5	98.8	42.7	0.17	0.13	0.05	0.000	0.000	0.000
18-39 risk averse	133.9	98.8	44.2	0.34	0.25	0.11	0.006	0.004	0.002
40-59 risk averse	90.4	66.9	29.5	0.83	0.62	0.27	0.061	0.044	0.019
60 + risk averse	109.3	75.9	34.7	6.21	4.30	1.98	1.856	1.276	0.589

Voluntary avoidance behaviour alone (scenario 2) was estimated to have averted nearly half of the infections, hospitalizations, and deaths from the counterfactual scenario compared with the outcomes averted in the scenario simulating the provincial "shutdown" (scenario 3) (Table 6).

Table 7 represents the age- and risk-specific rates of infections, hospitalizations, and deaths per 1000 population. Age-specific infection rates were projected to be highest in adults under the age of 40 whereas hospitalization and mortality rates were progressively higher with increasing age. Risk-specific infection rates were 37–60% higher and mortality rates were 8–25% lower for those in the risk taking group relative to the risk averse group. Hospitalization rates were equivocal, ranging from 13% lower to 5% higher in the risk taking group. While, age/risk-specific infection and hospitalization rates for those under the age of 18 were estimated to be similar regardless of risk status, both rates were lower in the risk averse group relative to the risk taking group in those older than 18 years. Age/risk-specific mortality rates were similar regardless of risk status in those under the age of 40 years however, mortality rates were lower for those older than 40 years and in the risk averse group compared with the risk taking group of the same age.

3.1. Sensitivity analysis

The sensitivity analysis for the avoidance behaviour parameter showed that the percent change from the original model outputs for the attack rate, total number of hospitalizations, and total number of deaths was lower than 15% in both scenarios that used the avoidance behaviour parameter (scenarios 2 and 3). The percent change for the model outcomes ranged from 8.7% to 12.5% for the attack rate, 8.9%–12.8% for cumulative hospitalizations, and 9.0%–13.0% for cumulative deaths.

4. Discussion

We present a model that explores the impact of individual avoidance behaviour and policy-mediated avoidance behaviour on epidemic outcomes in response to increasing epidemic growth during the second wave of SARS-CoV-2 infections in Ontario, Canada. Behavioural factors are key determinants of infectious disease dynamics and the outcomes of epidemics however, combining disease dynamics with behavioural observations is challenging (Funk et al., 2010; Verelst et al., 2016; Weston et al., 2018). Our unique approach used an analysis of empirical data collected during the second wave of SARS-CoV-2 infections in Ontario (Brankston et al., 2022) to estimate an age- and risk-stratified model parameter to serve as a behavioural feedback mechanism in response to increasing epidemic growth. This approach advances our understanding the complexities of interactions between behaviour and disease dynamics.

This analysis demonstrates that, while individuals respond to disease risk with voluntary changes in behaviour, the impact of individual avoidance behaviour alone is not likely to reduce transmission enough to suppress an epidemic of SARS-CoV-2. While individual avoidance behaviour in response to increasing epidemic growth reduced the projected attack rate by more than 20%, relying on individual responsibility would still have resulted in an overwhelming number of hospitalizations and deaths due to SARS-CoV-2 during the second wave in Ontario. In contrast, government issued policy in addition to voluntary avoidance behaviour was projected to have contributed the majority of behaviour change and resultant mitigation of transmission with a final epidemic attack rate that was 67% lower than a scenario with no government mitigation measures or individual avoidance behaviour.

Neither policy-mediated nor voluntary behaviour change had a substantial impact on the distribution of age- and risk-based outcomes. At both levels of risk taking behaviour, projected infection rates were concentrated in younger age groups while severe illness and mortality occurred disproportionately in the oldest age group. This is consistent with evidence demonstrating younger individuals are more likely to engage in riskier behaviours that may result in infections (Alsan et al., 2020; Brankston et al., 2021a, 2022; Seale et al., 2020) and evidence of the risk of severe illness and mortality being concentrated in the older age groups (Levin et al., 2020; Public Health Agency of Canada, 2022b). Interestingly, in all three scenarios, age/risk-specific infection, hospitalization, and mortality rates were lower in the risk averse group relative to the risk taking group in most age groups. These results provide evidence that engagement in precautionary behaviours is protective of severe disease and death due to COVID-19.

Consistent with the current results, previous models have projected moderate impact of voluntary avoidance behaviour on epidemic outcomes. For example, a model of the 2009 H1N1 influenza pandemic estimated that individual avoidance behaviour reduced the peak prevalence of infections by 31% and reduced the final attack rate by only 13% (Bayham et al., 2015). Similarly, engagement in voluntary avoidance behaviour was insufficient to control the second wave of SARS-CoV-2 in Hong Kong, necessitating the implementation of policy-mediated avoidance behaviour (Gao et al., 2021).

Collective action is paramount in responding to public health crises but it conflicts with the culture of individualism in Canada (Hofstede, 2001). This makes pandemic response challenging to navigate as decision-makers must strike a balance between individual rights and the collective good. Faced with a second wave of SARS-CoV-2, Ontario provincial decision-makers attempted to rely on individual accountability to mitigate transmission (Cameron-Blake et al., 2021). However, our results demonstrate that individual responsibility alone would not have been sufficient to control the second wave of SARS-CoV-2 in Ontario. Indeed, a government issued policy lasting two months was eventually implemented to mitigate transmission (Office of the Premier: Government of Ontario, 2020). Avoiding such lengthy and restrictive public health measures may require an examination of different approaches to pandemic response, which have varied between and within countries.

Prior to the widespread availability of vaccines, countries using suppression strategies implemented early, proactive measures with the goal of halting community transmission while countries using mitigation strategies aimed to ‘flatten the curve’ by acting in a targeted and stepwise manner to avoid overwhelming health care systems (Baker et al., 2020; Sachs et al., 2022). Previous research has demonstrated that the rapid and proactive government action involved in a suppression approach leads to lower levels of virus circulation (Aknin et al., 2022), fewer deaths (Loewenthal et al., 2020; Stockenhuber, 2020), and a reduced length of time measures need to remain in place for control of the epidemic (Stockenhuber, 2020). Compared with countries that pursued mitigation strategies, those that pursued suppression strategies had lower average policy stringency and higher life satisfaction (Aknin et al., 2022), the latter of which has been associated with greater engagement in avoidance behaviours (Krekel et al., 2020). Consequently, regions that implemented suppression strategies may have avoided long periods of strict control measures while at the same time encouraging voluntary avoidance behaviour and minimizing negative pandemic-related health outcomes (Aknin et al., 2022).

4.1. Limitations

Our model has several limitations. It does not account for stochasticity, geospatial effects, imperfect isolation of infected individuals, reinfection with SARS-CoV-2, or dynamic contact patterns. The survey data used to derive the avoidance behaviour parameters comes with several potential biases including non-representativeness of the sample (a risk with any survey), limiting participation to those who use the Internet, and self-report which introduces the potential for recall, response, and social desirability biases. This model contains merely a snapshot of the second wave of the pandemic in Ontario and individuals may respond to a second wave of infections differently than the first rise in cases potentially evoking less voluntary avoidance behaviour. Furthermore, individuals may have adopted stronger self-protective measures in the complete absence of government action that cannot be described by a linear extrapolation of the situation of moderate incidence under government mandates.

4.2. Conclusion

Building upon our unique approach of incorporating individual avoidance behaviour into transmission models will enhance our understanding of disease dynamics under a variety of conditions. Given the dynamics of SARS-CoV-2 in a pre-vaccine era in Ontario, Canada, relying on individual avoidance behaviour in the absence of government action was not sufficient to mitigate transmission of disease and the associated health outcomes. Government intervention was required to control the second wave of SARS-CoV-2 and reduce hospitalizations and mortality. Strong public health action and government leadership are crucial to minimize the impact of SARS-CoV-2. A suppression approach to pandemic control prior to vaccine availability may have minimized negative epidemic outcomes while avoiding lengthy and stringent control measures. Future research should attempt to identify characteristics of pandemic approaches that control disease transmission while limiting the stringency of control measures.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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CRediT authorship contribution statement

Gabrielle Brankston: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **David N. Fisman:** Writing – review & editing, Conceptualization. **Zvonimir Poljak:** Writing – review & editing, Methodology, Conceptualization. **Ashleigh R. Tuite:** Writing – review & editing, Conceptualization. **Amy L. Greer:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AT was employed by the Public Health Agency of Canada when the research was conducted. The work does not represent the views of the Public Health Agency of Canada.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2024.04.001.

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