Graphical Abstract

Comparing community mobility reduction between first and second COVID-19 waves

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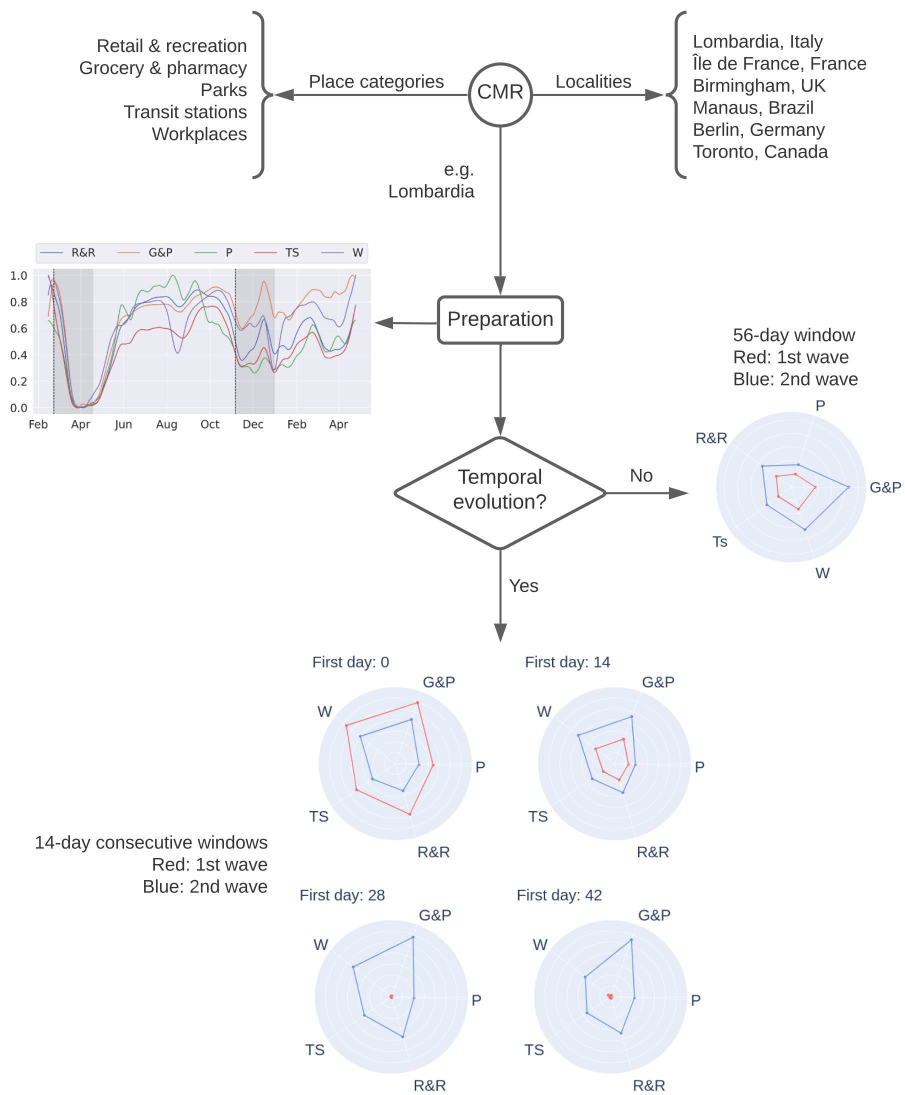

Highlights

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- We compare social distancing adherence in different localities during two COVID-19 waves.
- Reduction rates reveal contrasting social distancing dynamics over time.
- In general, mobility reduction was much higher during the first wave.
- Holiday season mobility reached pre-pandemic levels for some locations.

Comparing community mobility reduction between first and second COVID-19 waves

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Abstract

Background. In this paper, we conduct a mobility reduction rate comparison between the first and second COVID-19 waves in several localities from America and Europe using Google community mobility reports (CMR) data. Through multi-dimensional visualization, we are able to compare the reduction in mobility from the different lockdown periods for each locality selected, simultaneously considering multiple place categories provided in CMR. In addition, our analysis comprises a 56-day lockdown period for each locality and COVID-19 wave, which we analyze both as 56-day periods and as 14-day consecutive windows.

Methods. We use locality-wise calibrated CMR data, which we process through seasonal-trend decomposition by LOESS (STL) to isolate trend from seasonal and noise effects. We scale trend data to draw Pareto-compliant conclusions using radar charts. For each temporal granularity considered, data for a given place category is aggregated using the area under the curve (AUC) approach.

Results. In general, reduction rates observed during the first wave were much higher than during the second. Alarmingly, December holiday season mobility in some of the localities reached pre-pandemic levels for some of the place categories reported. Manaus was the only locality where second wave mobility was nearly as reduced as during the first wave, likely due to the P1 variant outbreak and oxygen supply crisis.

Keywords:
COVID-19, Social distancing, Google community mobility reports

1. Introduction

In December 2019, the World Health Organization (WHO) Country Office in the People's Republic of China reported cases of pneumonia of unknown etiology. In January 2020, WHO named *SARS-CoV-2* the novel coronavirus responsible for these cases, and the acute respiratory syndrome it caused COVID-19. Still in January, WHO classified COVID-19 as a public health emergency of international concern. By March 2020, COVID-19 had cases reported from all continents, and WHO declared it a pandemic. Up to August 11th, 2021, a fresh worldwide figure of over 200 million positive cases and over 4 million death records signify the severity of this viral infection, according to WHO.

Among the most relevant topics in multi-disciplinary COVID-19 research is social distancing (SD), which WHO actively promotes as a non-pharmaceutical intervention against COVID-19 (World Health Organization, 2020a). During the pandemic, mandatory and non-mandatory social distancing measures have drastically reduced social interactions, such as closing schools, reducing the use of public transport, and cancelling events and other activities that involve gatherings (Tuite et al., 2020; Candido et al., 2020). Some regions have adopted measures that restricted mobility more forcefully, and these measures of total or partial restriction are commonly known as *lockdowns* (Aquino et al., 2020). In fact, the different measures of social distancing enforced by some affected countries in 2020 helped bend the curve of the disease spread, and in Europe the first wave had been brought to control around spring 2020 (Woskie et al., 2020; Wellenius et al., 2021; Caristia et al., 2020).

The first wave hit American countries later than in Europe, but around May 2020 America had become the global epicenter of COVID-19, especially the United States and Brazil. The latter is one of the world leaders in number of cases and deaths, and experienced during most of 2020 uncontrolled transmission of SARS-CoV-2. This is largely a consequence of the difficulty faced by local governments to apply and maintain their population under decrees of social distancing (Oliveira et al., 2021; Silva and L., 2021). Although Brazil showed a downward trend in the number of deaths and cases of COVID-19 around September 2020, these indicators have never reached minimum levels similar to the beginning of the pandemic.

Meanwhile, many countries in Europe eased restrictions and experienced a second wave of the COVID-19 pandemic, despite the warnings about the consequences of premature lifting of SD measures (Xu and Li, 2020). It is legitimate to think that countries would manage the second wave a lot better, given the lessons learned during the first wave. However the reality in such countries tells a different scenario (Graichen, 2021): much higher infection numbers, more patients in ICUs, and in some countries also more deaths, implying that only a strict lockdown could help control the pandemic (Meintrup et al., 2021). In Brazil, around November 2020 the country once again showed a worsening in the epidemiological scenario and, in early 2021, some cities such as Manaus - capital of state of Amazonas - were experiencing the so-called second wave of COVID-19 (Emmerich, 2021).

Though the second wave has been controlled by many countries, recurring COVID-19 waves stress the lasting importance of SD measures. Indeed, countries that have been successfully controlling the spread of the disease during the recurring waves have widely adopted measures that include keeping people at least 6 feet apart, avoiding crowded places especially indoors, and the continued use of digital technologies to carry out daily activities such as studying and working (John Hopkins Medicine, 2020). This is especially important in the current scenario of (i) novel (and more dangerous) variants of concern; (ii) unequal access to vaccines, which WHO has repeatedly condemned, and; (iii) infodemic, with misinformation campaigns targeting SD and vaccination credibility.

In this paper, we compare community mobility reduction during the first and second COVID-19 waves in localities from America and Europe. Our goal is to understand whether social distancing through mobility reduction during the second wave was as strong as in the first wave. Specifically, our analysis comprises localities that experienced some of the most severe pandemic outbreaks (Johns Hopkins University, 2020), namely Lombardia (Italy), Île-de-France (France), Birmingham District (United Kingdom), and Manaus (Brazil). Furthermore, major leader localities such as Berlin (Germany) and Toronto Division (Canada) have also been included, for representativeness. In common, all of these cities have enforced rigid social distancing measures during the first trimester of 2020 to contain the first wave, and were forced backed into those rigid SD measures before the end of 2020 (Europe and Canada) or in early 2021 (Brazil) due to a second wave.

Our comparison is based on anonymized mobile device location history data, published by Google as community mobility reports (CMR) (Aktay et al., 2020). We consider all place categories provided, and progressively compare first and second wave mobility over a 56-day period, discretized as 14-day consecutive time windows. To account for all place categories, we compare mobility reduction from a given locality during the first and second wave SD decrees using multi-dimensional visualization through radar charts.

Results vary as a function of the locality considered, and hence we discuss each locality individually. Nonetheless, in general the initial mobility reduction during the first wave was higher than in the second wave. Alarmingly, most localities presented an increase in mobility for all categories during the December holiday shopping season, which had not been observed during Easter holidays. Though striking, these findings are explained by the reluctance from societies and governments in general to adhere to a second period of social distancing measures, especially after the significant economical cost of the first wave periods. In turn, this may be related to factors such as (i) "lockdown fatigue"; (ii) socioeconomic, political, and cultural aspects of each locality that make it difficult to adhere to measures of social distancing, and (iii) difficulties in maintaining SD over time (Wright and Fancourt, 2021; Woskie et al., 2020). Manaus is likely the most extreme example of this reluctance, as restrictive measures proposed to control the second wave led to riots and were only enforced through court decisions. Nonetheless, with the rapid surge in deaths due the P1 variant outbreak and its associated oxygen supply crisis, Manaus eventually nearly reached first wave mobility reduction rates, even if for a brief period.

The remainder of this paper is organized as follows. We initially briefly review related work in Section 2 and detail the methodology adopted in Section 3. Section 4 contrasts mobility reduction from different SD measures' periods for each locality. In Section 5, we further discuss SD as a public health policy in the context of the pandemic, relating this discussion to our findings. Finally, we conclude and discuss future work in Section 6.

2. Related work

The research on COVID-19 is marked by (i) the *volume* of works from the most diverse scientific fields, and in particular how these fields are bridged to produced relevant multi-disciplinary insights, and; (ii) the *speed* with which works are being made available to society, though to a very large extent as pre-prints that have not yet undergone peer review. In this section, we briefly discuss works that have already been peer-reviewed. In addition, since our work compares first- and second-wave data, we focus on works that concern the second wave. We group these works into the most recurring topics.

Planning for a second wave has been the topic of works dating as of March 2020 (Leung et al., 2020; Xu and Li, 2020; Middleton et al., 2020; Moghnieh et al., 2020; Panovska-Griffiths et al., 2020; Wilder-Smith et al., 2020). Given how early China was able to contain COVID-19 spread during its first wave, Leung et al. (2020) discuss the benefits of social distancing outside Hubei and stress the importance of second wave planning. Building on that work, Xu and Li (2020) state the need to model how different non-pharmaceutical interventions such as SD individually contributed to contain or mitigate the epidemic in China. In particular, authors emphasize understanding these individual contributions as key to second wave prevention planning.

Outside China, where first waves were not under control until spring 2020, second wave planning works can be identified as of July 2020. Building on the lessons from China, social distancing is further advocated for by Wilder-Smith et al. (2020). Middleton et al. (2020) discuss how the second wave was expected to hit Europe harder than the first wave, and highlight the effects of the winter season in northern hemisphere countries. Moghnieh et al. (2020) stress that until herd immunity has been achieved, not only a second wave but multiple peaks in COVID-19 spread should be expected. Finally, besides traditional non-pharmaceutical approaches discussed in other works, Panovska-Griffiths et al. (2020) also include school reopening as a planning factor for a second wave.

Analysis works date of after the second waves had started across Europe (Grech and Cuschieri, 2020; Saito et al., 2020; Diaz and Vergara, 2020; Contou et al., 2021; Graichen, 2021; Bontempi, 2021; Ioannidis et al., 2021), and focus on the development and characteristics of the second waves. Works from this category are as early as fall 2020, but the first ones assessed the second wave at a point where daily deaths were attenuated in comparison to the first wave (Grech and Cuschieri, 2020; Saito et al., 2020). In particular, Grech and Cuschieri (2020) performed this comparison globally, whereas Saito et al. (2020) focused on COVID-19 waves in Japan.

By winter 2020, the rise in the number of fatalities demonstrated that the second wave was harder than the first one (Diaz and Vergara, 2020; Contou et al., 2021; Graichen, 2021; Bontempi, 2021). Globally, Diaz and Vergara (2020) discuss the role of age and reinfection as distinguishing characteristics of the second wave. Other works focus on European nation-wide realities, namely France (Contou et al., 2021), Germany (Graichen, 2021), and Italy (Bontempi, 2021). More recently, Ioannidis et al. (2021) assessed shifts in age distribution and nursing home fatalities in 16 representative European Union countries, arguiging that first and second waves are similar concerning the former, but the latter was reduced during the second wave.

Modelling is the focus of the remaining works we identify. In more detail, some of these works focus on Europe (Cacciapaglia et al., 2020; Faranda and Alberti, 2020), whereas others target America (Aleta et al., 2020; Vaid et al., 2020; Renardy et al., 2020). Regarding Europe, Cacciapaglia et al. (2020) provide projections of temporal evolution of COVID-19 spread across different regions calibrated on first wave data, and model the impact of the corresponding SD. Faranda and Alberti (2020) model COVID-19 second wave infections in France and Italy via a stochastic susceptible-exposed-infected-recovered model.

Regarding America, Aleta et al. (2020) build an agent-based model of SARS-CoV-2 transmission in the Boston metropolitan area using anonymized, geolocalized mobility data with census, and demographic data. In particular, they show that hard SD measures coupled with testing, contact-tracing, and household quarantine could not only to prevent the failure of the healthcare system but also allow the return of economic activities. Vaid et al. (2020) combine a Bayesian susceptible-infected-recovered model, Kalman filter, and machine learning techniques to investigate the effects from SD policies in North America. Considering as factors casual and workplace contacts as well as reopening speed, Renardy et al. (2020) predict the most prudent action for controlling the second wave of COVID-19 in Michigan, US.

As discussed, the volume and speed with which scientific works on COVID-19 are being published is overwhelming. Nonetheless, we have not found peer-reviewed works comparing SD measures adopted by localities during the first and second waves. Below, we briefly comment on peer-reviewed works that discuss COVID-19 and mobility.

Mobility and how it was impacted by COVID-19 has been the focus of different works that vary as to their geographical scope. Some of those studies focus on national or regional realities (Borkowski et al., 2021; Helena et al., 2021; Chan et al., 2021; Cui et al., 2021). Other studies try to compare the impact in different countries (Zhang et al., 2021; Dingil and Esztergár-Kiss, 2021; Barbieri et al., 2021; Shibayama et al., 2021). Among all studies observed, only Chan et al. (2021) compare different COVID-19 waves, but do so only for the Hong Kong territory.

In the next section, we describe the methodology we adopt for comparing mobility in multiple countries and COVID-19 waves.

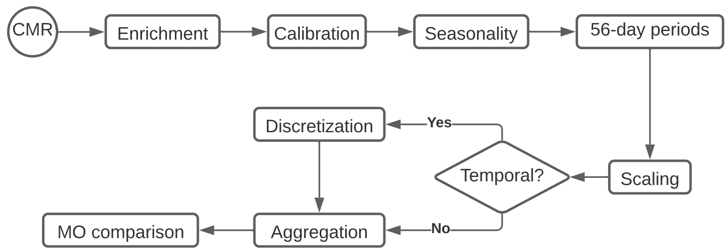


Figure 1: Methodology comprising data enrichment and preparation.

3. Methodology

To compare social distancing in the first and second COVID-19 waves, we assess the mobility data provided as community mobility reports (CMR) by Google. In this section, we detail data enrichment and preparation we adopt for their analysis. Figure 1 summarizes the process described in this section.

3.1. Data acquisition, description, and enrichment

CMR data is provided as a comma-separated values (CSV) file comprising over 135 countries, some of which further detailed on a regional level. Data is collected from users who willingly enable their location history, and is anonymized as described in Aktay et al. (2020). CMR per-locality data comprises six time series, one for each place category created by Google, given in Table 1. Each time series currently spans over one year, having started on February 15$^{\text{th}}$, 2020. For a single timestamp and category, the given value is computed relatively to a baseline, namely the median value, for the corresponding day of the week, computed for the period between January 3$^{\text{rd}}$, 2020 and February 6$^{\text{th}}$, 2020 (Google LLC, 2020).

In this work, we restrict our analysis to mobility in non-residential areas. Our rationale is that the indication that residential mobility should be maximized is not as clear as that mobility in non-residential places should be minimized. More precisely, Google does not specify the space granularity it adopts for residential places. As such, cultural traits such as social gatherings from neighbors that live

Table 1: Place category descriptions from Google CMR (Google LLC, 2020).

Category	**Places**
Grocery & pharmacy	Grocery markets, food warehouses, farmers markets, specialty shops, drug stores, and pharmacies
Parks	Parks, public beaches, marinas, dog parks, plazas, and public gardens
Transit stations	Public transport hubs, e.g. subway and bus stations
Retail & recreation	Restaurants, cafes, shopping centers, theme parks, museums, libraries, and movie theaters
Residential	Places of residence
Workplaces	Places of work

in a same building would have to be minimized, but Google does not disclaim how this category is processed.

As a representative sample in terms of outbreak severity, we select Lombardia (Italy), Île-de-France (France), Birmingham District (United Kingdom), and Manaus (Brazil). In addition, we also include Berlin (Germany) and Toronto Division (Canada) to account for localities where the second wave was not as hard and/or are situated outside Europe. We remark that these localities comprise different CMR spatial discretization granularities, with data for Lombardia and Île-de-France representing the second granularity level (a region) and data for the remaining localities representing the third granularity level (e.g., a district, a division, or a city). Nonetheless, since we only compare data from first and second waves for each locality individually, this difference in granularity does not affect our conclusions.

For the localities we assess, we have further enriched the data with their initial mobility restriction dates related to the first and second waves, given in Table 2. Specifically, in the first wave, we have used school suspension dates as the initial restriction dates, as our preliminary assessment showed this was the restriction measure that most significantly affected mobility. In the second wave, since schools have remained open in some places, the initial restriction dates are different for each location, but not much apart from each other. The only exceptions are: (i) Lombardia, for which the first wave restrictive measures

Table 2: Initial restriction dates for first and second waves, in 2020, considering each locality. Localities are ordered as a function of first wave restriction dates.

Wave	Lombardia	Île-de-France	Toronto Division	Berlin	Birmingham District	Manaus
1st	Feb 23rd	Mar 12nd	Mar 12nd	Mar 13nd	Mar 13nd	Mar 16th
2nd	Nov 6th	Oct 30th	Nov 21st	Nov 2nd	Nov 5th	Dec 26th

started nearly one month prior to the remaining localities, and; (ii) Manaus, for which the second wave restrictive measures started nearly two months after the remaining localities. Nonetheless, since our assessment is based on days since initial restriction dates, differences in starting dates do not affect our conclusions. Figure 2 illustrates CMR data for Lombardia, as well as the restriction dates for each wave for that locality (vertical dashed lines).

3.2. Data preparation

We follow guidelines provided by Google for the assessment of CMR data (Google LLC, 2020). Specifically, Google recommends (i) calibrating data in a locality-wise basis; (ii) handling noise incurred by holidays or other exceptional circumstances, and; (iii) balancing the difference in magnitude between categories.

To meet these guidelines, we first process the whole time series for each locality and place category to ensure that the data previous to the first wave first mobility restriction date present zero mean. Next, we isolate data trend from weekday seasonality effects and noise using seasonal-trend decomposition by loess (**STL**, (Cleveland et al., 1990)). We remark that monthly seasonality effects cannot be addressed with the currently available CMR data, as the current span of the data is little over one-year long. Last, we balance the contribution of individual place categories, i.e., data for each category is scaled to a common range per locality.

To compare mobility reduction during the first and second waves, we focus on the 56-day periods in each wave after the corresponding initial restriction date.

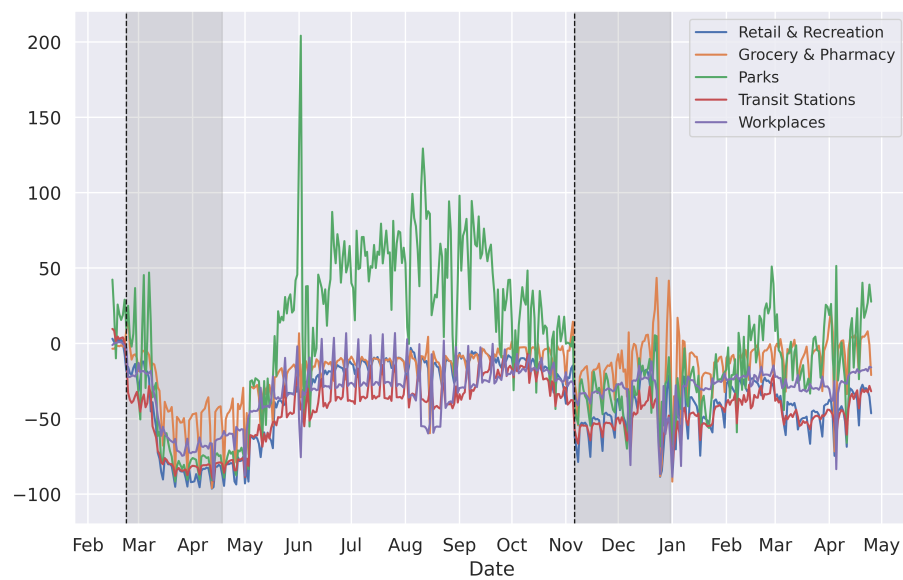


Figure 2: Original CMR data for Lombardia. Shadowed zones indicate the 56-day periods from each COVID-19 wave considered for the analysis, which start on the corresponding initial restriction date (vertical dashed lines).

We select this 56-day duration for two reasons. First, the first lockdowns lasted no longer than 60 days for the localities considered, in general. In addition, a 56-day period can be further discretized into 14-day windows, matching the maximum incubation period for SARS-CoV-2. Figure 2 depicts the 56-day periods for Lombardia (shadowed areas) using the original data, as discussed.

To draw conclusions that simultaneously account for all place categories, we compare the prepared data from the different waves for a given locality using radar charts. Whichever the temporal granularity considered (whole 56-day period or 14-day consecutive windows), per-category data from different waves are aggregated using the area under the curve (AUC) approach to enable comparison. Given the use of prepared and aggregated data, the direct interpretability of mobility reduction in radar charts is lost. Yet, this approach increases the soundness of the insights we discuss in the next section.

4. Results

Social distancing (SD) has been promoted by WHO as a critical non-pharmaceutical intervention against COVID-19, and hence localities have proposed mobility restriction measures to enforce it during each wave. Given the contrast between approaches taken by each locality, we start this section providing a unified perspective into the measures adopted. We then proceed to a per-locality discussion, where we first discuss results from an aggregated 56-day period perspective, and then from a temporal evolution perspective considering 14-day consecutive windows. We conclude with remarks on the more recent trends observed after the second wave period considered in this analysis.

4.1. Social distancing measures

Though we do not compare different localities directly, we initially discuss common SD measures adopted by localities to provide context to the analysis we conduct next. Table 3 indicates whether an SD measure affecting the mobility for the given category has been enforced in the selected locality during the given COVID-19 wave. We remark that we: (i) do not include *Residential*, as it is not considered in our assessment; (ii) do not include *Grocery & pharmacy*, as no locality has enforced measures directly related to this category, and; (iii) include *Schools* as a separate column, as school closing potentially affected multiple categories.

Two insights deserve highlighting at this point. First, for the first wave set of measures Île-de-France and Lombardia adopted stricter measures than the remaining European localities (especially Birmingham District). Second, comparing first and second wave restriction measures, we notice how stricter measures were during the first COVID-19 wave. As discussed, this is an effect of the socioeconomical toll incurred by the first wave, which made governments and societies less prone to restrictions when preparing for a second wave. Nonetheless, most of the localities later adopted stricter measures such as school closing as of January 2021, though it was also common to observe measures being relaxed for the December holiday shopping season.

Table 3: Social distance restriction measures adopted by the selected localities during the first and second COVID-19 waves. Localities are given in the order we discuss them in this section, starting from the ones where the pandemic outbreaks were more severe.

Locality	**Wave**	*Parks*	*Retail & recreation*	*Transit stations*	*Workplaces*	*Schools*
Lombardia	1st	✓	✓	✓	✓	✓
	2nd	*In part*	*In part*	✓	✓	—
Île-de-France	1st	✓	✓	✓	✓	✓
	2nd	*In part*	✓	*In part*	*In part*	—
Birmingham District	1st	—	✓	—	*In part*	✓
	2nd	—	✓	—	*In part*	—
Manaus	1st	✓	✓	✓	✓	✓
	2nd	*In part*	*In part*	✓	✓	*In part*
Berlin	1st	✓	✓	✓	*In part*	✓
	2nd	✓	*In part*	—	*In part*	—
Toronto Division	1st	✓	✓	*In part*	*In part*	✓
	2nd	✓	✓	*In part*	*In part*	✓

4.2. Lombardia

Italy's most wealthy and populous region, Lombardia was by May 2020 the hardest hit region in Europe. Until August 12th, 2021, there were over 860,000 cases and nearly 34,000 deaths in Lombardia according to the Johns Hopkins University, representing almost one fifth and one fourth of Italian cases and deaths, respectively. During the first wave, Lombardia initially adopted restriction measures regionally on February 23rd, which were later strengthened and made national by the Italian government. Specifically, the second set of restriction measures was decreed on March 8th, prohibiting any kind of mobility apart from certain health or professional needs. A third set of restriction measures was enforced in March 22nd and, among the stricter measures, any sport and physical activity in outdoor spaces was forbidden. Regarding the second wave, the Italian government labelled Lombardia a *red zone* in November 2020, with a rising number of daily new cases. The measures enforced prohibited in and out movement of the city and closed shops, bars, and restaurants, among other measures.

Figure 3a provides our comparison of the first (blue) and second (red) waves of Lombardia, in which per-category data from each 56-day period is aggregated using the area under the curve (AUC) approach. In more detail, this polar coordinate plot depicts (i) categories as angles and (ii) relative mobility aggregated over the given time period as *radii*. More importantly, this multi-dimensional visualization simplifies the simultaneous comparison of mobility reduction from all place categories in different waves of a same locality, as follows. According to Pareto-dominance, mobility reduction from wave w_1 is considered more effective than mobility reduction from wave w_2 iff the polygon given for w_1 is contained by the polygon given for w_2 (i.e. w_1 dominates w_2). This is the case in this initial analysis given in Figure 3a, where each 56-day period is aggregated as a whole for Lombardia. The mobility during the first wave is considerably reduced for all place categories in comparison to the mobility during the second wave.

To complement this analysis, Figure 4a (top) depicts the prepared time series for the whole period comprised by CMR data, where initial restriction dates are given as dashed vertical lines and the 56-day periods from each wave are given as shadowed areas. These time series plots confirm that first wave mobility reduction was much higher than during the second wave. Furthermore, it shows that reduction during the second wave varied substantially over the period considered. We further investigate this temporal evolution of social distance adherence using the radar charts given in Figure 4a (bottom), where each 56-day period is discretized prior to aggregation as 14-day consecutive windows. From left to right, spanned over two lines, each radar chart depicts a single 14-day window, with the initial day of the window given above the chart, counted as number of days since the corresponding initial restriction date.

From the radar charts, we observe that the mobility reduction in the first wave dominates the reduction in the second wave for all windows except for the first (between 0 and 13 days since each initial restriction). This is an effect of the gradual implementation of SD measures in Lombardia during the first wave, as previously discussed. Furthermore, having been the first Western country to

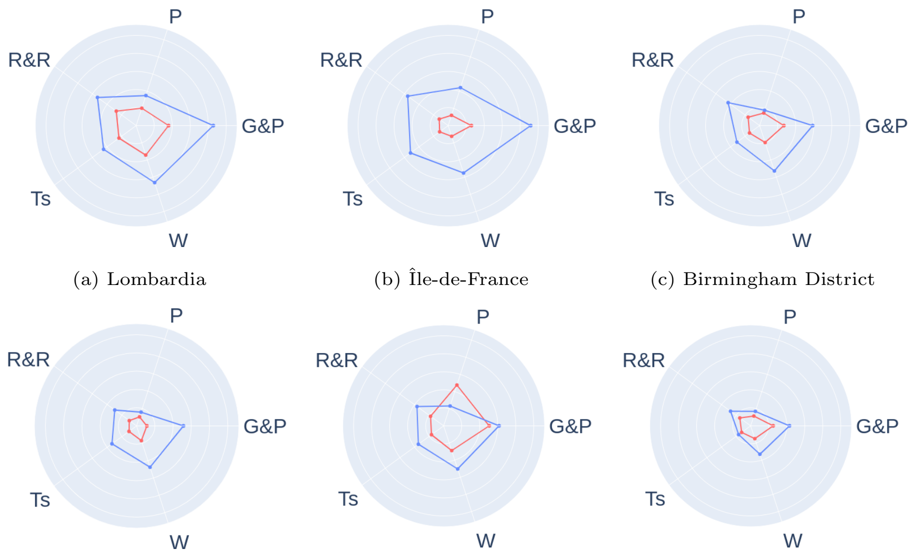
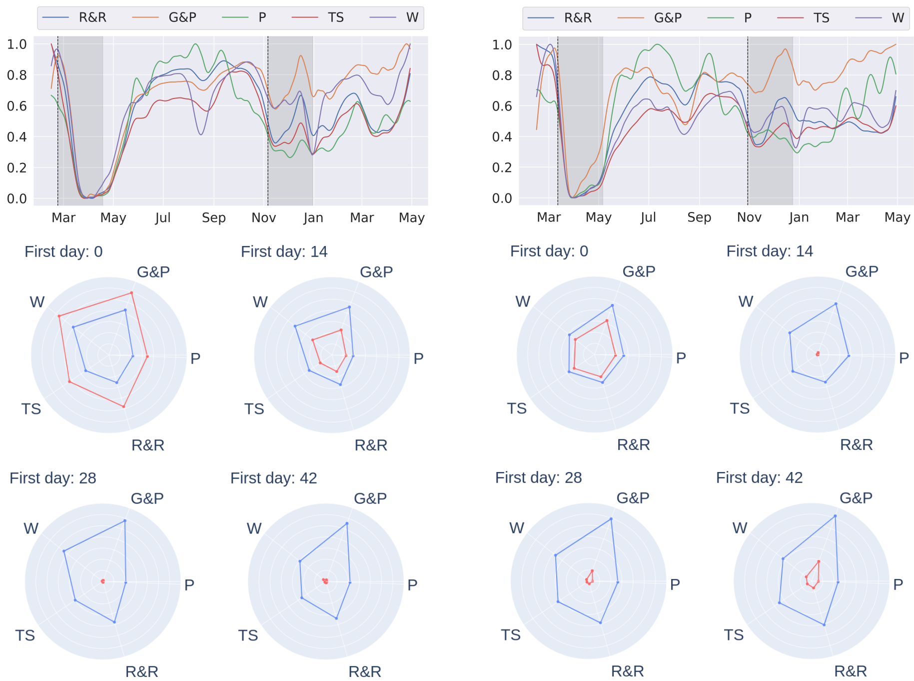


Figure 3: Comparison of the mobility reduction rates in the first (red) and second (blue) COVID-19 waves of the selected localities. Values for each (abbreviated) place category are given by the AUC aggregation of the whole 56-day period. Charts range from the minimum (0) to the maximum (56) possible AUC value for the period considered. For brevity, place categories are abbreviated. W: *Workspace*; G&P: *Grocery & Pharmacy*; P: *Parks*; R & R: *Retail & Recreation*; Ts: *Transit stations*

face the COVID-19 pandemic, Italian society in general did not fully realize the severity of the situation. By contrast, for the second wave the mobility reduction starts even prior to the restriction measures implementation, at a period that coincides with the first official notice of measures to come.

Finally, we make two remarks concerning scaling effects. As observed in Figure 4a (top), the lowest values for all categories across the whole series are observed during the first wave. More specifically, the lowest values are seen on the dates that comprise the third and fourth 14-day windows we consider. As a result, scaling makes these values very close to zero, reflecting in the very small polygons in the corresponding radar charts. By contrast, the mobility values for *Grocery & Pharmacy* during the third and fourth windows of the second wave become very close to maximum, having reached a worrysome pre-pandemic



(a) Lombardia (b) Île-de-France

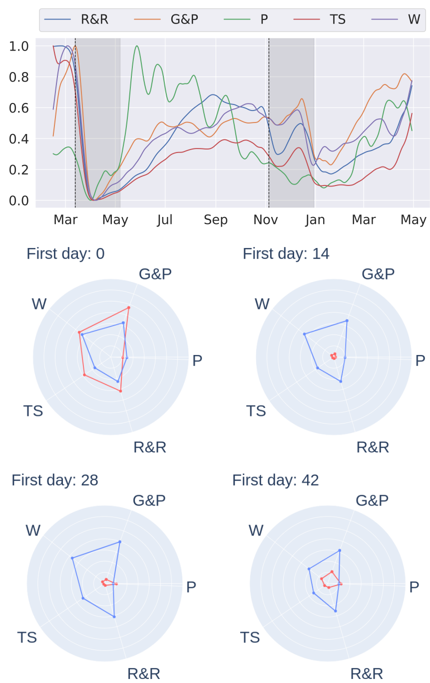
Figure 4: Temporal mobility analysis for Lombardia (left) and Île-de-France (right). Top: prepared time series for the different place categories. Initial restriction dates are given as dashed vertical lines, and periods covered by the consecutive windows in both waves are given as shadowed areas. Bottom: radar charts comparing first (red) and second (blue) COVID-19 wave mobility reduction over 14-day consecutive windows. The first day in each window counted as the number of days since the corresponding initial restriction date is given. Charts range from the minimum (0) to the maximum (14) possible AUC value for the period considered. For brevity, place categories in both types of plots are abbreviated. W: *Workspace*; G&P: *Grocery & Pharmacy*; P: *Parks*; R & R: *Retail & Recreation*; Ts: *Transit stations*.

level. Given that the initial restriction date for the second wave in Lombardia is early November, these windows correspond to mid and late December, and this increase is probably explained by the December holiday shopping season. Likewise, all other place categories also see increases in this period, though not to the same extent as for *Grocery & pharmacy*.

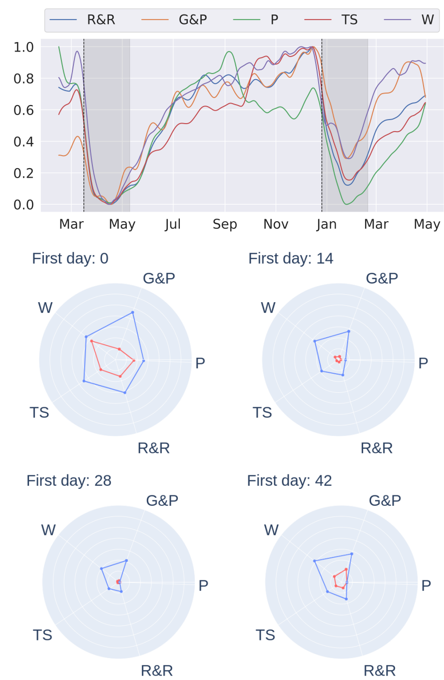
4.3. Île-de-France

The Paris-comprising region of Île-de-France records the highest number of cases and deaths in France to date. As of August 12th, 2021, Île-de-France reports nearly 125,000 hospitalized cases and over 20,000 deaths in total, according to the *Ministère des Solidarités et de la Santé*. During the first wave, Île-de-France adopted a strict lockdown approach, with school suspension and fines for people in the streets without a valid permit. By the end of October, the government announced France was in the grip of a brutal second wave, with Île-de-France reporting the highest daily infection rates since the beginning of the pandemic. This time, however, schools remained open, and different industries such as construction and cultural were exempted from suspensions. Given the expectedly lower transmission of COVID-19 in outdoor spaces (Rowe et al., 2021), parks and beaches were not closed, but access to them were restricted to nearby residents and for a limited period of time.

Figure 3b depicts the comparison of the first and second waves in Île-de-France aggregating each 56-day time period. Similarly to what was observed in Lombardia, the mobility reduction during the first wave (red) dominates the reduction during the second wave (blue), indicating a higher social distancing adherence during the first wave. This is illustrated in the time series plot given in Figure 4b (top), and also holds for all 14-day consecutive windows given in the radar charts of Figure 4b (bottom). Another observation that is worth notice is the steep decrease in mobility for all categories during the first wave when we progress from the first time window to the remaining. Since first wave restrictions in France were adopted later than in Italy, society was already more akin to believe in the need for a lockdown, specially with the rise in the number of daily cases and deaths. Finally, mobility in *Grocery & pharmacy* reaches pre-pandemic levels during December, depicted in the third and fourth windows of the second wave. This is similar to what had been discussed for Lombardia. The remaining categories also see an increase, though not to the same extent.



(a) Birmingham District



(b) Manaus

Figure 5: Temporal mobility analysis for Birmingham District (left) and Manaus (right). In the radar charts, first wave mobility is given in red, whereas second wave is given in blue.

4.4. Birmingham District

Birmingham District is the most populated district in England, with Birmingham being the second-largest city in England and the United Kingdom and also the second-largest urban and metropolitan area. Being an international commercial center and an important transport hub, with an economy dominated by the tertiary sector, its population is ethnically mixed encompassing several cultures and religions, which poses a challenge in terms of social distancing adherence. Until August 12th, 2021, there were over 136,000 cases and over 2,700 deaths in Birmingham city alone according to the Gov.uk COVID-19 dashboard. During both waves, mobility restriction measures were milder for Birmingham than for the remaining European localities, as previously discussed. Furthermore, the second lockdown started on November 5th and lasted only until December 2nd, having been relaxed for the December holiday shopping season. It was only near the end of December that stricter measures were enforced, amid the surge of the B.1.1.7 variant (World Health Organization, 2020b).

Figure 3d depicts the comparison between the first and second waves in Birmingham District taking into account the whole 56-day time period for each wave. Similarly to the analysis of previous European localities, the mobility reduction for the first wave (red) dominates the mobility reduction for the second wave (blue). However, the differences in mobility reduction for *Parks* is very small, an effect of not having applied restrictive measures regarding this category during either COVID-19 wave. These insights are illustrated as a time series plot in Figure 5a (top), though we remark that mobility in *Parks* during the first wave is not as constant as during the second wave. This plot also shows the effect of relaxing measures in the beginning of December, as well as of the more restrictive measures imposed near the end of that month.

The 14-day consecutive window analysis given as radar charts in Figure 5a (bottom) confirm insights related to *Parks* and to alleviating and hardening restrictive measures. Concerning *Parks* mobility, only for the second window the mobility reduction during the first wave is greater than during the second. For all other windows, *Parks* renders mobility reduction during the different waves incomparable.[1] Regarding changes to restrictive measures in December, the third and fourth windows respectively show the highest and lowest mobility reduction rates for the second wave periods. The third window contrasts with previously discussed European localities, in that Birmingham district does not present pre-pandemic mobility levels for *Grocery & pharmacy* (though all categories do see an increase in mobility). *Parks* is again the exception, for which the decrease observed is explained by the heavy snowstorm that hit Birmingham in early December, naturally restricting outdoor activities. For the last window,

[1] In the context of Pareto-dominance, two waves are said to be *incomparable* if neither dominates the other.

a strong reduction in mobility is seen for all categories, but not to the point of reaching levels seen during the first wave.

4.5. Manaus

Manaus is capital and the largest city of the Brazilian state of Amazonas. It is the seventh largest city in Brazil, with an estimated population of over 2 million people. Located in the center of the world's largest rainforest, Manaus is an international industrial hub for the country, as well as a medical hub for the region. Though its health system is not among the best structured in Brazil, it serves a large number of indigenous ethnicities, who are both part of the COVID-19 risk group and difficult to reach due to logistic reasons. Due to these conditions, Manaus was the first Brazilian city to face a collapse in its health system during the first wave. Indeed, among all localities considered in this work, Manaus was the one most hardly struck, with even its necroteries failing to cope with the rise in daily deaths. By August 12th, 2021, Manaus had 200,000 confirmed cases and over 9,000 deaths, according to *Fundação de Vigilância em Saúde do Amazonas*.

On March 16th, restriction measures were adopted throughout the state of Amazonas to contain the spread of the virus, similarly to the rest of Brazil. Initial second wave signs started in mid-December, but it was not until January 2021 that non-essential activities were suspended.[2] By mid-January, Manaus faced an oxygen supply crisis, and a semi-curfew was stated. At that time, the P1 variant was discovered, and so stringent measures of social distancing followed by the end of January. Indeed, this was the first time during the pandemic in which SD measures in a Brazilian major city became very close to what is expected of a lockdown. By mid-February, commerce and others social activities had been reinstated.

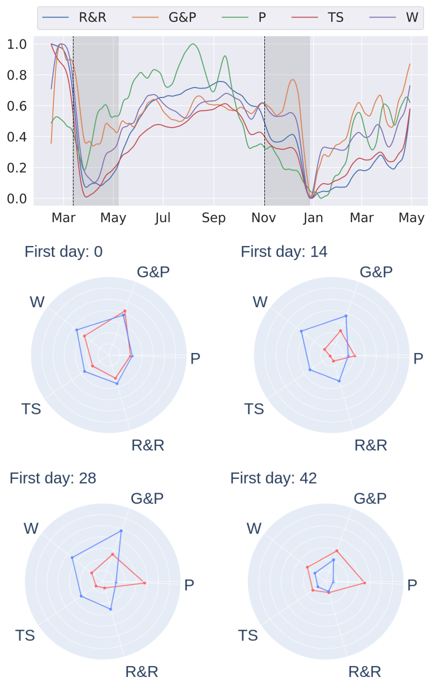
[2] The first set of measures, dating of late December, were reversed due to popular riots. After a court order in early January, they were reinstated and delimit the beginning of our analysis period, as given in Table 2.

Figure 3b depicts the comparison of the first and second waves in Manaus aggregating each 56-day time period. Similarly to the previous locations, social distancing adherence during the first wave was higher than during the second wave. A temporal evolution assessment is given in Figure 5b, where we see from the time series plot (top) that in both waves mobility levels only reached minimal values after a few weeks that restrictions had been stated. In addition, the first wave period was preceded by Carnaval, and for that reason we see mobility levels right before the second waves that were actually higher than pre-pandemic levels. Finally, during the first wave the minimal mobility levels lasted longer and were lower during the second wave. This is partially explained by the brevity of the actual lockdown period during the second wave, as discussed.

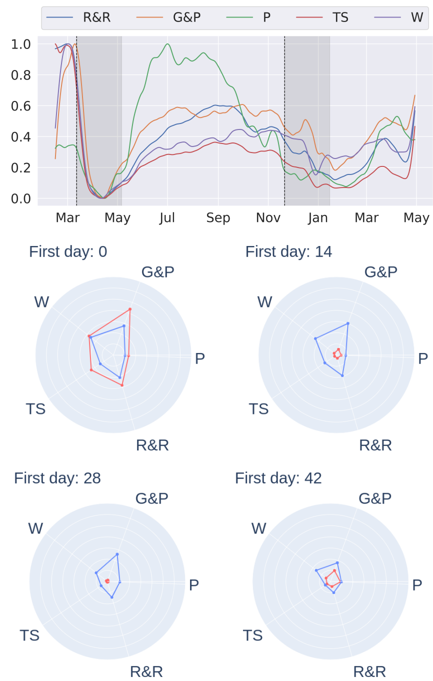
Radar charts given in Figure 5b (bottom) confirm that mobility reduction during both waves followed a similar pattern. Yet, mobility prior to second wave restrictions was much higher than prior to first wave restrictions, as discussed. For this reason, first wave reduction dominates second wave reduction for all time windows considered. Indeed, the only categories for which we see similar values during both waves are (i) *Parks*, increasingly more as windows progress in time, and; (ii) *Workplaces*, though to a lesser extent and only during the first window.

4.6. Berlin

Berlin, Germany's capital and largest city, is also the most populous city of the European Union, according to population within city limits. Based on the most recent figures, as of August 12th, 2021, Berlin had recorded the highest number of COVID-19 cases in Germany, with nearly 185,000 cases and nearly 3,600 deaths, according to Johns Hopkins University. During the first wave, Berlin was not among the more preemptive German regions in terms of promoting social distancing measures, though it followed the measures enforced nationally. Nonetheless, Germany did not adopt a mandatory stay-at-home measure like Île-de-France. For the second wave, Berlin initially stated a semi-curfew and made masks mandatory by mid-October. Given how mild these measures were,



(a) Berlin



(b) Toronto Division

Figure 6: Temporal mobility analysis for Berlin (left) and Toronto Division (right). In the radar charts, first wave mobility is given in red, whereas second wave is given in blue.

we consider as initial restriction date the national light lockdown enforced in early November. In particular, not all measures employed during the first wave were applied for the light lockdown, e.g. schools were kept open. The restriction rules were strengthened by mid-December, including school suspension.

Figure 3e depicts the comparison of the mobility in the first and second waves when we aggregate the 56-day period for each wave. Differently from the previously discussed localities, the mobility reduction rates from both waves in Berlin are considered incomparable. Mobility for *Parks* was decisive for this, being much higher during the first wave than during the second wave. This is illustrated as a time series plot in Figure 6a (top), in which we see that mobility reduction for *Parks* during the first wave lasted for a very brief period, having even reached around May a level higher than before the pandemics.

Furthermore, we notice that in the first wave *Grocery & pharmacy* mobility never reduced to the same extent as for other categories nor localities previously discussed. In this plot, the effect of the December holiday shopping season is only observable for *Grocery & pharmacy* mobility, differently from previous European localities. Moreover, we can see the effect of the more restrictive measures imposed near the end of that month. In fact, mobility levels for all categories become lower even than those observed in the first wave.

The temporal evolution of mobility restriction in Berlin is further detailed as radar charts given in Figure 6a (bottom). As discussed, *Parks* second wave mobility continually decreased over time, whereas in the first wave it was only reduced during the first window. From a Pareto-dominance perspective, mobility reduction from both waves are incomparable for all but the last window. We then discuss the most relevant insights from each window comparison. When we isolate the first window, mobility reduction from both waves are very similar for most categories, and are considered incomparable because of *Grocery & pharmacy*. During the second window, mobility reduction in the second wave remains mostly unchanged, whereas in the first wave it had a big increase. The remaining windows depict second wave mobility reduction in December. The increase in the third window due to the holiday shopping season is only observable for *Grocery & pharmacy*, as previously discussed. In contrast, when we assess the fourth window we see that the stricter measures employed by end of December make the reduction during the second wave dominate the reduction in the first wave.

4.7. Toronto Division

Toronto is the largest city in Canada and is considered a world leader in areas such as business, finance, technology, entertainment, and culture. Toronto has a large population of immigrants from all over the world, being a multicultural city where enforcing social distancing should be a challenge. As of August 12th, 2021, the city of Toronto reports over 166,000 cases of COVID-19 and over 3,600 deaths in total according to the Ontario Ministry of Health. During the first wave, Toronto announced (i) schools would not resume after break in mid-March; (ii) shutting of non-essential services on the following week, and; (iii) shutting of outdoor spaces at the end of that month. For the second wave, a variety of wide-scale public health measures, including business and organizational closings, were put into effect by the end of November 2020 in Toronto as a last resort to control the COVID-19 spread. In December 26th, the Ontario government announced a province-wide shutdown applying stricter restriction measures such as closure of schools after the Christmas holiday.

Figure 3f depicts the comparison of the mobility reduction rates during the first and second waves in Toronto Division when aggregating the 56-day period for each wave. Similarly to most localities, the mobility observed in the first wave is lower than the mobility observed in the second wave for all place categories simultaneously. Yet, *Parks* and *Transit stations* mobility levels become quite similar between different waves, and to a lesser extent also *Retail & recreation*. The effects of the incremental restrictive measures in either wave are only observable in the temporal evolution assessment given in Figure 6b.

Concerning the time series plot given in Figure 6b (top), we see that mobility in the first wave only reached minimal level in April, due to the incrementally announced restrictive measures. However, the reductions observed brought mobility to a very low level, which was sustained almost until the end of the first wave. This result is similar to what was observed in Lombardia, where we observed that the decrease in mobility during the first wave was progressive. It is also important to highlight that the mobility reduction in Toronto Division during the second wave had already started to some extent as of October 2020. Indeed, mobility levels in the period between the first and second waves was the lowest we have observed among all localities. Finally, for Toronto Division we observe an increase in *Grocery & pharmacy* mobility in the holiday shopping season as for other localities, but in this case accompanied by a decrease in the remaining categories.This could be explained by the recency of restriction measures, implemented in Toronto Division by the end of November.

Regarding the radar charts given in Figure 6b (bottom), we see that in the first window mobility reduction during the second wave dominates reduction during the first wave. This is explained by the mobility levels before the start of each wave, as discussed: though first wave reduction was sharper, prior to this window mobility levels were pre-pandemic. In contrast, reduction in the second wave was more gradual, but prior to this window mobility levels were much lower than pre-pandemic.

The remaining radar charts reflect the decrease in mobility in both waves. For the first wave, this reduction reaches a very low level in the second and specially third windows, and only partially reverses this trend in the fourth window. In contrast, reduction in the second wave is never reversed, but is more gradual. As a result, mobility reduction in the first wave dominates reduction in the second wave for the second, third, and fourth windows. This is also an effect of the stricter measures adopted by late December, which correspond to the third time window given for this locality. For the last time window, though, the mobility in both waves is quite similar, even if not incomparable.

4.8. Post-second wave analysis

Even if results observed are alarming, reduced mobility observed close to the end of the second period in all localities but Manaus sheds hope that more recent restriction measures could help prevent an even stronger disaster. Specifically, observing the 56-day period that followed the second wave period considered in the analysis for those localities, we can see that the mobility reduction rates never again reached pre-pandemic or even between-wave levels. From Figure 4, we see that during the following 56-day period Lombardia and Île-de-France kept the reduction rates nearly at the same level as at the end of the second wave period considered, except for *Workplaces*. For Birmingham (Figure 5a) and Toronto (Figure 6b), the reduction rates in the following 56-day period are at least as high as and often even higher than the rates observed in the second wave period considered. The extreme situation is observed in Berlin, where for circa a week in the following 56-day period all categories reach first wave reduction rates. Though this is not sustained for all categories, reduction rates are still impressively high for the rest of that period. Manaus is an exception to this pattern, as discussed. The 56-day period that followed the second wave period considered sees an increase in mobility for all categories, some of which even reach between-wave levels.

5. Social distancing as a public health policy in the pandemic

Social distancing has never been discussed as much as in the context of COVID-19, despite (i) being a public health policy known to epidemiologists for a long time, and; (ii) having been applied in recent outbreaks such as SARS, MERS and others (Kumar et al., 2020). Non-pharmacological measures such as this are necessary to interrupt the transmission chain of viruses such as SARS-CoV-2, especially when effective treatments or vaccines are not available. In these cases, one of the first public health policies to be taken are the decrees that limit the mobility of the population. Penalties for infringing decrees may range from (i) legal sanctions, in the strictest cases, or; (ii) moral sanctions, in the less strict cases.

One of the main conclusions of this article is that, in general, the community mobility level increased from the first to the second wave. This result may indicate that, even at the risk of repeating a dramatic epidemiological situation experienced at the beginning of the pandemic, population risk perception in relation to COVID-19 may have become smaller from one wave to another. In this context, a public policy that can be adopted by governments is to improve their communication strategies with the population regarding the spread of COVID-19 through physical contact and exposure to crowded and poorly ventilated places.

Regarding communication, it is also worth noting that COVID-19 triggered a recognized state of infodemic around the world (Anwar et al., 2020), in which the dissemination of fake news found fertile soil, especially in less developed or developing countries, such as Brazil (Ceron et al., 2021; Galhardi et al., 2020). Fake news potential to affect people's behavior towards COVID-19 has been reported by other authors (Saling et al., 2021; El-Far Cardo et al., 2021). Relating to social distancing, the spread of beliefs such as the inefficacy of SD measures to contain the pandemic may have contributed to making population adherence to decrees last for a shorter period of time. In addition, fake news indicating that the disease was already under control may have stimulated a sense of relaxation regarding SD at the time of the second wave, to some extent.

It is also important to highlight that the effects of social distancing on the economy comprised one of the main difficulties faced by governments in keeping the population at home and/or with as few people circulating on the streets as possible (Cifuentes-Faura, 2021; Chang et al., 2021). This is especially true in countries with a higher proportion of employees with informal employment relationships and/or whose performance of work activities cannot be adapted to the home office model. In these cases, social distancing must be combined with public social assistance policies for those who lose their jobs and/or a significant portion of their income, so that people effectively have the material conditions to remain at home.

Another measure that can be important is the application of social distancing or lockdown to the right extent. Finding a balance between controlling COVID-19 transmission and closing activities is paramount. This balance will reduce the impact of adverse effects such as unemployment and lower labor market productivity. Moreover, this balance will minimize the adverse effects of "lockdown fatigue" that contribute to reducing the adherence of population to measures of social distancing over time. Evidently, finding this period is not an easy task. Yet, some studies in the literature present mathematical modeling alternatives that can contribute to the application of public policies of social distancing to be carried out at an optimal point (Köhler et al., 2021; Pataro et al., 2021).

Although the empirical exercise carried out in this article comprehends phases of the pandemic in which vaccines against COVID-19 were not yet available, the results found remain important even with the mass vaccination of the world population in progress (Si et al., 2021). As demonstrated by the findings of this article, keeping the movement of people under control is an arduous task. Acting in addition to economic and risk perception factors in relation to the disease, cultural factors should be taken into account by authorities to precede new waves. For example, results indicated an increase in mobility for all place categories during the December holiday shopping season. On the eve of major holidays, redoubling (i) inspections of public spaces and maximum people capacity of commercial establishments, and (ii) promoting educational campaigns on hygiene and social distancing can be prophylactic to pressure on the health system a few weeks later.

As long as a significant portion of the population is not fully immunized and, from a global perspective, the level of community movement in certain countries continues beyond the pace of vaccination and produces variants that threaten the effectiveness of available immunization agents, social distancing will continue being a public health policy of primary necessity. For restrictive measures to become secondary, it will be necessary to advance the pace of vaccination, and for that, it is necessary, among other things, that inequality in access to immunizing agents be overcome, or the world will continue to experience successive waves of the COVID-19 pandemic.

6. Conclusions

Since the emergence of SARS-CoV-2 back in December 2019 in China, the world has been facing a severe global health crisis due to COVID-19. Due to the insufficient information on the transmission patterns and the lack of vaccines or, more recently, the still insufficient number of fully immunized population, and specific pharmaceutical treatment alternatives, non-pharmaceutical interventions such as social distancing play an important role for COVID-19 control. Several countries have implemented a series of social distancing measures such as closing schools, prohibiting mass gatherings, restricting travel, and even enforcing lockdown to reduce virus transmission. These measures have been introduced gradually and in differing ways, to a greater or lesser extent, locally and globally in the different countries.

In this work, using Google community mobility reports (CMR) data for different localities, we have compared social distancing in the first and second COVID-19 waves. The analysis comprised 56 days since the initial restriction date in each wave at the selected localities, and was further detailed using 14-day consecutive windows to assess for temporal evolution of mobility reduction. Furthermore, the localities assessed represent severely affected regions and/or Europe and America. Though we did not compare localities directly, we have observed how often (i) mobility reduction during the first wave was stronger than during the second wave; (ii) the increase in mobility from all categories during the December holiday shopping season, and; (iii) the contrasting results for *Parks* and *Grocery & pharmacy*.

More recent data indicates that most localities considered extended the second wave measures beyond the timespan initially assessed here. The only exception is Manaus, for which mobility reaches again between-wave levels. Several factors could justify this, which we believe future work should investigate. The first is that in northern hemisphere localities the winter season and the novel variants arrived later than the period we investigated. A second reason is that in Manaus the different government levels (federal, state, and city) had conflicting views on the importance of social distancing, and financial aid was not available to the vulnerable segments of society. According to the literature, adherence to these measures is also related to greater trust of the governed in their governors (Seale et al., 2020; Brodeur et al., 2021), which, in addition to other aspects such as the conduct of the pandemic by the local administration and the early return of economic activities between the the first and second wave may have contributed to the sanitary chaos observed in particular for this location compared to the other regions analyzed.

Indeed, in all localities but Manaus, the mobility levels between the first and second wave have never reached pre-pandemic levels. The reductions observed during the first wave have brought mobility to a very low level and the localities, to some extent, have kept it controlled between waves. However, Manaus was not able to keep the low level reached at the end of the first wave, and mobility levels between waves even surpassed the pre-pandemic stage.

In any case, the results that point to a smaller reduction in mobility during the first wave compared to the second wave shed light on possible measures that public authorities can take in situations where reducing social interactions becomes a matter of life and death. One of them is the timing of the application of social distancing measures. Finding a balance between controlling Covid-19 transmission and closing activities will reduce the impact of adverse effects such as unemployment and lower labor market productivity, and also minimize the adverse effects of "lockdown fatigue" that contribute to reducing the adherence of population to measures of social distancing over time. Evidently, finding this period is not an easy task, however, some studies in the literature present alternatives for mathematical modeling that can contribute to the application of public policies of social distancing to be carried out at an optimal point (Köhler et al., 2021; Pataro et al., 2021).

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