On how COVID-19 mitigation measures can reshuffle the risk of infection: a case study from Montreal, Canada

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Abstract

To control the spread of COVID-19, various non-pharmaceutical interventions (NPIs) were introduced. Restrictions on mobility and activities were among the widely adopted NPIs. The introduction of these NPIs was often based on their global positive effect, with little regard to their micro-level implications. In this paper, we investigate the macro and micro implications of three NPIs: work from home, school opening and university closure, and leisure and shopping restrictions.

Two hypothetical scenarios from Montreal are compared: with and without NPIs. An agent-based simulation is used to investigate the impacts of these scenarios. Results show that the three NPIs can significantly reduce the incidence rate of COVID-19 in the population. However, the benefit of this reduction is unequally distributed in the population. Some citizens benefit more from these interventions than others depending on their socio-demographic and economic characteristics or residential location. Findings suggest that these NPIs can exacerbate existing disparities in terms of exposure to COVID-19 and give less benefit to those who are most exposed to the virus. These findings can be informative to decision-makers in the design of efficient and fair COVID-19 mitigation strategies.

Keywords: COVID-19, non-pharmaceutical intervention, work from home, school opening, school closure, mobility restrictions, equity, agent-based.

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1 Introduction

In nearly two years, the severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2), responsible for COVID-19, claimed more than 5.5 million lives and impacted billion of others (WHO 2021b). In response to this catastrophic situation, decision-makers have adopted various mitigation measures to control the spread of the virus or to mitigate its dire consequences (Blavatnik School of Government 2021). Before the development of COVID-19 vaccines, most of these measures were non-pharmaceutical. These non-pharmaceutical interventions (NPIs) can include travel ban, mobility restrictions, social gathering ban, physical distancing, school and university closure, non-essential business closure, remote work, night curfew, or lockdown. For some of these interventions, research has already demonstrated their effectiveness in reducing the incidence rate of COVID-19 in the population (Badr et al. 2020; Chang et al. 2020; Haug et al. 2020). Nevertheless, the wider impacts of these interventions are often overlooked.

NPIs were often introduced based on their global positive effect in reducing the incidence rate in the population, with little regard to their local implications on individuals or specific groups of individuals. In this paper, the focus is put on three NPIs: (1) work from home (WFH), (2) school opening and university closure, and (3) leisure and shopping restrictions. To prevent the spread of COVID-19 in the workplace, the World Health Organization identifies remote work as a cornerstone measure (WHO 2021a). This recommendation is based on many studies that support the reduction effect of remote work on the incidence rate of COVID-19 (Galmiche et al. 2021; Mauras et al. 2021; Song et al. 2021). WFH has however various unintended ramifications, starting with the disparity in the ability to work remotely and to work from home. WFH is not an option for all workers (Bui et al. 2020; Government of Canada 2020). This is likely to fuel existing disparities and engender new ones in terms of the risk of infection by COVID-19.

Many countries took strict precautions against COVID-19 outbreaks in schools and chose to close some or all their educational facilities (Blavatnik School of Government 2021). In Montreal, primary schools were closed from March to May 2020 and most university courses went virtual through 2020 and 2021. Imposing school closure or lifting this obligation is a controversial measure that has been the subject of many research studies (ECDC 2020, 2021). On one hand, research indicates that, with active community transmission, school closure can contribute to a reduction of the incidence rate, especially when taken in conjunction with other NPIs or in the presence of highly transmissible new variants of SARS-CoV-2 (Brauner et al. 2021; Haug et al. 2020; Hyde 2020; Lee et al. 2020; Puntis 2020). On the other hand, school-aged children are less likely to be severely sick when infected with COVID-19. More importantly, school closure endangers, among other things, the educational proficiency and well-being of children (Wu et al. 2021). Consequently, the European Centre for Disease Prevention and Control recommends school closure as a last resort intervention (ECDC 2021).

Another mitigation measure is to limit leisure activities. Social gathering ban, closure of bars and restaurants, closure of recreational, entertainment and shopping centers, or night curfews have all been widely adopted to limit the spread of the virus during leisure times (Blavatnik School of Government 2021). The strict adoption of these restrictions can help control the spread of the virus. Haug et al. 2020 and Brauner et al. 2021 show that the ban of small social gatherings is effective in reducing the incidence rate of COVID-19. Galmiche et al. 2021 find that attending restaurants, bars or gyms is associated with a high risk of infection.

Previous research is, to some degree, concordant with the fact that the above-mentioned NPIs can contribute to a global reduction in the incidence rate of COVID-19. Based on this recommendation, these NPIs were widely adopted to control the pandemic across the globe. Nonetheless, the implications of these interventions are still overlooked, or at least, not measured. Qualitative re-

search supports that these implications can be, for example, discriminatory against women, visible minorities, migrants, or low-income households (Hooper et al. 2020). In this research, we examine and assess how mitigation measures, namely: WFH, school opening and university closure, and leisure and shopping restrictions, can change the risk of infection at a global and individual level and who benefits the most and the least from such measures.

This investigation is essential to better understand the ramifications of NPIs, especially when previous research shows that, in the absence of mitigation measures, the exposure to the virus is already unequally distributed in the population (Bui et al. 2020; Hooper et al. 2020; Manout and Ciari 2021). This research identifies whom NPIs benefit the most and the least and why. These findings can be informative to decision-makers in the design of efficient and fair COVID-19 mitigation strategies.

The next section details the research methodology and main research assumptions. Results are presented in section 3 and are discussed in section 4. Section 5 concludes this research by discussing its policy implications and limitations.

2 Methods and Materials

To investigate how COVID restrictions on activities and mobility can change the course of the pandemic, an ideal experimental protocol would compare two epidemic situations of Montreal: business-as-usual with no NPI versus with NPIs, everything else being equal. In practice, it is hardly possible to observe these scenarios in the same study area and at the same time. In the case of Montreal, various mitigation measures have been introduced shortly after the official onset of the pandemic. These interventions have swiftly and significantly changed individual behaviors, which makes the comparison of similar scenarios inaccessible.

In the absence of the ideal experimental protocol, an alternative research protocol is to rely on computer simulation. Computer simulation is a convenient research approach to investigate what would have been the pandemic situation in Montreal in the presence and absence of mobility and activity restrictions, everything else being equal. These hypothetical scenarios are used to assess the impact of NPIs.

Epidemic models and computer simulation have proved to be key tools in the fight against COVID-19. They have been largely used by health authorities and decision-makers to foresee the dynamics of the pandemic and adopt appropriate measures to control it. We use a state-of-the-art integrated simulation framework that incorporates a transportation and an epidemic agent-based model (figure 1). This framework has been used and validated to model the spread of COVID-19 in various contexts (Kersting et al. 2021; Manout and Ciari 2021; Müller et al. 2021). Two hypothetical scenarios are simulated: (1) no mobility or activity restrictions (business-as-usual (BAU) or no NPI scenario) and mobility and activity restrictions (NPI scenario). These scenarios do not replicate the current pandemic situation in Montreal, but offer the possibility to explore some of the implications of the above-mentioned NPIs.

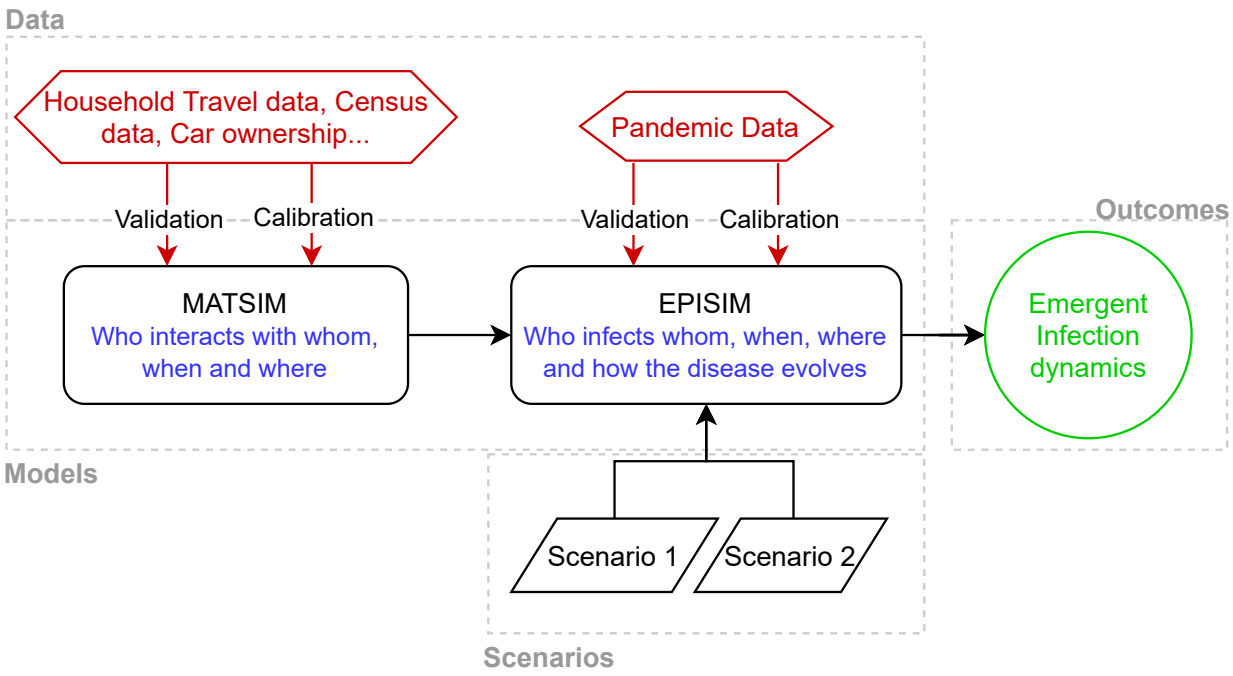


Figure 1: Research methodology adapted from Manout and Ciari 2021

2.1 Methods

2.1.1 Simulation framework

Activity and mobility simulation: MATSim is a transportation agent and activity-based simulation framework (Horni et al. 2016). MATSim can simulate where agents perform their daily activities, for how long and which travel mode they take to get there. MATSim agents are goal-oriented. They seek to maximize their daily activity plans by performing all their planned activities like work, shopping, or leisure and by minimizing unproductive times spent in congestion or waiting. To optimize these plans, agents rely on a co-evolutionary optimization strategy. They try out different variants of their original plan by marginally changing their routes, travel modes, or departure times. At the end of a simulation day, called iteration in MATSim, each agent scores its daily plan and decides whether to keep this plan or to try out a new variant the next day. After a sufficient number of iterations, agents can achieve an optimal plan given the choices made by other agents, i.e. interactions with other agents. At equilibrium, MATSim outcomes provide rich information on the daily plans of individuals. This information can be re-framed as a social interaction network, an important input to epidemic models.

MATSim is open-source and can be found here: https://github.com/matsim-org/

Epidemic simulation: EPISIM is an epidemic agent-based model (Müller et al. 2021). EPISIM includes two sub-models: (i) transmission or propagation of the virus and (ii) progression of the state of infected agents. EPISIM simulates the propagation of a virus in a population given its social interaction networks. These networks are provided by MATSim. Each agent performing an activity that may involve an interaction with others bears a risk of infection. This risk is computed by EPISIM using equation 1 (adapted from Manout and Ciari 2021):

$$\begin{cases} P_{A\to B} = 1 - \exp(-\theta \times R) \\ R = T_{A-B} \times CI_{A-B} \times (1 - M_A) \times (1 - M_B) \geq 0 \\ \theta > 0 \end{cases} \quad (1)$$

$P_{A\to B}$ is the probability that agent A infects B. If both agents are susceptible, i.e. not infected, $P_{A\to B} = 0$.

R is the risk run by agent B while interacting with agent A. $R \in [0, +\infty[$.

T_{A-B} is the interaction duration. The longer the duration the higher the risk. $T \in [0, 24h]$. T is inferred from MATSim co-presence duration.

CI_{A-B} is the contact intensity between agents A and B. $CI \in [0, +\infty[$. This intensity depends on many unobserved parameters. We assume that $CI_{A-B} = 1$ for all interactions, except for some activities. Leisure activities often involve interactions with close contacts which entails close interactions, everything else being equal. We assume that for leisure activities ($CI_{A-B} = 2$). We also assume that healthcare workers are often in close interaction with patients ($CI_{A-B} = 2$).

M_A and M_B are for mask-wearing measures. $M \in [0, 1]$. All agents are assumed to use face masks and to use similar masks. Given this assumption, we can assume that $M_A = M_B = M$ for all agents. The estimation of M is included in θ. With appropriate data, it is possible to simulate various mask-wearing adherence scenarios and the use of different face-covering practices with varying degrees of protection.

θ is estimated to fit simulation outcomes to observed infection data, namely: the number of infections and hospitalizations.

We assume that all agents have the same susceptibility, i.e. capacity to contract SARS-CoV-2, and infectiousness, i.e. capacity to transmit the virus. With appropriate data, this assumption can be revisited.

Despite its agent-based approach, MATSim does not provide detailed social interaction networks; except for household and family interactions. We assume that in a given facility at a given time, an agent can interact with a maximum of 8 randomly chosen other agents. To refine this assumption, data on social interaction during COVID can be used.

For each infected agent, EPISIM simulates the progression of the disease following a stochastic age-dependent progression model (figure 2). This model is inspired by the Susceptible-Infected-Recovered (SIR) approach (Kermack and McKendrick 1927). The probability to move from one compartment to another is calibrated using COVID-19 data of Montreal and the Quebec province (table 1).

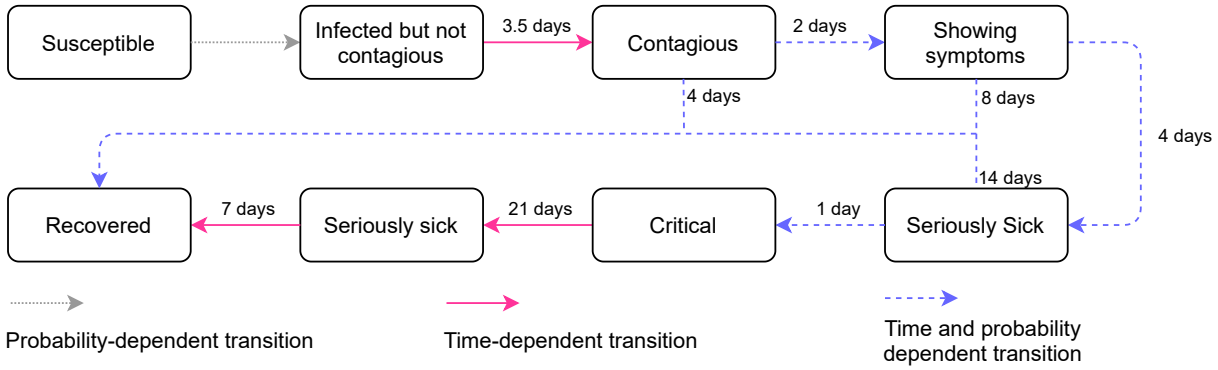


Figure 2: EPISIM progression model (Manout and Ciari 2021)

Age (years)	Probability of seriously ill (%)	Probability of critically ill (%)
Under 14	2.3	12.5
15 – 19	1.1	16.1
20 – 29	1.8	19.4
30 – 39	3.3	24.4
40 – 49	5	27.3
50 – 59	9.9	28.7
60 – 69	20.5	30.3
70 – 74	34.3	22.1
Over 75	25	5

Table 1: Age-dependent COVID-19 progression probabilities from infected to seriously and critically sick (INSPQ 2020)

EPISIM is open-source and can be found here: https://github.com/matsim-org/matsim-episim-libs.

2.1.2 COVID mitigation scenarios

Two epidemic scenarios are simulated: with and without NPIs. In the baseline scenario, no policy intervention to limit individual activities or mobility is introduced. Individuals are assumed to perform their pre-COVID-19 daily plans with no behavioral change or adaptation (except for infected and symptomatic agents that are put in quarantine). In the NPI scenario, three restrictions are introduced: WFH, school opening and university closure, and leisure and shopping activity restrictions. To evaluate the implications of these NPIs on the spread of the virus, the outcomes of both scenarios are compared. Despite being hypothetical, these scenarios can help explore the net effect of the above-mentioned NPIs.

Work from home: In Canada, as in many other countries, public authorities have recommended or even imposed working remotely from home (WFH) to limit the spread of the virus (Blavatnik School of Government 2021). Nevertheless, not all workers can work from home and the possibility to work remotely depends on the economic sector and job category. The introduction of WFH can therefore engender disparities among workers with regard to the risk of infection. To examine these implications in the case of Montreal, we simulate a scenario where remote work is adopted at its maximal potential (table 2) and that it is performed exclusively from home. We also assume that non-essential sectors like accommodation and food services (NAICS 72), and arts, entertainment and recreation (NAICS 71) are partially and totally closed, respectively.

School opening and university closure: In the aftermath of the first COVID-19 wave, health authorities recommended school closure as a last resort. To evaluate the implications of this measure, we assume that all primary and secondary schools in Montreal are open and that only 30% of college and university students attend courses in person.

Leisure and shopping restrictions: Due to COVID-19, non-essential activities have often been restricted to limit the spread of the virus. Leisure and shopping activities that require social gatherings or social interactions were limited. In the NPI scenario, we assume a reduction of 50%

NAICS	Sector	Teleworking (%)
11	Agriculture, forestry, fishing and hunting	4
23	Construction	11
31-33	Manufacturing	19
44-45	Retail trade	22
21	Mining, quarrying, and oil and gas extraction	24
48-49	Transportation and warehousing	25
62	Health care and social assistance	28
81	Other services (except public administration)	31
56	Administrative and support, waste and remediation services	35
22	Utilities	39
53	Real estate and rental and leasing	48
61	Educational services (excluding students)	50
41	Wholesale trade	57
91	Public administration	58
51	Information and cultural industries	69
54	Professional, scientific and technical services	84
52	Finance and insurance	85
55	Management of companies and enterprises	90
72	Accommodation and food services	90*
71	Arts, entertainment and recreation	100**

Table 2: Potential of teleworking according to the North American Industry Classification System (NAICS). *partial closure **total closure (based on Government of Canada 2020 and authors' assumptions)

in leisure activities and 20% in shopping activities. The magnitude of these reductions is in line with observations from Google Mobility Trends in Montreal (Google 2020).

In Montreal, the proportion of indoor/outdoor leisure activities is season-dependent. We assume that from November to January, 90% of leisure activities are indoor. In August, 70% of leisure activities are assumed outdoor. In between, the share of outdoor activities is linearly interpolated. These shares can be updated with more detailed data if available. The indoor/outdoor ratio has a direct impact on the contact intensity parameter in equation 1.

2.2 Case study

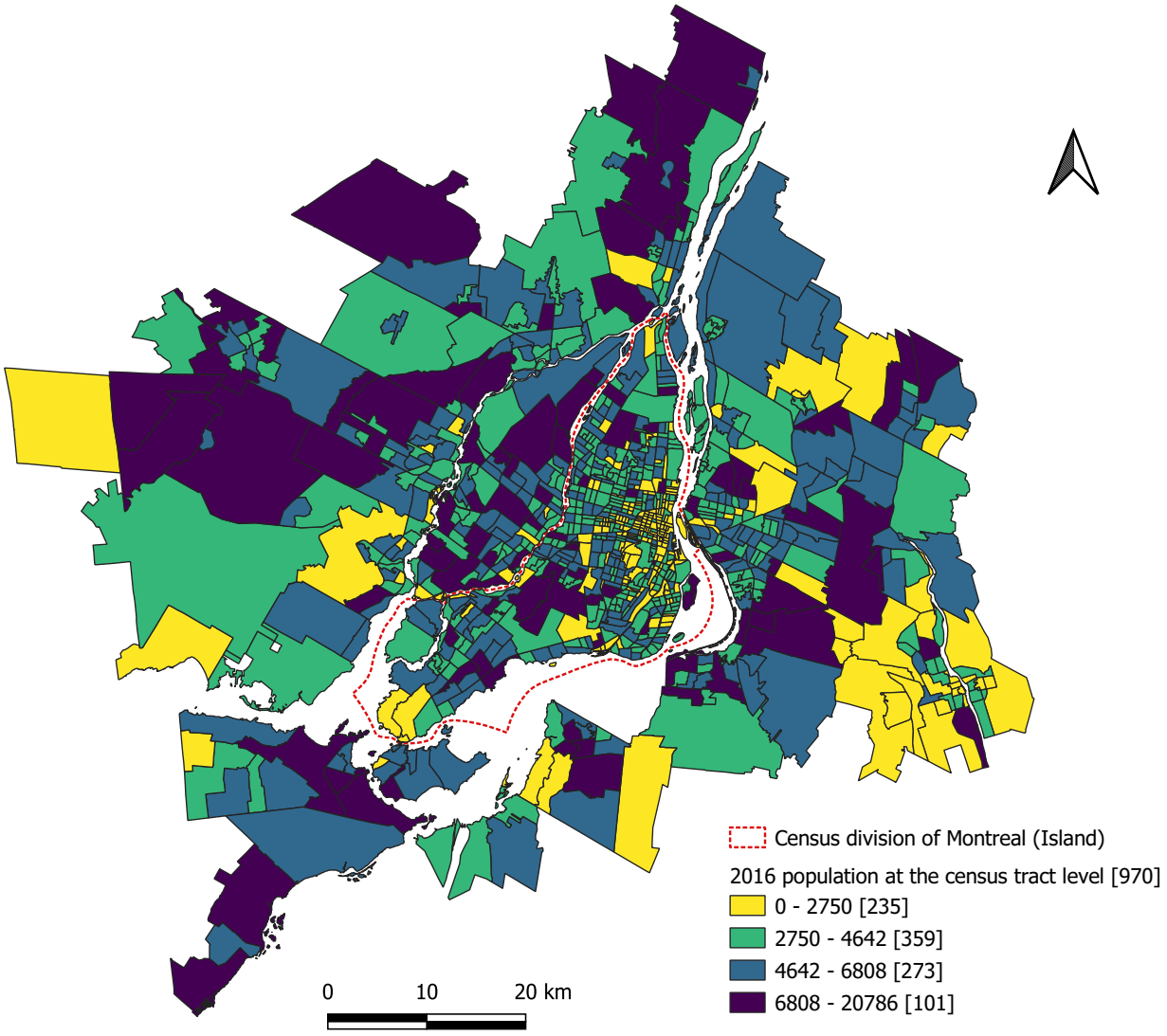


Figure 3: Distribution of the population in the census metropolitan area of Montreal according to the census of 2016

Montreal is the largest metropolitan area in the province of Quebec and the second-largest in Canada. Its population exceeds 4 million. Half of this population lives on the island of Montreal

(figure 3).

Montreal and the Quebec province have been harshly hit by the first wave of COVID-19 (INSPQ 2021). In response to this situation, local authorities have introduced various mitigation measures, including WFH for non-essential workers, school closure, non-essential business closure, regional and national travel ban, social gathering ban, and night curfew.

To model the spread of COVID-19 in Montreal, data on the daily activity and mobility routines of Montrealers and their socio-demographic characteristics are required. However, this information is unavailable for 4 million individuals. To get around this limitation, we combine various data sources and use statistical models to reconstruct a synthetic population of 4 million agents that is similar in most relevant aspects to the real population of Montreal.

Specifically, the synthesis of this population relies on numerous data sources: census data (Statistics Canada 2017), household travel surveys (HTS) (MTQ 2013), car ownership (SAAQ 2016), housing data (MAMOT 2014). Census data provides valuable information on the total population, but it does not provide joint distributions of individual characteristics. HTS data, on the other hand, provides detailed information on individuals and joint distributions, but it is often for a limited sample of the population (5% in Montreal). By mixing both data sources, we can reconstruct the detailed characteristics of the whole population. For that, the Hierarchical and Iterative Proportional Updating (HIPU) method is used to compute the expansion factors of HTS data and to clone households and persons in order to match the total population of Montreal (Konduri et al. 2016; Ye et al. 2009). This method is largely used in agent-based modeling and has already been validated in various contexts.

Daily activities of synthetic agents are defined using the open-source EQASIM pipeline (Hörl and Balać 2020). The pipeline was adapted to Canadian data. Daily activities of agents are cloned from the HTS data using a statistical matching algorithm. The location of activities is performed using the method of Hörl and Axhausen 2021. This method infers the location of activities by replicating the distribution of travel demand (i.e. origin-destination distribution) and travel distances.

Census data is open-access and available here: https://www12.statcan.gc.ca. HTS, car ownership, and housing data have been made available on request.

EPISIM outcomes are compared with observed data to calibrate the model. Data on intensive care hospitalization due to COVID-19 is used to calibrate EPISIM (parameter $\theta = 10^{-5}s^{-1}$ in equation 1).

3 Results

Simulation results indicate that restrictions on mobility and activities, as described in the NPI scenario, can help reduce the incidence rate of COVID-19. Nonetheless, they can also reshuffle the risk of infection among individuals according to their daily activities, socio-demographic characteristics, economic sector, or residential location.

3.1 The impact of mobility and activity restrictions on the infection curve

The introduction of mobility and activity restrictions of the NPI scenario has a significant impact on the spread of the virus in Montreal (figure 4). These mitigation measures can reduce and delay the infection peak of the pandemic. The strict adoption of these measures reduces by 47% the total number of infections in Montreal in comparison with the BAU scenario. These measures also

reduce the maximum number of active infections, i.e. the peak of the curve, by 67% and delay its occurrence by nearly 9 weeks in comparison with the BAU scenario.

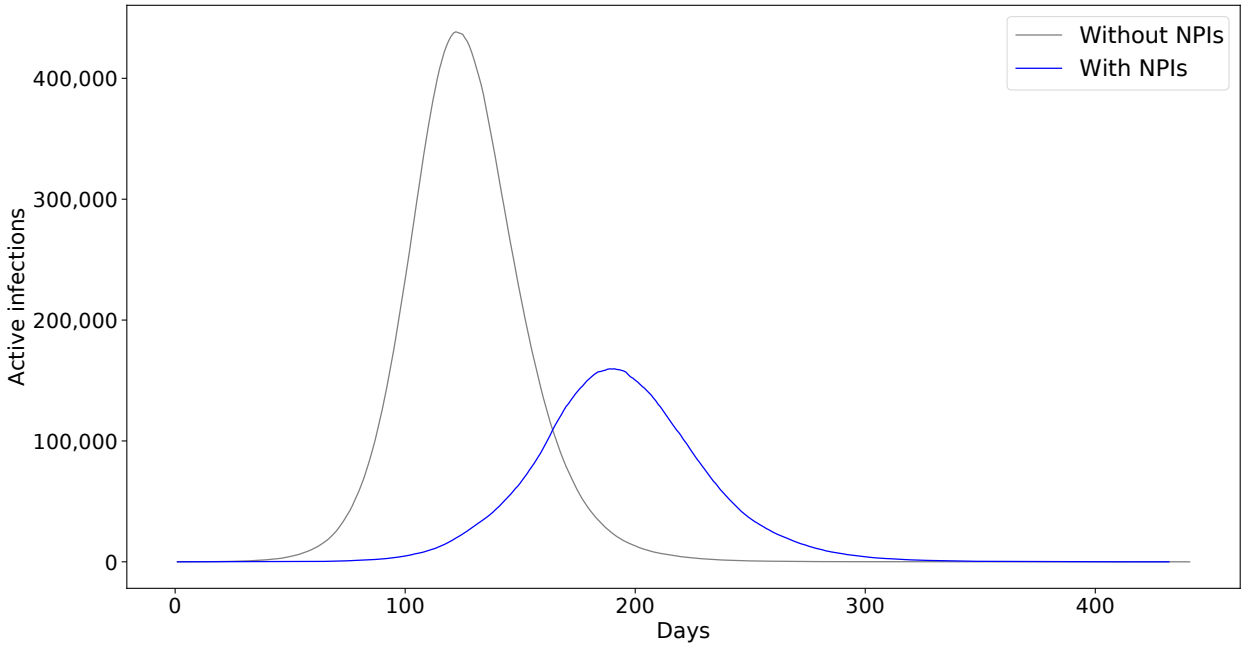


Figure 4: Infection curve before and after the introduction of NPIs

The introduction of mobility and activity restrictions is also found to redistribute the risk of infection in the population. In other words, despite their global positive outcome, studied COVID-19 mitigation measures induce disparities in the risk of infection at the individual level. According to simulation outcomes, without NPIs, the GINI index of the distribution of infections in the population is about 0.61. This index increases to 0.79 with NPIs. This means that NPIs engender more disparities in terms of the risk of infection in the population while reducing the total number of infections in the population. The next sections examine these disparities.

3.2 The risk of infection in daily activities

Restrictions on activities to limit the spread of COVID-19 changes the absolute and relative exposure risk of individuals. In comparison with the BAU scenario, the introduction of WFH reduces the risk of infection in the workplace by nearly 67%(figure 5). As expected, WFH involves fewer physical interactions in the workplace and therefore less exposure to the virus.

When all primary and secondary schools are kept open and 30% of college and university students attend courses in person, the decrease in the risk of infection in educational facilities is 23%. 70% of these infections are among school-aged children, i.e. those under the age of 15 years old. In the BAU scenario, this share is 58%.

In comparison with the BAU scenario, restrictions on leisure and shopping activities contributes to a reduction in the risk of infection in these activities by 92% and 73%, respectively.

By targeting specific activities, like work or leisure, mitigation measures help reduce the propagation of the virus in other places/activities like home or public transportation. Thanks to the reduction in the risk of infection in the workplace, schools, and leisure and shopping activities, the

number of infections in homes, public transportation and other activities decreases by 36%, 81% and 52%, respectively.

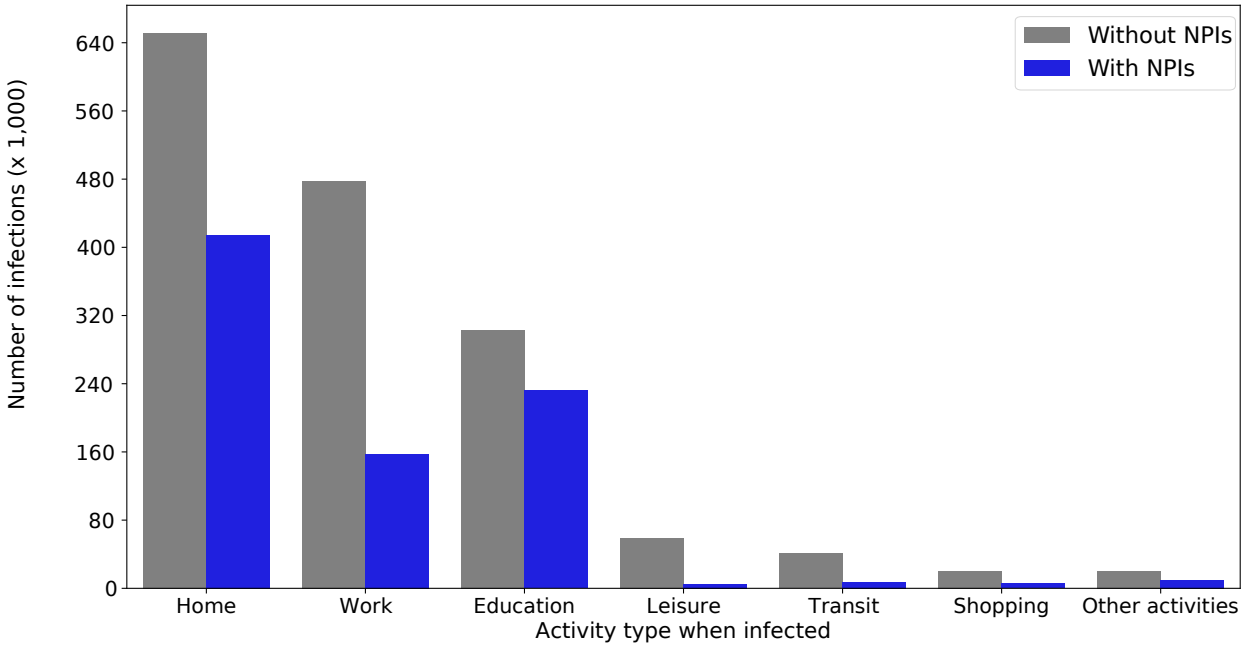


Figure 5: Number of infections in daily activities before and after the introduction of NPIs

Findings confirm that NPIs reduce the global risk of infection in the population. Nevertheless, this benefit is not uniformly distributed between daily activities. Simulation outcomes show that in the absence of NPIs, 41%, 30%, and 19% of infections take place at home, workplace, and school, respectively (figure 6). After the introduction of activity and mobility restrictions, 50%, 19%, and 28% of infections take place at home, workplace, and school.

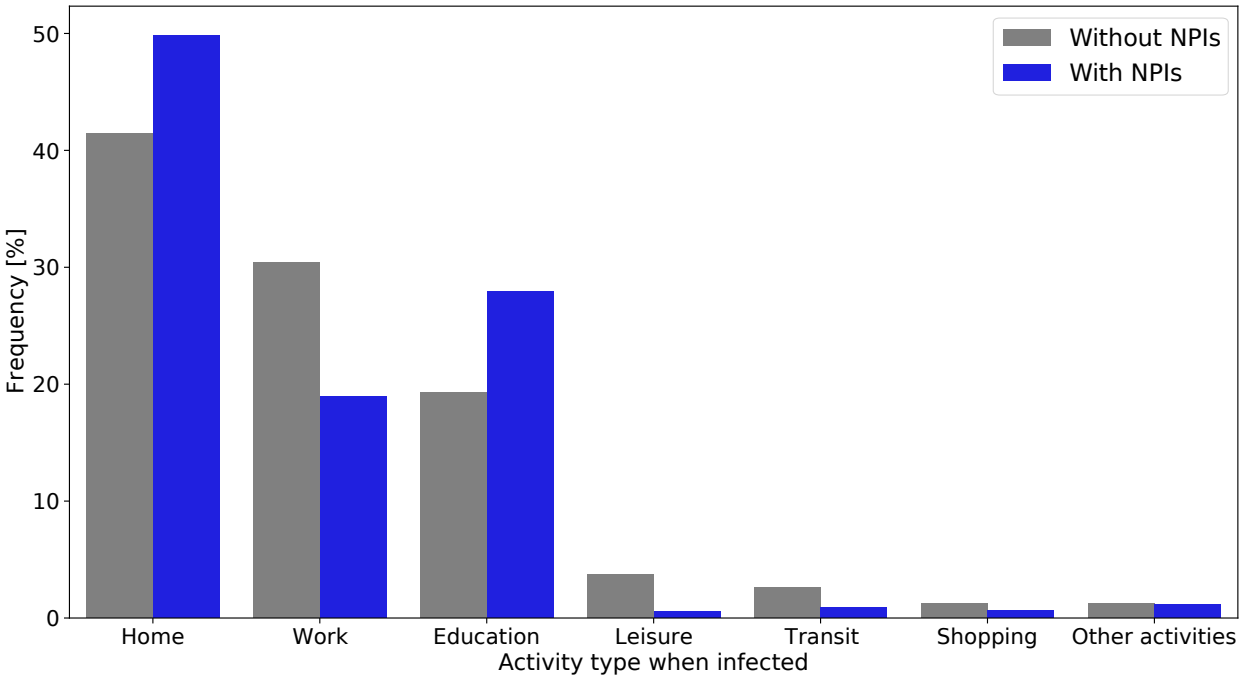


Figure 6: Share of infections in daily activities before and after the introduction of NPIs

3.3 The risk of infection in the workplace

Not all workers can work remotely, and even less from home. The possibility to work remotely depends on the economic sector (table 2), and within the same sector, on job category. WFH can, therefore, engender significant disparities among workers concerning the risk of infection.

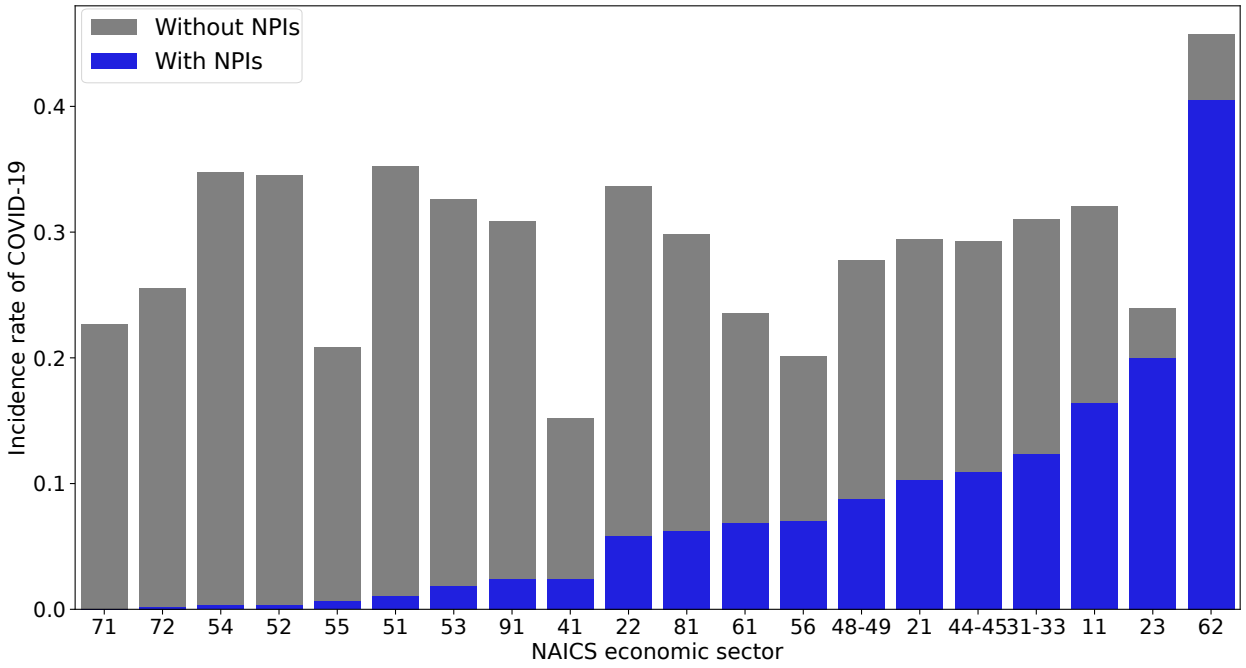


Figure 7: Incidence rate of COVID-19 in the workplace before and after the introduction of NPIs according to the NAICS classification

As expected, WFH can significantly reduce the risk of infection in the workplace (figure 5). The reduction is proportional to the potential of remote work of each sector (figure 7). The higher the potential the higher the reduction in the risk of infection. The reduction in the risk of infection in the workplace ranges from 11% (NAICS 62) to 100% (NAICS 71) with a standard deviation of 25%.

In sectors like finance and insurance (NAICS 52) or professional, scientific and technical services (NAICS 54) where the potential of remote work is very high, the reduction in the risk of infection is nearly 95%. In economic sectors where the potential of remote work is moderate, i.e. between 20% and 40%, the reduction in the exposure risk is significant (greater than 50%). In economic sectors with a very low potential for teleworking, i.e. less than 20%, like construction (NAICS 23) or manufacturing (NAICS 31-33), the reduction in the risk of infection is still significant (between 30% and 60%).

The healthcare and social assistance sector (NAICS 62) is the exception to this rule: the reduction in the risk of infection for healthcare workers is 11%: the least reduction among all economic sectors. This is due to the high exposure of these workers to the virus during their work-related interactions, as translated by the high contact intensity in equation 1.

WFH is found to exacerbate the disparities in terms of the risk of infection between workers of different economic sectors. In the BAU scenario, the GINI index of the status of infection among workers is 0.68. In the NPI scenario, this index increases to 0.89. The increase in the GINI index illustrates how WFH can widen the gap between workers of different sectors concerning the risk of infection in the workplace. This discrepancy has far-reaching consequences, not only on workers themselves, but also on their households, neighborhoods, and more generally their social interaction networks.

From a gender perspective, the introduction of WFH in a job market where genders are not equally distributed among sectors/jobs, fuels the disparities between men and women in terms

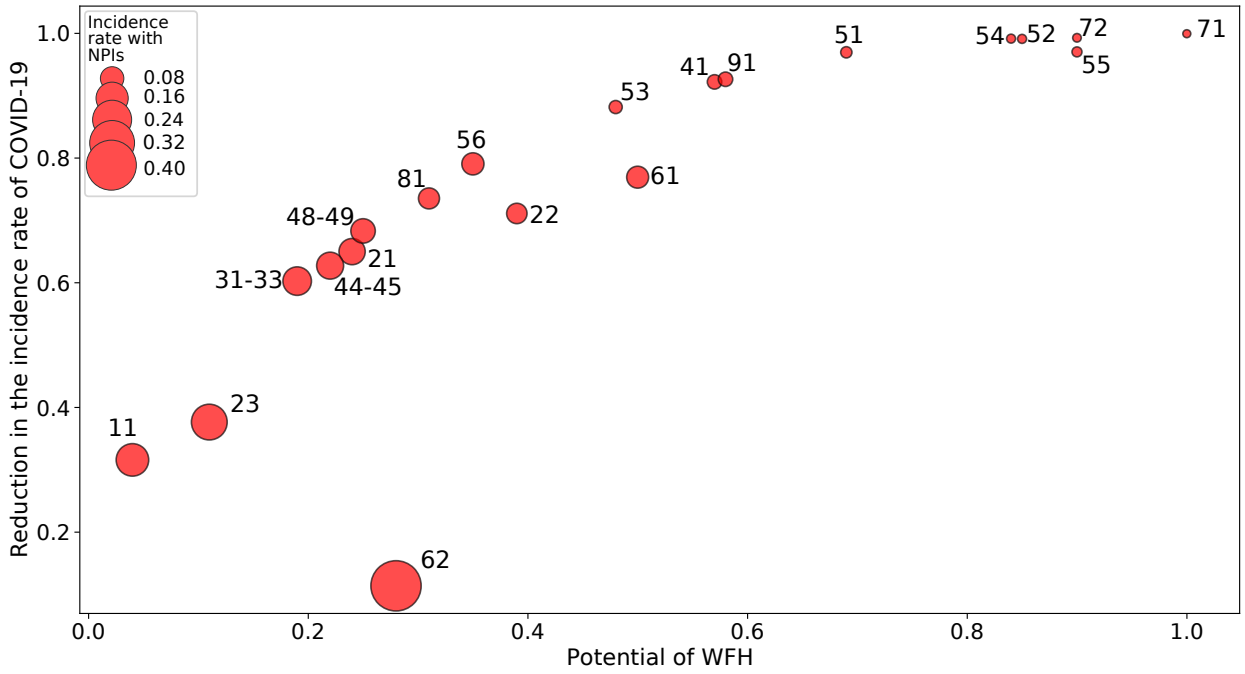


Figure 8: Simulation outcomes: reduction of the incidence rate of COVID-19 in the workplace function of the potential of remote work

of COVID-19. In Montreal, the share of women in the workforce is 47%. In the BAU scenario, the share of female workers in total workplace infections is also 47%. In the NPI scenario, this share increases to 55%. With the WFH recommendation, the absolute risk of infection for both genders decreases, but women become much more exposed to the virus than men. This is due to the unequal distribution of men and women in the economic sectors of Montreal. Female workers are over-represented in essential sectors like healthcare (78% of the workforce) or education (67% of the workforce) that benefit the least from studied NPIs.

Finally, simulation results show that the marginal reduction in the risk of infection brought by remote work decreases when the rate of remote work increases (figure 8). In other words, when the rate of remote work increases, its marginal benefit in reducing the risk of infection in the workplace decreases. For example, teleworking 5 days instead of 3 brings less reduction in the risk of infection in the workplace than teleworking 3 days instead of one. This finding can be of importance when designing COVID-19 remote work strategies.

3.4 The risk of infection at home

NPIs are found to contribute to a global improvement of the epidemic situation in Montreal. As a result, the absolute number of infections due to home-based activities decreases by nearly 36% in comparison with the no NPI scenario (figure 5). However, the restrictions on some out-of-home activities (work, leisure, or university) engenders, inevitably, an increase in the time spent at home. This explains the increase in the relative share of infections at home, from 40% to 50%, relatively to other activities (figure 6).

The health benefit of NPIs is not uniformly distributed among households. Some households are found to benefit more from these interventions than others (figure 9). Simulation results show that

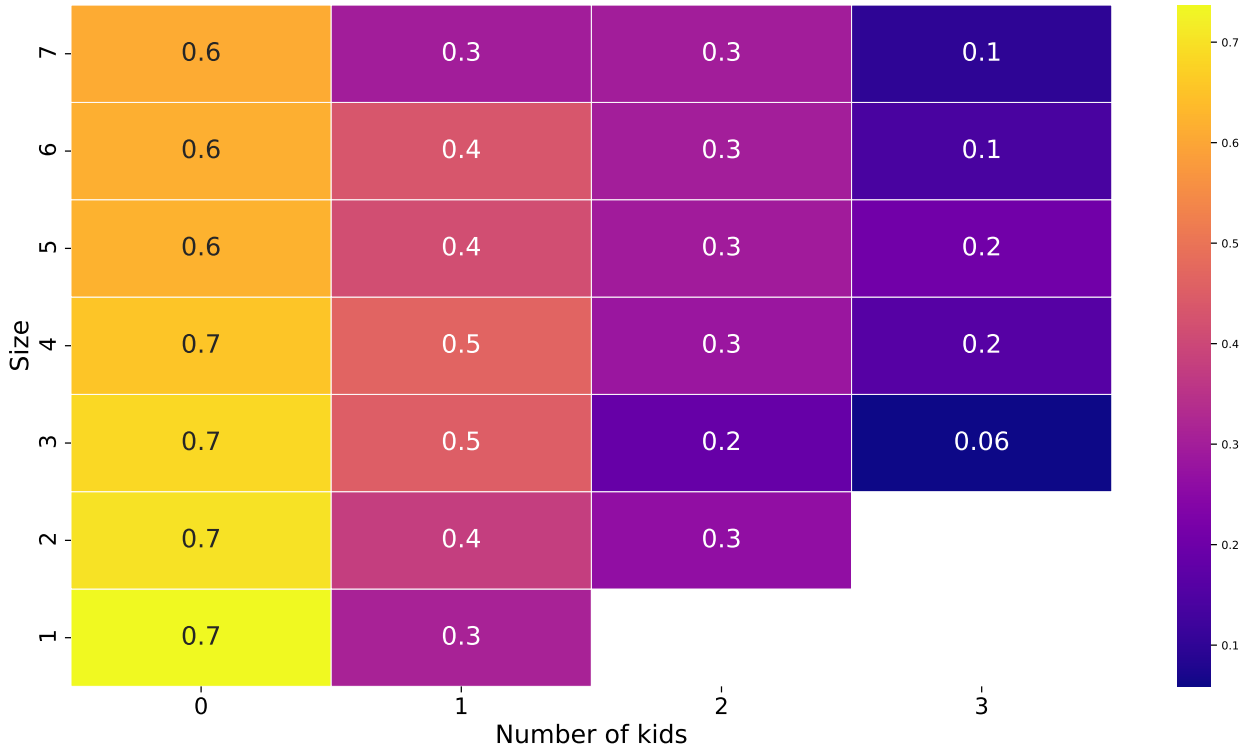


Figure 9: Reduction in the risk of infection in households according to their size and number of children

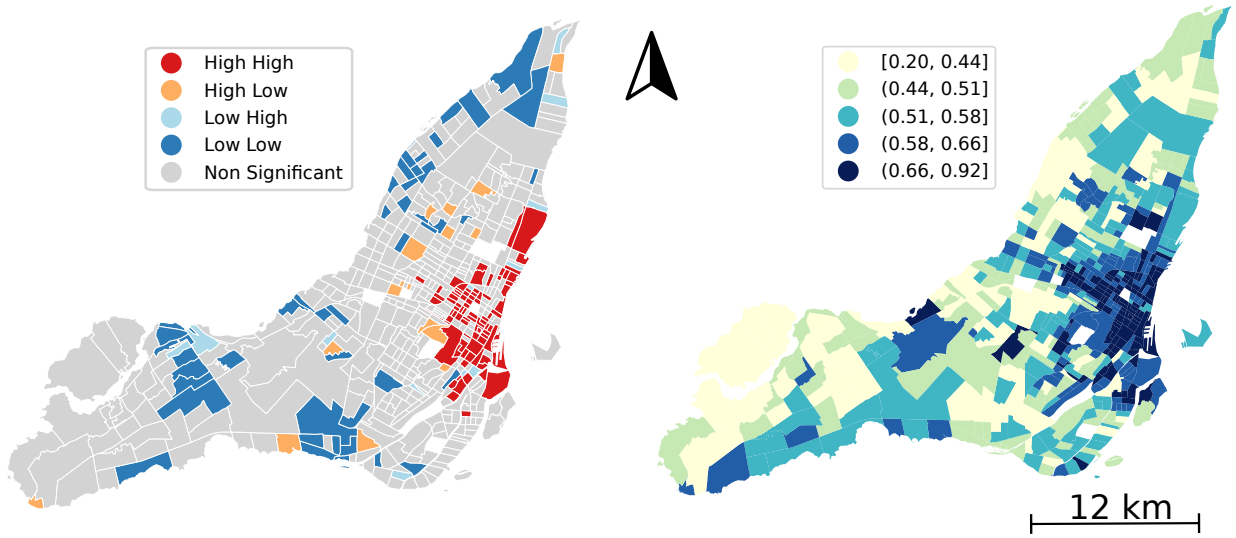
the distribution of the risk reduction benefit depends on the number of school-aged children in the household, size of households, number of workers, and their economic sectors. This benefit decreases with the number of children, size, and number of workers. In comparison with the BAU scenario, the infection risk of a two-adult household, for example, decreases by 74% after the introduction of COVID-19 restrictions, whereas, in households of size 5 with 3 kids, this risk decreases only by 20% (figure 9). More household members, be they children or workers increase the chances of virus introduction to the home (Manout and Ciari 2021).

Besides the effect of size, the number of workers, and school-aged children, the economic sector of working members is also of major importance. For example, households of finance and insurance (NAICS 52) workers benefit more significantly from the WFH than households of healthcare workers (HCW) (NAICS 62). For a household of two members and one worker of finance and insurance (NAICS 52), the reduction in the risk of infection is 4 times that of a similar household where the worker is a HCW. For a household of 5 members and one worker of the professional, scientific and technical services (NAICS 54), the reduction in the risk of infection is 3 times that of a similar household with the worker being in the construction sector (NAICS 23). Similar conclusions can be drawn for other economic sectors where the potential of remote work is dissimilar. Therefore, WFH does not only engender disparities with regard to the risk of infection among workers of different sectors, but also among their households. This finding highlights the magnitude and the ramifications of the unintended implications of WFH as a COVID mitigation measure.

3.5 Impact of NPIs on the geography of COVID-19

Mitigation measures to limit the spread of the virus can also reshuffle the spatial distribution of the risk of infection (graphic B in figure 10). Some places benefit more than others from the introduction of NPIs. Moran's test of spatial auto-correlation rejects the complete spatial randomness of the distribution of the incidence rate reduction of NPIs ($p < 0.001$). For instance, the central business district of Montreal (Red zones in graphic A in figure 10) is where the reduction of the risk is the highest. On the other hand, the North-East and South-West areas of the island of Montreal (blue areas in graphic A) are where the reduction of the risk is the lowest.

From a socio-demographic perspective, different populations live in the red and blue clusters. In areas where the reduction in the risk of infection is the highest, namely ninth decile or D9, households have fewer children, fewer workers (1.08 worker per household) and less size than households in areas where the reduction of the risk is least, namely first decile or D1. In D1 and D9 areas, 49% and 17% of households have at least one child, respectively. Furthermore, 22% and 52% of households are single-person in D1 and D9 areas, respectively. The average number of workers per household is 1.41 and 1.08 in D1 and D9 areas, respectively. Moreover, in D1 and D9 areas, 7% and 16% of workers are in professional, scientific or technical services, respectively. Finally, the average share of healthcare and social workers in D1 and D9 areas is 13% and 9%, respectively.



(A) Local Moran's statistics (LISA) (B) Reduction in the rate of infection

Figure 10: (A) Reduction of the incidence rate of COVID-19 at the census tract level in Montreal due to the introduction of NPIs. (B) Local Moran's statistics of spatial auto-correlation (LISA) of this reduction.

4 Discussion

Our findings confirm that NPIs like remote work, university closure, and leisure/shopping restrictions can be effective in controlling the spread of the virus. The reduction in the number of infections is not limited to the activities directly targeted by the restrictions (work, education, or leisure), but extends to most daily activities. This finding is supported by many studies from different contexts that recommend imposing physical distancing or mobility restrictions to control the spread of the

virus (Badr et al. 2020; Brauner et al. 2021; Chang et al. 2020; Conyon et al. 2020; Haug et al. 2020; Johanna et al. 2020; Li et al. 2021; Paoluzzi et al. 2021; Vinceti et al. 2020; Zhou et al. 2020). Based on data from 131 countries, Li et al. 2021 show that the introduction of NPIs like school and workplace closure or the ban of social gatherings are associated with a decrease in the reproduction number R of SARS-CoV-2. Chang et al. 2020 and Badr et al. 2020 show that mobility restrictions are correlated with a decrease in the incidence rate of COVID-19. The relaxation of these NPIs is also found to cause an increase of R. Brauner et al. 2021, Haug et al. 2020 and Paoluzzi et al. 2021 draw similar conclusions from other contexts and using different research methodologies.

As regards the micro-level implications of NPIs, our findings confirm that NPIs reshuffle individual risk of exposure to the virus. The change depends, among other things, on the daily activity plans of individuals, their socio-demographic characteristics, and residential location. Remote work as a mitigation strategy is, by design, an inequitable intervention that favors some economic sectors and some workers over others. Consequently, when remote work is adopted at its maximal potential, the risk of exposure to COVID-19 in the workplace becomes more dependent on the economic sector than before (Hooper et al. 2020). In other words, WFH exacerbates the disparity between workers in terms of COVID-19. Added to this is the fact that different economic sectors may attract different workers with different socio-demographic backgrounds. In Canada, as in many other western countries, economic sectors with low potential for remote work often offer lower wages and require less education than economic sectors with a high potential for remote work (Government of Canada 2018). In many countries, women are, also, over-represented in essential sectors and among front-line workers. In this case, various studies show that women, visible minorities, and low-income households are often over-exposed to the virus in the workplace (Bui et al. 2020; Gold et al. 2020; Hooper et al. 2020).

Manout and Ciari 2021 show that in the absence of NPIs, large families with many school-aged children or workers bear more risk of infection than households with fewer children or workers, everything else being equal. Our findings show that, despite the reduction of the absolute risk brought by NPIs, these highly exposed households are found to benefit the least from the reduction of the risk of infection. In other words, the introduction of NPIs does not address the pre-existing inequality in terms of virus exposure, instead, it exacerbates its magnitude.

Health implications of the unfair distribution of the benefit of NPIs go beyond the impact on concerned individuals to affect their households and social networks. Simulation results reveal that households of workers from economic sectors with a high potential of remote work benefit more from the reduction in the risk of infection brought by WFH than the the rest of households, everything else being equal (size, number of workers, and children). This finding is supported by Song et al. 2021, who, empirically, show that being an essential worker or cohabiting with one bears more risk of infection than in the case of non-essential workers, for example.

Another important finding is the decreasing marginal health benefit of the WFH strategy. This result is of importance to the design of the WFH recommendations, especially, in an economy where many economic sectors and jobs are not compatible with a fully remote work strategy. In this case, our results show that the introduction of partial remote work, i.e. based on employee or day rotations, can significantly reduce the risk of infection in the workplace and the population, in general. This finding is in line with an empirical study by Galmiche et al. 2021 that shows that partial remote work decreases the risk of infection of workers by 24% and that total remote work reduces this risk by 30%. When switching from partial to total remote work, the risk of infection reduces only by 6 points. A similar conclusion can also be drawn from a modeling study by Mauras et al. 2021 on the effectiveness of remote work in mitigating COVID-19 outbreaks in workplaces.

Given these findings, we advocate the deficiency of focusing on the "curve-flattening" goal with-

out considering the individual and ripple effects of NPIs. This research shows that the implications of some NPIs can go beyond flattening the curve to engender other micro-level unintended consequences. These consequences can engender new disparities or fuel existing ones to the detriment of the most vulnerable populations. We also advocate for a need to investigate, consider and address these implications by health authorities and decision-makers when designing COVID-19 mitigation strategies.

To achieve this, researchers and health authorities need, first, to adopt appropriate tools capable of examining the impacts of their decisions, not only on the population as a whole, but also on groups of individuals or individuals themselves. The agent-based approach, as shown by this research and others before (Lorig et al. 2021), can be useful.

The equity perspective, i.e. treating people differently according to their needs to reach an equal outcome, should also be considered when designing COVID-19 mitigation strategies (Stratil et al. 2020). In other words, health authorities should improve the protection of citizens who benefit the least from NPIs and give priority to them over those who benefit the most from these NPIs. The reinforced protection and priority of these individuals should also be extended to their families and social networks who bear a higher risk of infection than others, as highlighted by this research. This priority can be, for instance, in terms of COVID-19 tests, masks, treatments, or even vaccines. The absence of such a safety net specifically designed to target citizens who are highly exposed to the virus and who benefit the least from mitigation measures can erode their trust in decision-makers and adherence to rules. Counter-intuitively, the damage to trust can instigate opposition to policy intervention and weaken its acceptability, as demonstrated by previous research on the link between equity, trust, and acceptability (Gilson 2003; Gilson et al. 2007).

5 Conclusion

We examine how some COVID-19 mitigation measures can have unintended health implications at the global and individual levels. Previous research often focused on the global impacts of such interventions and hardly discussed and measured their micro-level implications on individuals (Stratil et al. 2020). We investigate the impact of three NPIs that were largely adopted to control the pandemic: WFH, school opening and university closure, and leisure/shopping restrictions. Global and individual implications of these measures on the risk of infection are studied in the case of Montreal, Canada using two hypothetical scenarios: with and without NPIs.

This research shows that if NPIs can reduce the global risk of infection, their micro-level implications can also be unfair on several levels. They benefit some citizens more than others. More importantly, results suggest that, in some cases, those who are the most exposed to the virus in the BAU scenario benefit the least from the introduction of NPIs. These findings call for a more appropriate design of mitigation measures that should account for their micro-level implications.

6 Limitations and future work

This research has several limitations, starting with the use of a synthetic population to simulate the spread of COVID-19 in Montreal. The definition of this population relies on data collected prior to the pandemic (2013 for the HTS and 2016 for census data). These data do not reflect the evolution of activity and travel practices after the onset of the pandemic. Furthermore, available HTS describes the mobility and activities of an Autumn workday in Montreal and does not include weekends. To address this limitation, workday and weekend activities are assumed to be similar.

This coarse assumption produces an overestimation of the number of infections in activities like work or education, that are less likely to be conducted on weekends than on workdays. This assumption also underestimates the number of infections in leisure activities which are, on the other hand, more often performed during weekends. Despite this fact, this assumption should not impact our findings on the disparities induced by NPIs on different populations. To address this shortcoming, data on the daily variability of individual activities and especially their evolution due to COVID-19 is necessary. This data can be obtained through multi-day surveys or passive data collection, for example.

In the BAU scenario, we assume that agents are unaware of the pandemic. Individuals are assumed to perform their daily routines as before. This assumption is unrealistic. In many countries, people adapted their daily routines even before the introduction of policy restrictions (Deforche et al. 2021). Future research can investigate the implications of anticipated adaptations of daily routines due to COVID-19 on infection dynamics.

Simulation scenarios assume that people do not take individual protective measures in reaction to their over-exposition to the virus. In reality, those who benefit the least from NPIs, like front-line workers, for example, are more likely to enhance their individual protective measures. In this case, the magnitude of the discrepancy between those who benefit the most and the least from NPIs should decrease. Future research need to improve these scenarios.

Another limitation of this research is SARS-CoV-2 variants of concern: delta and Omicron. EPISIM results are calibrated with data from the first COVID-19 wave. The Delta and Omicron variants are not considered even if they are more virulent than the original strain of the virus. The modeling of different concurrent variants and the dynamics of their spread is out of the scope of this research. The choice to not include these variants has a significant impact on the shape of the infection curve and the efficacy of some NPIs. However, under the assumption that these variants spread randomly in the population, previous findings on the disparity in the distribution of the benefit of NPIs are expected to hold even with the existence of these variants. Future research should investigate this assumption.

The epidemic simulation does not include the effect of vaccination on the spread of the virus. The dynamics of vaccination are difficult to predict and account for in the epidemic model. The effect of vaccines on the new COVID-19 variants is also difficult to quantify. Research is ongoing to address these gaps. With appropriate data and thanks to the flexibility of the agent-based approach, these limitations can be addressed.

The modeling of the propagation of the virus in hospitals is very simplistic. COVID patients are not assigned to hospitals. The high incidence rate in these facilities is driven by a higher contact intensity than in other workplaces ($CI = 2$). Future work needs to address this limitation by explicitly modeling infection dynamics in healthcare facilities.

Finally, the modeling framework lacks feedback from EPISIM to MATSim. EPISIM policy restrictions that involve an update of activity plans are not simulated in MATSim. This can induce inconsistencies in travel demand, and consequently in epidemic outcomes. This limitation can be addressed by using data on individual activity plan adaptations during COVID.

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