Assessing the Impact of Alternative Responses to COVID-19: Stopping the Spread in Newfoundland and Labrador, Canada

Une évaluation de l'impact des réponses alternatives au COVID-19: arrêter la propagation à Terre-Neuve-et-Labrador, Canada

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***Abstract*— The COVID-19 global health crisis has had a significant impact on societies worldwide. To evaluate the effectiveness of transmission prevention strategies, infectivity modeling can be used to interpret and analyze various virus responses. In this study, compartmental modeling approaches are used to model and quantify the success of various control techniques, such as social behaviors. Newfoundland and Labrador (NL), a province in Canada, is a relatively isolated and easily-monitored region that can be used to study the characterization and effectiveness of infectivity model coefficients. The province has few points of entry and a lower contact frequency than densely populated urban districts. Based on the results, the implications of social distancing removed an estimated 85% of the susceptible population from potential exposure to a viral transmission. The modeling also determined a basic COVID-19 reproductive number of 3.7 in NL, higher than the globalized average of 2.3. Compartmental models are used to determine the validity of alternative pandemic responses, such as nonvaccine social practices to fight the wave of infection. The overall impact of COVID-19 in NL is concluded to have been effectively controlled by the implementation of social distancing behaviors, allowing for accurate quantification of modeling parameters.**

***Résumé*— La crise sanitaire mondiale du COVID-19 a eu un impact énorme sur les sociétés du monde entier. Pour évaluer l'efficacité des stratégies de prévention de la transmission, la modélisation de l'infectiosité peut être utilisée pour interpréter et analyser les nombreuses réponses des virus. Dans cette étude, les approches de la modélisation compartimentée sont utilisées pour modéliser et quantifier le succès des techniques de contrôle, comme les comportements sociaux. La Terre-Neuve et Labrador (NL), une province du Canada, est une région relativement isolée et facilement contrôlable qui peut être utilisé pour étudier la caractérisation et l'efficacité des coefficients du modèle d'infectiosité. La province a une fréquence de contact plus basse, et moins de points d'entrée, que les villes urbaines plus peuplées. En se basant sur les résultats, les implications de la distanciation sociale ont retiré en estimation 85% de la population sensible à l'exposition d'une transmission virale. Le modèle a aussi déterminé un nombre élémentaire de reproductivité du COVID-19 qui vaut 3,7 à Terre-Neuve et Labrador, plus haute que la moyenne mondiale de 2,3. Les modèles compartimentés sont utilisés pour déterminer la validité des réponses alternatives pandémiques, comme les pratiques sociales non-vaccinales pour combattre la vague de l'infection. L'impact total de la COVID-19 à Terre-Neuve et Labrador a conclu à un contrôle efficace par l'implémentation des comportements de la distanciation sociale, ce qui permet une quantification précise des paramètres de la modélisation.**

***Index Terms*— COVID-19, epidemiology, infectious disease modeling, Newfoundland and Labrador (NL), susceptible, exposed, infected, and recovered (SIR and SEIR).**

NOMENCLATURE

S	Susceptible population.
E	Exposed population.
I	Infected population.
R	Recovered population.
N	Total population ($N = S + E + I + R$).
β	Transmission rate.
α	Infection rate.
γ	Recovery rate.
c	Contact rate.
a	Disease-related death rate.
d	Average death rate (not disease-related).

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b	Birth rate.
R_0	Basic reproductive number—the average cases caused by one infected individual into a totally susceptible population.
$R(t)$	Effective reproductive number—average number of secondary cases per primary case occurring at time t.

I. INTRODUCTION

THE impacts of the Severe Acute Respiratory Syndrome 2019 novel coronavirus (SARS-CoV-2), also known as COVID-19, are transcendent on a global scale, claiming over 525 000 lives by the beginning of July 2020 [1]. COVID-19 infectivity is particularly impactful. Due to the easy transmissibility of the virus, all of Canada's provinces and territories were prompted to enact the State of Emergency, close K-12 schools, and enforce various levels of lockdowns for at-risk facilities and regions [2]. The timing and scale of a provincial response play a vital factor in the containment of COVID-19.

Epidemics are often analyzed through the use of susceptible, exposed, infected, and recovered (SIR and SEIR) modeling, or other forms of infectivity modeling, as seen in applications within Wuhan, China [3], [4], Africa [5], and the United States [6]. Such investigations into viral transmissibility can prove if social behaviors are helping prevent larger outbreaks of infectious disease, as shown in the analysis of the United States in comparison to other high-population countries in the study by Dandekar and Barbastathis [6].

The results of the investigation into infectivity modeling illustrate the effectiveness of controls implemented by the province of Newfoundland and Labrador (NL). Through a process of curve-fitting using the epidemiological trends from coronavirus cases in the province, various growth and stagnation parameters were modeled, which ultimately demonstrated control of the viral transmission. The purpose of this article is to overview historic responses to a pandemic, in comparison to the successful control seen in 2020 against the COVID-19 pandemic using infectivity modeling. This will be used to evaluate the potential implications of alternative responses to global health crises implemented on a local scale.

This article is organized as follows. Section II provides context for the regional characteristics of NL and how this played a factor in the 2019 Coronavirus and 1918 Flu pandemics. Section III introduces the use of infectivity models for COVID-19 (the SIR and SEIR approaches), followed by results of applying the modeling in Section IV. This article is then concluded in Section V.

II. NL: A BACKGROUND

NL, Canada's most easterly province, is home to just over 519 000 people, with the considerable majority inhabiting the island portion of the province [7]. Unlike many provinces of mainland Canada that are accessible by air, road, water, or rail, the island of Newfoundland is only connected by a limited number of daily flights, or a selective few ferry crossings [8]. The province's geographical isolation has played a significant role in the control of viral transmissibility, recently having COVID-19 reach the province 50 days after the first reported case in Canada [9]. A vaccine for the virus is estimated to arrive for emergency use within the first quarter of 2021, at the earliest [10], indicating the importance of monitoring the isolation and social behaviors that positively control viral growth for the interim period.

A. Introduction to the 2019 Novel Coronavirus

On March 15, 2020, a reported 300 individuals attended a wake at Caul's Funeral Home in the province's capital city, St. John's, located in its eastern region [11]. Two days later, a second funeral was held in the establishment's chapel [11]. Unknowingly, the index case for the virus in St. John's was in attendance during that time and has been traced as the cause for the NL COVID-19 outbreak [12].

This initial surge in case counts is estimated to be contributing to 73% of the positive coronavirus cases in NL on March 29, 2020 [13]. Twenty-seven days after the first wake, two of the three deaths in the province were from the same region, originating from Caul's Funeral Home [14], [15]. This rapid increase in COVID-19 cases, starting within the 14-day incubation period of the Caul's Funeral Home visitations, can be seen in the infectivity modeling in Section II-B.

B. Response to COVID-19 and Caul's Funeral Home

By March 23, 2020, the infectivity caused by the funeral home events showed an accelerated number of documented COVID-19 cases, and government officials closed all nonessential services, and ordered individuals arriving from outside the province, regardless of their travel origins, to self-isolate for 14 days [16]. The travel regulations were escalated on April 30, 2020, when nonresidents were prohibited from entering the province, unless given an exemption order from NL's Chief Medical Officer of Health [17]. These timely enactments, combined with the March 18, 2020, order to social distance, are believed to have played a considerable role in the 20-day streak of not having any developing coronavirus cases between April 7 and April 27, 2020 [18].

Due to its limited population size, NL has also been able to implement a rigorous testing program to combat the virus. Originally restricted for individuals who were simply considered carriers of COVID-19, testing criteria expanded twice, once on April 4, 2020, to include anyone whose personal or work circumstances create more chances to have contracted the virus, and expanded again on April 15, 2020, to anyone showing two or more symptoms [19], [20]. The consistent testing for coronavirus in NL has led to a high negative testing rate, as shown in Fig. 1 sourced from the province's COVID-19 Data Hub [21].

Table I summarizes the government enactments, social changes, and significant events for the month of April 2020 and the corresponding daily active COVID-19 case count. There appears to be a trend of decreasing active cases for each subsequent addition of government measures. Note, however, that there is a delay between government

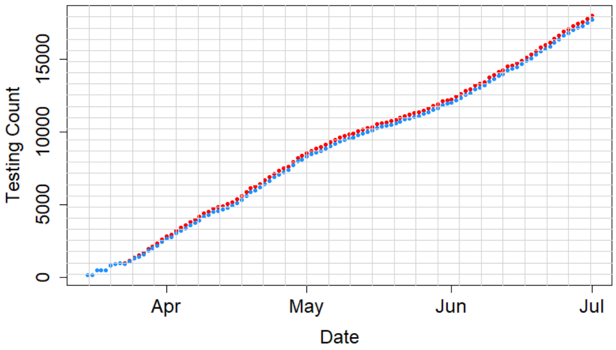

Fig. 1. Overview of cumulative COVID-19 tests over time (red) and the corresponding negative return on testing (blue) in NL, March 15, 2020–July 1, 2020. The minimal gap between trends indicates a limited number of cumulative cases.

TABLE I
APRIL 2020 TIMELINE OF ACTIVE COVID-19 CASES AND CHANGES IN SOCIAL BEHAVIORS, NL

Date	Active Cases	Event/Action/Change in Behaviour
2020-04-01	164	N/A
2020-04-02	172	School gatherings for evaluations cancelled
2020-04-04	184	Testing criteria expanded (persons of high risk)
2020-04-06	192	Second reported death
2020-04-07	177	Parks closed
2020-04-09	138	Third reported death
2020-04-15	85	Testing criteria expanded (2 or more symptoms)
2020-04-17	77	Public Health Emergency extended
2020-04-22	54	Airport access restricted by health authority
2020-04-27	34	Travelers required to sign a declaration form
2020-04-30	30	Non-residents no longer allowed entry

enactments, impact on public behaviors, and their effect on active cases (due to virus incubation times and delays in obtaining test results).

C. Historic Analysis of the 1918 Influenza

The 1918 Flu Pandemic, influenza of type A, known commonly as the Spanish Flu, is often regarded as the most influential pandemic to surface in history, with an estimated 500 million cases worldwide and 10% of cases ending in death [22]. Due to the global scale of COVID-19, it is interesting to draw parallels in the societal response to both pandemics.

Active cases of COVID-19 in NL hit an initial peak on April 6, 2020 [21]. At that time, the province had an active case total of 192 [21] (see Fig. 2 for active cases over time). Considering the population for the province as of January 2020 [23], the active cases per 10 000 people were 3.68. Comparatively, the deaths from the second wave of Flu in the Dominion of Newfoundland (which, at the time, was not yet a province of Canada) reached 1179 [24]. At the time of the Flu, the population is estimated to be half of what it was at the start of the COVID-19 pandemic [25]. Therefore, the mortalities per 10 000 people of the second Influenza wave were 45.2. At their peaks, the magnitude of Spanish Flu deaths in Newfoundland was 12 times that of the cases of COVID-19, despite their reproductive numbers being very close.

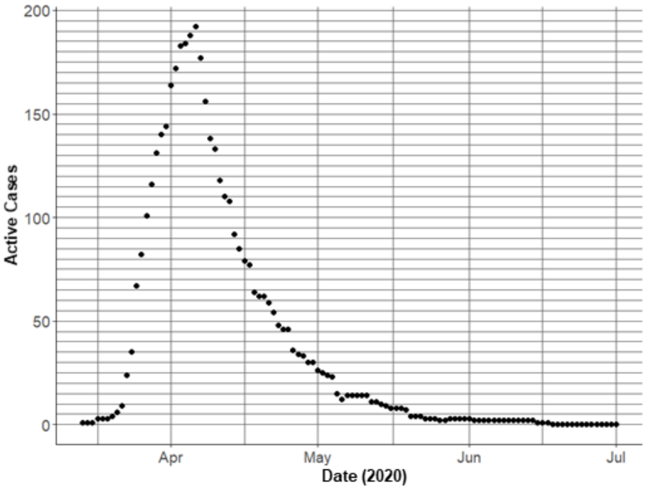

Fig. 2. Active COVID-19 cases on any given day in NL, spanning from the first reported case on March 14, 2020–June 15, 2020 (last active case).

The estimated R_0 value (the average number of cases caused by one infected person into a susceptible population) of the Spanish Flu was approximately 2 [26], whereas R_0 used in our modeling for COVID-19 was 2.3. A potential explanation for the considerable difference in case counts for both pandemics could be the timeliness and approach to intervention by the government and respective social distancing behaviors. Furthermore, the use of modern technology and telecommunications provided effective and efficient means to mobilize against the spread of COVID-19. As of March 18, 2020, the Minister of Health and Community Services for NL declared a Public Health Emergency and the special measures that would go into immediate effect to protect the general public [27]. This contrasts with the action of the Newfoundland government in 1918. An article in The Evening Telegram was published on October 15, 1918, ordering the public to limit gatherings and close buildings where possible (see Fig. 3) [28]. This article, released over a month after the generally accepted start to the second wave of the Spanish Flu [29], shared many of the same mandates of the COVID-19 Special Measures Order [16] but was issued much later in the epidemiological timeline.

A research team from the University of Missouri applied agent-based modeling on a northern Newfoundland community to observe the potential outcomes that could have been generated upon altering various media parameters [9]. Their research showed that the death and case rate could have been lowered if the public health measures have been implemented sooner following, or even in anticipation of, the first death. Although COVID-19 and the H1N1 of the Spanish Flu are different in their methods of infectivity [30], it can be assumed that the hurried actions of the 2020 NL health authorities have been a contributing factor to the province's relatively low virus impact.

III. INFECTIVITY MODELING

Compartmental models have been widely used to study infectivity modeling. The formulations of these models are a set of ordinary differential equations that evolve the dynamics

SPANISH INFLUENZA.

Instructions to Outport Magistrates.

Requests are constantly being sent to the Board of Health by Outport Magistrates for instructions in dealing with the influenza epidemic. The following points are to be noted:—-

1. The disease is highly contagious.

2. It is spread very largely by contact one with another.

3. It is advisable to prohibit any unnecessary gathering of people about stores, street corners, etc.

4 Close schools, churches, theatres, etc., if there is any indication of spread of disease.

5. Avoid a panic, but take this thing seriously and co-operate with the doctors, following strictly the advice given.

6. Good ventilation is very important—therefore admit sunlight and fresh air as much as possible.

7. Do not allow the patient to spit, and when coughing cover the mouth.

8. Never neglect the precaution of washing the hands before eating or after contact with a sick person.

Quarantine is difficult to establish with any degree of success and the presence of the police in an attempt to enforce quarantine would create more panic.

N. S. FRASER,
oct15,6i **Acting Medical Officer of Health.**

Fig. 3. Article published in Newfoundland's primary newspaper, The Evening Telegram, on October 15, 1918, officially providing directives on the Spanish Flu from the dominion's Medical Officer of Health [26].

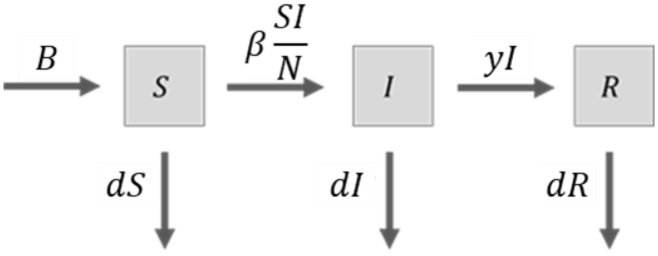

Fig. 4. Standard SIR model that shows the dynamics of disease propagation through a population.

between various population states, to be outlined briefly in the following. The two most common methods are known as SIR and SEIR [31].

An SIR model is based on the assumption that a susceptible individual becomes infected and is simultaneously able to infect other susceptible individuals. The person remains infectious until either they have recovered or passed away (died) [32]. SIR models are based on a susceptible class S, infected class I, and then a recovered or removed class R. A parameter y is used to model the recovery rate, where $1/y$ represents the average number of days a person is infectious. Fig. 4 illustrates the standard SIR model dynamics.

The SIR model is summarized by the following set of differential equations:

$$\dot{S} = B - dS - \beta\frac{SI}{N} \tag{1}$$

$$\dot{I} = \beta\frac{SI}{N} - dI - yI \tag{2}$$

$$\dot{R} = yI - dR \tag{3}$$

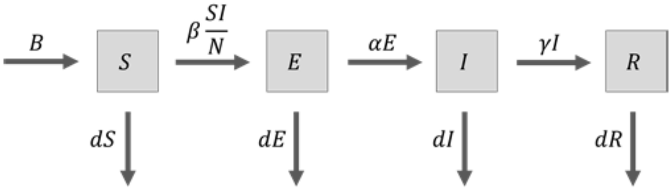

Fig. 5. Standard SEIR model that shows the dynamics of disease propagation through a population, now considering the exposure class.

where B represents the birth rate of the virus, N represents the total population size, β is known as the transmission rate that is the effective contact transmission rate from infected people, d represents the per capita death rate, and the notation $\dot{x}$ represents a time derivative of x.

In an SEIR model, if a susceptible individual comes into contact with an infected individual, they move into a latent exposed class E before becoming infectious. This modification improves the general SEIR model results over the SIR model as it is more realistic. Furthermore, a new term referred to as the mean generation time or serial interval is introduced and is defined as $G = 1/\alpha + 1/\gamma$. Here, α is defined as the infection rate such that $1/\alpha$ is known as the meantime from exposure until a person becomes infectious [33]. Fig. 5 summarizes the standard SEIR model.

Including (1) from earlier, the SEIR model is summarized by the following set of differential equations:

$$\dot{E} = \beta\frac{SI}{N} - dE - \alpha E \tag{4}$$

$$\dot{I} = \alpha E - (d + a)I - \gamma I \tag{5}$$

$$\dot{R} = \gamma I - dR. \tag{6}$$

In [31], SIR and SEIR models used for modeling infectious diseases were implemented, and coefficients to model social distancing were proposed. The impacts of social distancing were studied and explored through numerical simulations, and mathematical formulations show that the turning point between these two groups is when the effective reproductive rate is equal to 1. However, Yawney and Gadsden [31] did not take into consideration the effects of hot spots forming, such as retirement homes, long-term care homes, or agricultural processing plants.

In the case of COVID-19, the susceptible class is exposed to the virus as a function of the reproduction number, R_0, and the size of the infected class. The exposed class transitions to the infected class at a rate inverse to the incubation period, $1/\alpha$. The recovered class grows as a function of the infected class and the recovery rate. The number of deaths grows as a function of the number of infected individuals and the disease-related death rate, a. SEIR models demonstrate how, without intervention, a virus can enter a population and quickly spread.

Fig. 6 shows the general state-transition behavior of the SEIR model when an additional social distancing parameter is added, which removes a proportion of the susceptible population. In Fig. 6, p is defined as the proportion of individuals removed from the population. Furthermore, variations of the SEIR model may have the recovered class return to

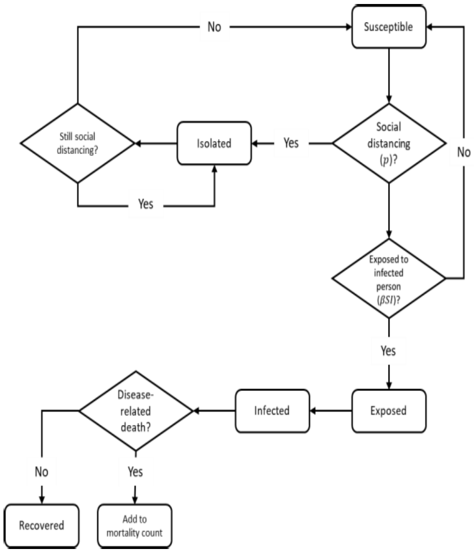

Fig. 6. Flowchart of the procedural process of the SEIR compartmental model, considering the logic of social distancing as a "media parameter."

TABLE II
SEIR MODEL VARIABLES

Parameter	Value	Significance
R_0	*3.7*	Basic reproductive number [37]
a	*0.014*	Disease related death rate [38]
b	9.9×10^{-3}	Per capita death rate [40]
d	7.6×10^{-3}	Per capita birth rate [41]
N_0	5.21×10^{5}	Initial population size [42]
nu	*0.0*	Vaccination rate (no vaccine yet)
α	*0.2*	Inverse of incubation period
γ	*0.2*	Inverse of transmission period
Social distancing (media parameter)	*N/A*	Changes in social distancing, removing 85% of population from susceptible
Caul's Funeral Home	*N/A*	Changes in susceptibility from the cluster of cases originating from Caul's Funeral Home

the susceptible class after some period [susceptible, exposed, infected, recovered, susceptible (SEIRS)] or enter directly to the susceptible population after infection (SIS). This would be seen after the response "no" to the mortality check seen in Fig. 6, rather than concluding at that point of recovery. This would be in the case if no immunity was gained from having the virus, or if it was only "short-term" immunity. It is still currently unclear how the role of immunity from COVID-19 plays a factor in the epidemiology of the virus, and so this variation is not used [34]. In addition, if the virus becomes seasonal (such as influenzas A, B, and C or the common cold) or if it is more likely to be transmitted during certain times of the year, the SEIR model can be adapted as a variable contact rate model in which an individual is periodically more likely to become infected.

The basic reproduction number, R_0, takes on the definition of "the number of new infections produced by a typical infected individual in a population at a disease-free equilibrium" [35]. When this reproduction number exceeds 1, exponential growth in case numbers occurs. The dynamics of this disease-spread are governed by the law of mass action. On the other hand, an epidemic is contained when $R_0 < 1$. However, this is sufficient but not necessary as the basic reproduction number may be above 1 and epidemics can be contained when the effective reproductive number, $R(t)$, falls below 1.

The reproductive number is one of the most discussed characteristics for the transmission method of a virus, as it gives an average number of individuals that one person infects with a given virus. Estimates for the COVID-19 R_0 value vary widely, from 1.4 to 6.5 [36]. This number is dependent on multiple factors, including how easily a virus can infect a new host, as well as the environment and culture of the community in which it is spreading.

IV. CASE STUDY: NL

Fitting the numerical SEIR model to the actual rate of cases in NL can provide an estimate of the R_0 value in the province. Assessments from various raw, publicly available data sources can be used to estimate the infectivity rate coefficients, the distribution spread, and patient recovery data. Known clusters (such as Caul's Funeral Home) can be implemented as subgroups of the population, where the R_0 value (and in turn, β) would be significantly higher than what is present outside of this scenario. Various antispread parameters (social distancing, restricted air travel, and communal lockdowns) can also be added as media parameters to monitor the effectiveness of such preventative measures.

The most basic way of using this model to represent COVID-19 cases in the province is to use an estimated value for the reproduction number R_0 of 2.3 [37], the disease-related death rate (a) of 0.014 [38], a transmission period of five days, and an incubation period of five days. Media parameters can also be introduced to allow computational consideration for the cultural and social behaviors of a population. These various parameters are summarized in Table II. To find the closest fit, values of the R_0, a, and p were iterated repeatedly to find the combination with the lowest error. This ideal curve fit has an R_0 of 3.7, the disease death rate of 1.3%, and an 85% effectiveness in social distancing. The comparison between this model and the actual cases can be seen in Fig. 7.

The reproductive number found in this model is much higher than the estimated value of 2.3, sourced from the Imperial College London report [37]. This may be attributed to factors within NL, which increases transmission, specifically the Caul's Funeral Home cluster of cases in the period of March 13–15, 2020. To model "Caul's Cluster," the contact transmission rate is increased for a defined period of time, escalating the risk for exposure within the susceptible population. This proportion, c, had the best fit for the model when the susceptible population was at an 80% increased risk. This model also had a lower overall reproduction number of 3.35. The effectiveness of social distancing remains the same at 85%.

The relatively few cases of COVID-19 causes difficulty in accurately estimating the reproduction number in NL.

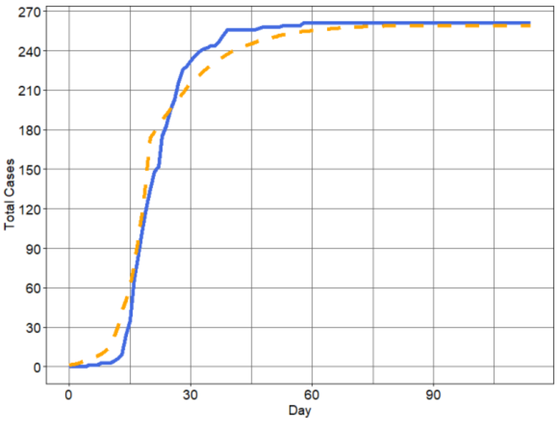

Fig. 7. Comparison of the fitted model for COVID-19 cases in NL (orange dashed lines) and the actual monitored data from the Provincial Data Hub (blue solid line).

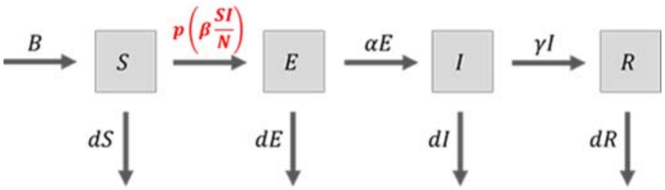

Fig. 8. Adapted SEIR model to include a coefficient, p, which reduces the overall transfer from S to E, attributed to social distancing.

The large grouping of cases sourced to one incident confuses this even more, where a single individual causing the specific outbreak is not representative of the average number of people infected per one case. However, it is clear from the early and rapid growth of the virus that the reproductive number is higher than the globally averaged 2.3, and there was a higher potential for COVID-19 to spread widely throughout the few communities on the eastern portion of the island. This modelling also demonstrates that social distancing was highly effective at restricting the spread of the coronavirus in NL. Fig. 8 is an updated version of Fig. 5, and illustrates how the rate of transfer from Susceptible to Exposed is altered slightly when the p parameter is present in the model. Fig. 9 illustrates the cumulative case count predicted if social distancing was not enforced, using the effectiveness rate of the model. To achieve this, the social distancing parameter that was introduced earlier to represent an average reduction in contacts, p, is to be removed.

If this parameter is fitted such that the modeled and actual curves are following the same trend, the effectiveness from the social distancing behaviors can be quantified (as stated on the previous page, 85% effective). With all variables fitted to the actual curve, it is then possible to remove this p parameter and analyze the potential outcome if social distancing has not been enforced and followed. This is the procedure followed to produce the resultant curve shown in Fig. 9.

A. Validation of Results and Procedures

For this study, the date of the introduction of COVID-19 cases in NL was assumed to be on day 60 (March 14, 2020) following the first introduction of COVID-19 cases within Canada on January 15, 2020. Therefore, the parameter estimation was considered up to and including March 13, 2020, and used the most recent five days in that period as validation for the parameters. Furthermore, the assumption was made that the number of reported cases is equivalent to 20% of the total number of cases based on early assumptions of mild/asymptomatic cases making up 80% of the total caseload. Otherwise stated, the predicted infected count, which represents the total number of infected cases, was reduced by a factor of 5 for comparison to the reported numbers [31].

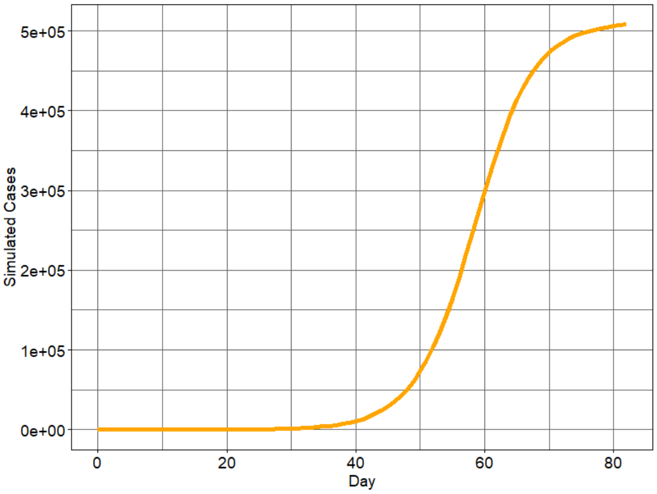

Fig. 9. Based on the 85% effectiveness of social distancing, this plot illustrates the predicted accelerated and widespread impact of COVID-19 if social distancing mandates have not been followed.

V. CONCLUSION

The NL response to the COVID-19 pandemic represents an important opportunity, demonstrating the many dimensions of the health crisis, which were well controlled through the inherent environment of the province. The considerable geographical isolation yields an opportunity to quantify specific magnitudes of the epidemiologic model, such as the allocation of individual characterizing parameters and coefficients. The restricted population size and reduced social interactions of the general population enabled an accurate and specific R_0 value assignment, 3.7. Due to only a single cluster producing the majority of infected cases, the contact tracing carried out by public health authorities was also simplified, which supported an easy (yet precise) estimation of the c value of 80%.

The successful performance of NL during the pandemic justifies the predicted effectiveness of social distancing, the leading method for mitigating the effects of an infectious disease. This achievement is also indicative of the significance of the role played by a population's inclination to stop the spread of a virus, such as COVID-19. Timely actions with appropriate social behaviors were demonstrated to greatly impact the outcome of a pandemic within a region, as seen by the modeled 85% social distancing favorability in COVID-19, and the adverse effect during the 1918 Spanish Flu. Through infectivity modeling, it is shown that the results of such alternative response strategies are essential in the control of an otherwise fatal epidemiological crisis.

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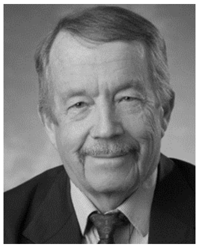

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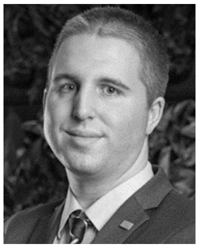

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