Appendix A. Supplementary Figures and Tables

Table A1. Descriptive Statistics

Panel A: City-Pair-daily Level Data

Sample Period	Jan 12, 2019 - Mar 12 , 2019		Jan 1, 2020 - Feb 29, 2020	
	Mean	S.D	Mean	S.D
CityPair Intensity	0.011	0.052	0.007	0.044
CityPair Flow Population	997.044	4,722.465	668.792	3,970.201

Panel B: City-daily Level Data

Sample Period	Jan 12, 2019 - Mar 12 , 2019		Jan 1, 2020 - Feb 29, 2020	
	Mean	S.D	Mean	S.D
Outflow Intensity	1.159	1.568	0.717	1.478
Outflow Population	105,287.503	142,443.319	65,126.768	134,310.998
Inflow Intensity	1.159	1.608	0.717	1.058
Inflow Population	105,261.037	146,127.871	65,142.334	96,153.964
WithinCity Flow Intensity	4.472	0.818	3.592	1.493
WithinCity Flow Population	1,492,950.639	1,346,858.619	1,188,276.693	1,223,892.324
# of New Confirmed Cases	0	0	3.721	105.176
# of Total Confirmed Cases	0	0	78.364	1,313.831
# of New Deaths	0	0	0.129	2.960
# of Total Deaths	0	0	2.181	50.409
# of New Heals	0	0	1.792	31.757
# of Total Heals	0	0	17.211	259.659

Notes: This table presents the descriptive statistics of the variables used in this study, with Panel A corresponding to the city-pair daily level variables and Panel B corresponding to the city daily level variables. The sample covers a period between Jan 12 and Mar 12 in 2019, and between Jan 1 and Feb 29 in 2020. The two periods in 2019 and 2020 cover the same lunar calendar.

Table A2. Various Levels of Prevention and Control Measures in Different Cities

City	Province	Start Date	Cases as of Feb 29, 2020
Panel A. Complete Shutdown			
Wuhan	Hubei	2020/1/23	49122
Huanggang	Hubei	2020/1/23	2905
Ezhou	Hubei	2020/1/23	1391
Xiaogan	Hubei	2020/1/24	3518
Jingzhou	Hubei	2020/1/24	1579
Suizhou	Hubei	2020/1/24	1307
Huangshi	Hubei	2020/1/24	1014
Yichang	Hubei	2020/1/24	931
Jingmen	Hubei	2020/1/24	925
Xianning	Hubei	2020/1/24	836
Shiyan	Hubei	2020/1/24	672
Xiantao	Hubei	2020/1/24	575
Tianmen	Hubei	2020/1/24	496
Enshi	Hubei	2020/1/24	252
Qianjiang	Hubei	2020/1/24	198
Shennongjia	Hubei	2020/1/24	11
Xiangyang	Hubei	2020/1/28	1175
Panel B. Partital Shutdown			
Wenzhou	Zhejiang	2020/2/2	504
Haerbin	Heilongjiang	2020/2/4	198
Hangzhou	Zhejiang	2020/2/4	169
Ningbo	Zhejiang	2020/2/4	157
Zhengzhou	Henan	2020/2/4	157
Zhumadian	Henan	2020/2/4	139
Fuzhou	Fujian	2020/2/4	72
Panel C. Checkpoints and Quarantine Zones			
Chongqing	Chongqing	2020/1/31	576
Yinchuan	Ningxia	2020/1/31	35
Wuzhong	Ningxia	2020/1/31	28
Fangchenggang	Guangxi	2020/2/2	19
Huaian	Jiangsu	2020/2/3	66
Huaibei	Anhui	2020/2/3	27
Xinyang	Henan	2020/2/4	274
Nanjing	Jiangsu	2020/2/4	93
Xuzhou	Jiangsu	2020/2/4	79
Changzhou	Jiangsu	2020/2/4	51
Linyi	Shandong	2020/2/4	49
Nantong	Jiangsu	2020/2/4	40
Zhenjiang	Jiangsu	2020/2/4	12
Jingdezhen	Jiangxi	2020/2/4	6
Jining	Shandong	2020/2/5	258
Nanchang	Jiangxi	2020/2/5	231
Qingdao	Shandong	2020/2/5	60
Nanning	Guangxi	2020/2/5	55
Sanya	Hainan	2020/2/5	54
Kunming	Yunnan	2020/2/5	53
Cangzhou	Hebei	2020/2/5	48
Jinan	Shandong	2020/2/5	47
Haikou	Hainan	2020/2/5	39
Taizhou	Jiangsu	2020/2/5	37
Taian	Shandong	2020/2/5	35
Shijiazhuang	Hebei	2020/2/5	29
Zaozhuang	Shandong	2020/2/5	24
Yangzhou	Jiangsu	2020/2/5	23
Rizhao	Shandong	2020/2/5	16
Suqian	Jiangsu	2020/2/5	13
Dongying	Shandong	2020/2/5	0
Xinyu	Jiangxi	2020/2/6	130
Shangrao	Jiangxi	2020/2/6	123
Panel C. Checkpoints and Quarantine Zones			
Jiujiang	Jiangxi	2020/2/6	118
Yichun	Jiangxi	2020/2/6	106
Zhuhai	Guangdong	2020/2/6	98
Suzhou	Jiangsu	2020/2/6	87
Ganzhou	Jiangxi	2020/2/6	76
Maanshan	Anhui	2020/2/6	38
Pingxiang	Jiangxi	2020/2/6	33
Shenyang	Liaoning	2020/2/6	28
Jian	Jiangxi	2020/2/6	22
Neijiang	Sichuan	2020/2/6	22
Dalian	Liaoning	2020/2/6	19
Yingtan	Jiangxi	2020/2/6	18
Jinzhou	Liaoning	2020/2/6	12
Yibin	Sichuan	2020/2/6	12
Huludao	Liaoning	2020/2/6	12
Panjin	Liaoning	2020/2/6	11
Dandong	Liaoning	2020/2/6	8
Yaan	Sichuan	2020/2/6	7
Tieling	Liaoning	2020/2/6	7
Chaoyang	Liaoning	2020/2/6	6
Anshun	Guizhou	2020/2/6	4
Liaoyang	Liaoning	2020/2/6	3
Benxi	Liaoning	2020/2/6	3
Fushun	Liaoning	2020/2/6	0
Shenzhen	Guangdong	2020/2/7	417
Guangzhou	Guangdong	2020/2/7	346
Hefei	Anhui	2020/2/7	174
Chengdu	Sichuan	2020/2/7	143
Tianjin	Tianjin	2020/2/7	136
Tangshan	Hebei	2020/2/7	58
Lianyungang	Jiangsu	2020/2/7	48
Lanzhou	Gansu	2020/2/7	36
Guiyang	Guizhou	2020/2/7	36
Suining	Sichuan	2020/2/7	17
Guangyuan	Sichuan	2020/2/7	6
Foshan	Guangdong	2020/2/8	84
Qinhuangdao	Hebei	2020/2/8	10
Ziyang	Sichuan	2020/2/8	4
Dongguan	Guangdong	2020/2/9	99
Huizhou	Guangdong	2020/2/9	62
Wuxi	Jiangsu	2020/2/9	55
Hanzhong	Sanxi	2020/2/9	26
Mianyang	Sichuan	2020/2/9	22
Deyang	Sichuan	2020/2/9	18
Beijing	Beijing	2020/2/10	413
Shanghai	Shanghai	2020/2/10	337
Baotou	Inner Mongolia	2020/2/12	11
Ereduosi	Inner Mongolia	2020/2/12	11
Xilinguole	Inner Mongolia	2020/2/12	9
Chifeng	Inner Mongolia	2020/2/12	9
Bayannaoer	Inner Mongolia	2020/2/12	8
Hulunbeier	Inner Mongolia	2020/2/12	7
Huhehaote	Inner Mongolia	2020/2/12	7
Tongliao	Inner Mongolia	2020/2/12	7
Wulanchabu	Inner Mongolia	2020/2/12	3
Wuhai	Inner Mongolia	2020/2/12	2
Xingan	Inner Mongolia	2020/2/12	1
Alashan	Inner Mongolia	2020/2/12	0

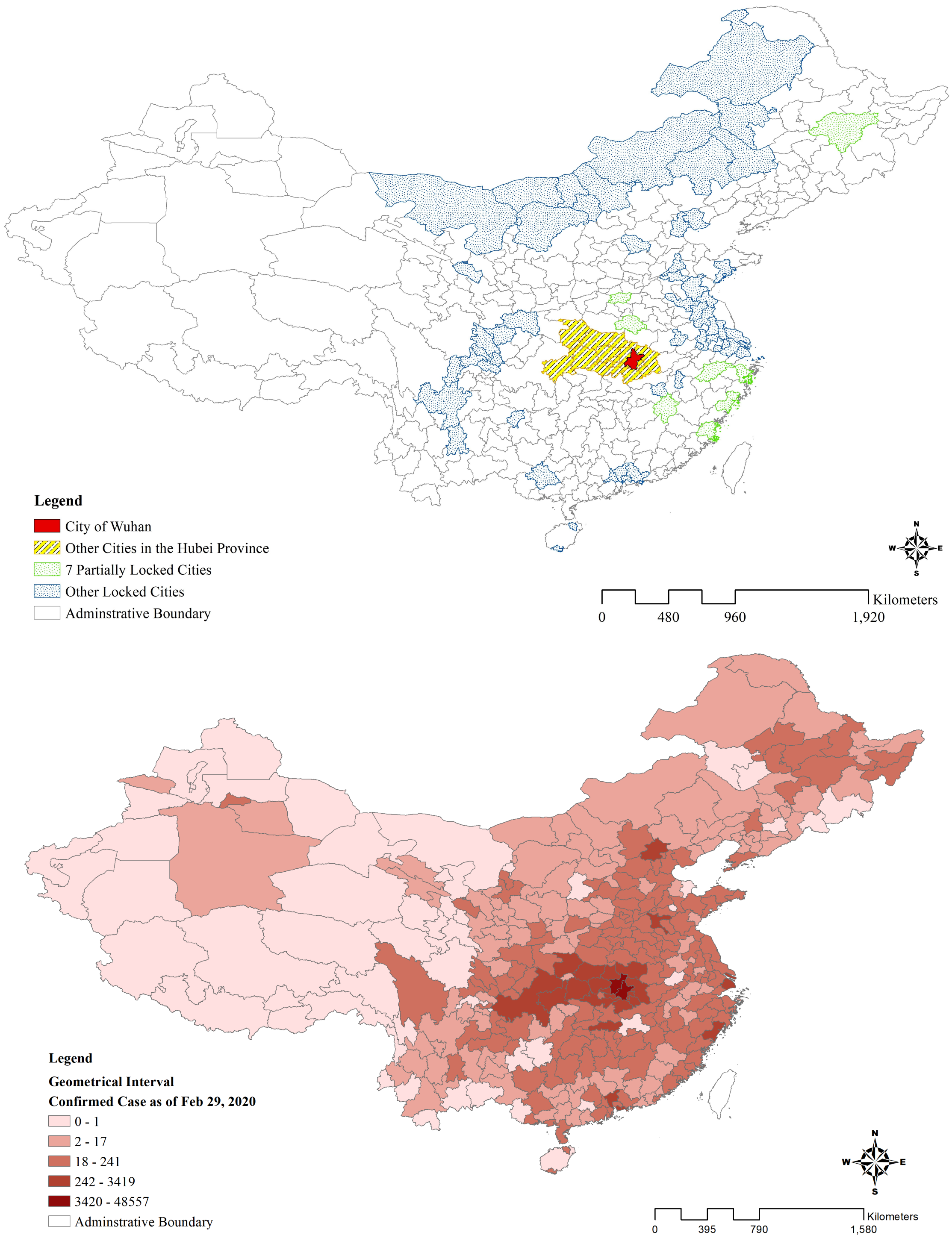
Notes: This table summarizes different levels of prevention and control measures across 115 cities. Panel A lists 17 cities with completed lockdown, which means all public transport and private vehicles are banned in the city, all residential buildings are locked down, and residents are not allowed to leave the city. 7 Cities in Panel B are under partial lockdown, the majority of the public transportation has been temporarily shut down, checkpoints have been set up to control the inflow population, and surveillance and tighter controls in each neighborhood. 91 Cities in Panel C set up checkpoints and quarantine zones, and public transport maintains normal operation.

Table A3. Summary Statistics of Cities with Different Level of Controls

	Wuhan	7 Partial Lockdown Cities	Other Unlocked Cities
# of Total Cases as of Feb 2, 2020	5,142	101	13
Daily Average Population Inflow (2019 Sample Period)	466,682	294,799	78,006
Daily Average Population Outflow (2019 Sample Period)	420,900	282,995	78,789
Daily Average Within-City Population Flow (2019 Sample Period)	3,270,509	3,305,080	1,316,090
Permanent Population (2019)	9,785,388	8,433,975	3,524,548
GDP (Trillion CNY) (2019)	1,153	811	92

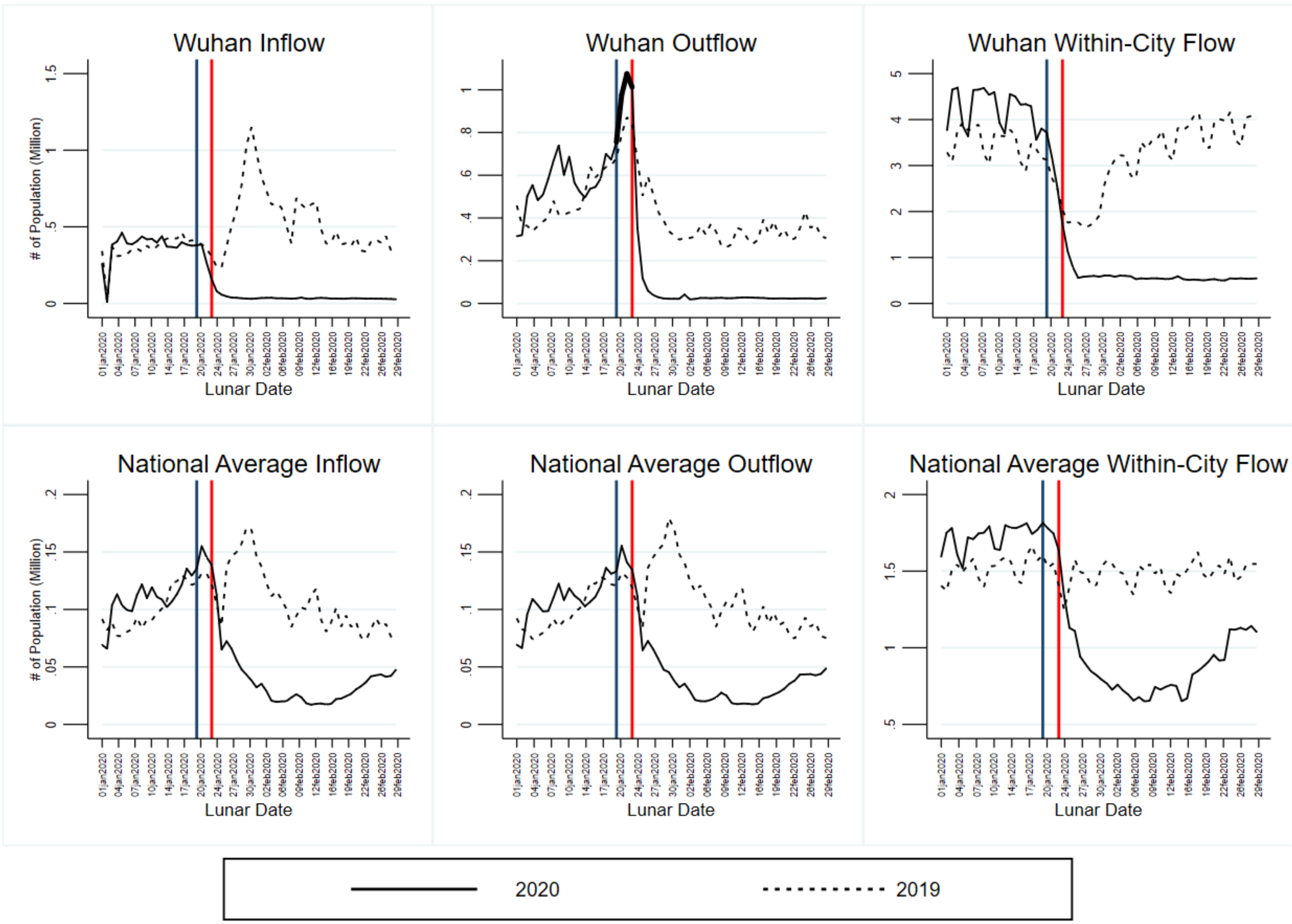
Notes: This table provides summary statistics on the count of total confirmed cases as of February 2, 2020, and on daily average population inflow, outflow, and within-city flow between January 12 and March 12 in 2019, and on permanent population GDP as of December 2019, for cities with different level of controls.

Figure A1. Cities with Control Measures and the Confirmed COVID-19 Cases



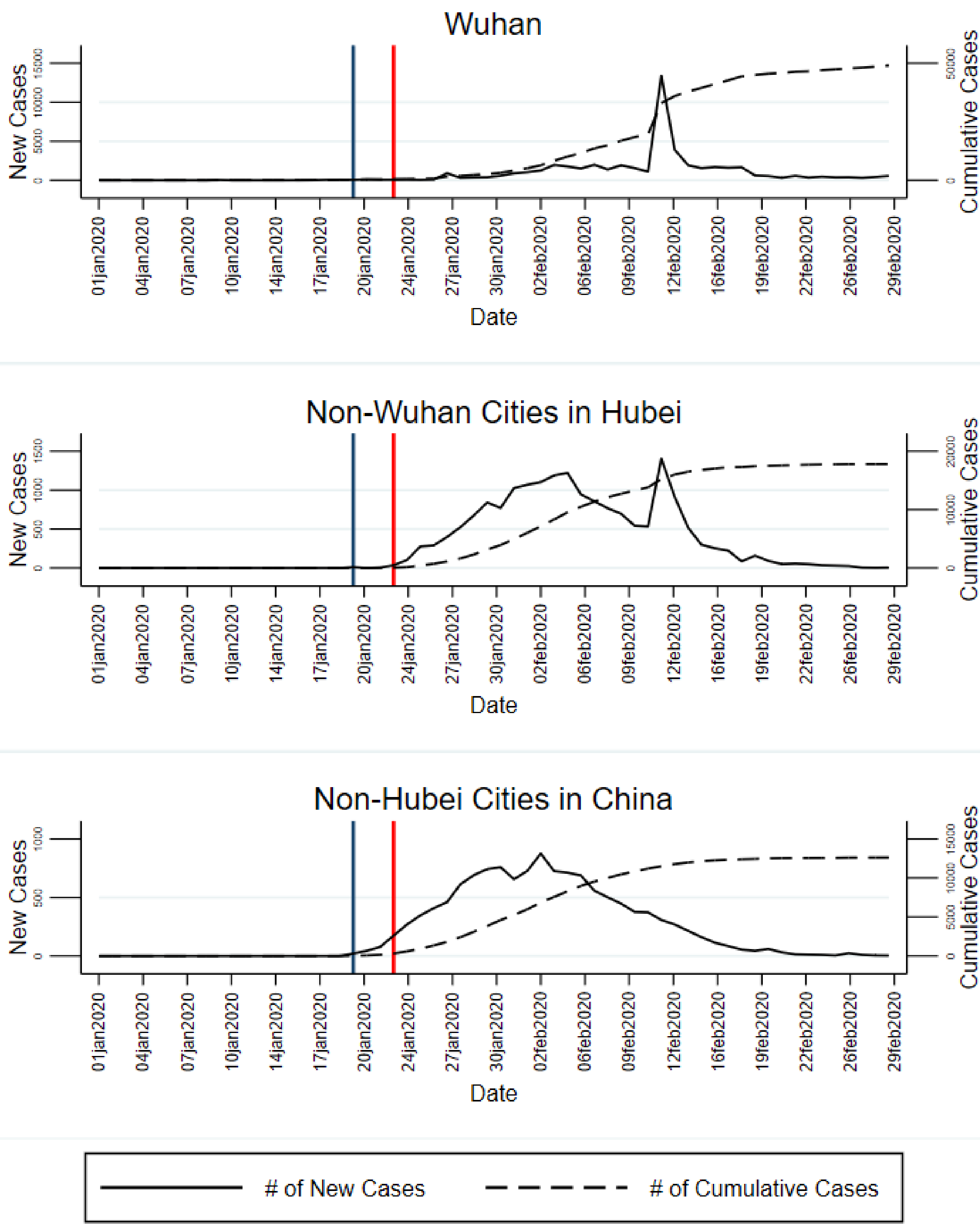
Notes: This figure presents the geographic distributions of cities with different levels of control measures and the number of Confirmed COVID-19 Cases as of Feb 29, 2020. The maps were plotted with ArcGIS 10.2 (ESRI).

Figure A2. Inter-city and Within-city Population Flows



Notes: Top figures show the inflows into Wuhan, outflows from Wuhan and within-Wuhan flows, for year 2020 (in the solid line) and year 2019 (in the dashed line), matched by the lunar calendar; and the bottom shows the corresponding figures for the national city averages. The blue vertical line indicates the date of January 20, 2020 when the health ministry confirmed human-to-human transmission of COVID-19; and the red vertical line indicates the date of January 23, 2020 when Wuhan was locked down.

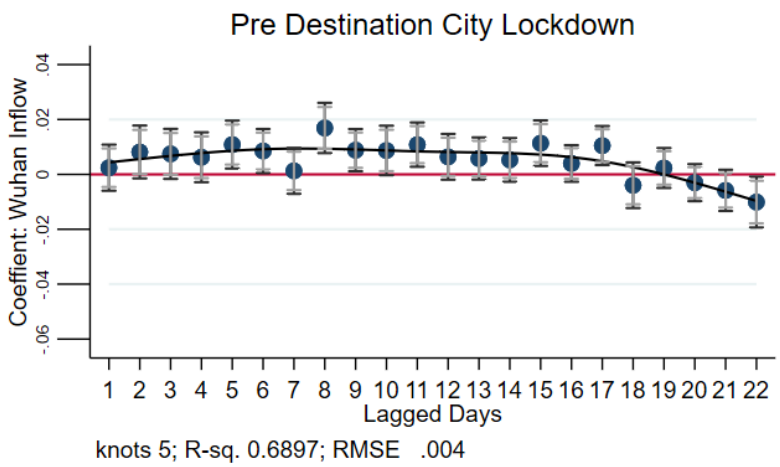
Figure A3. Daily Confirmed Cases and Cumulative Confirmed Cases

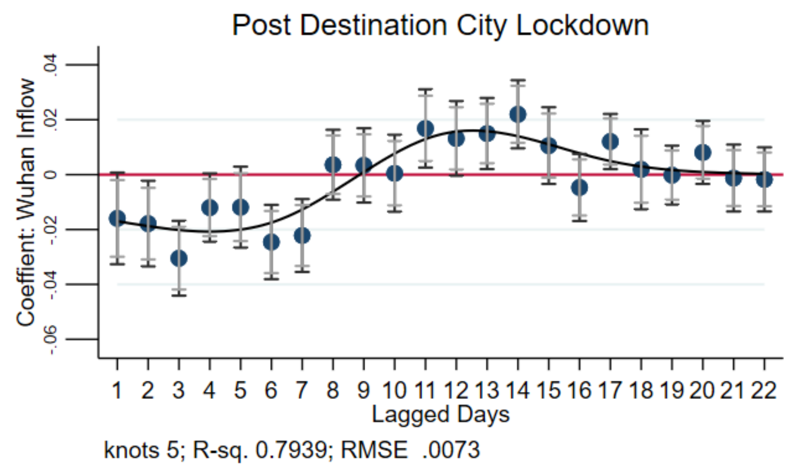


Notes: This figure shows the daily confirmed, dead, and healed cases in Wuhan, other cities in Hubei Province, and cities outside of Hubei Province.

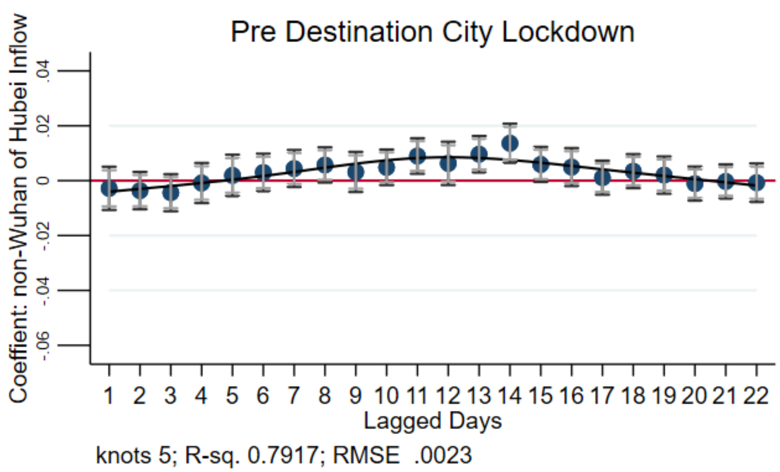
Figure A4. Dynamic Impacts of Pre and Post Destination City Lockdown

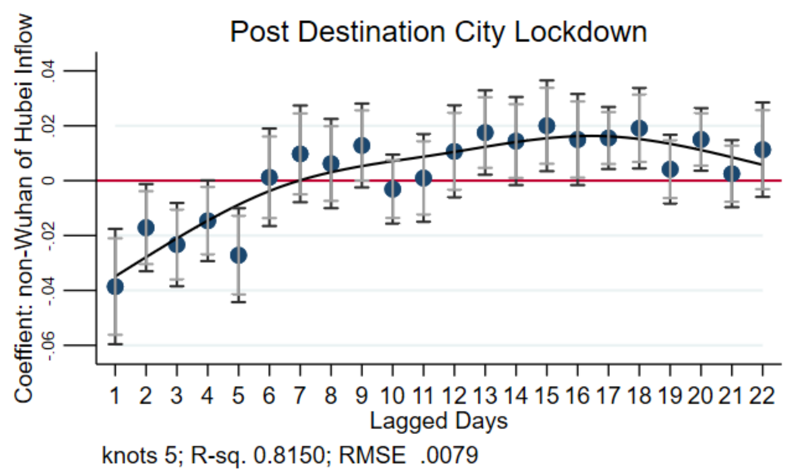
Panel A: Inflows from Wuhan





Panel B: Inflows from non-Wuhan Cities of Hubei

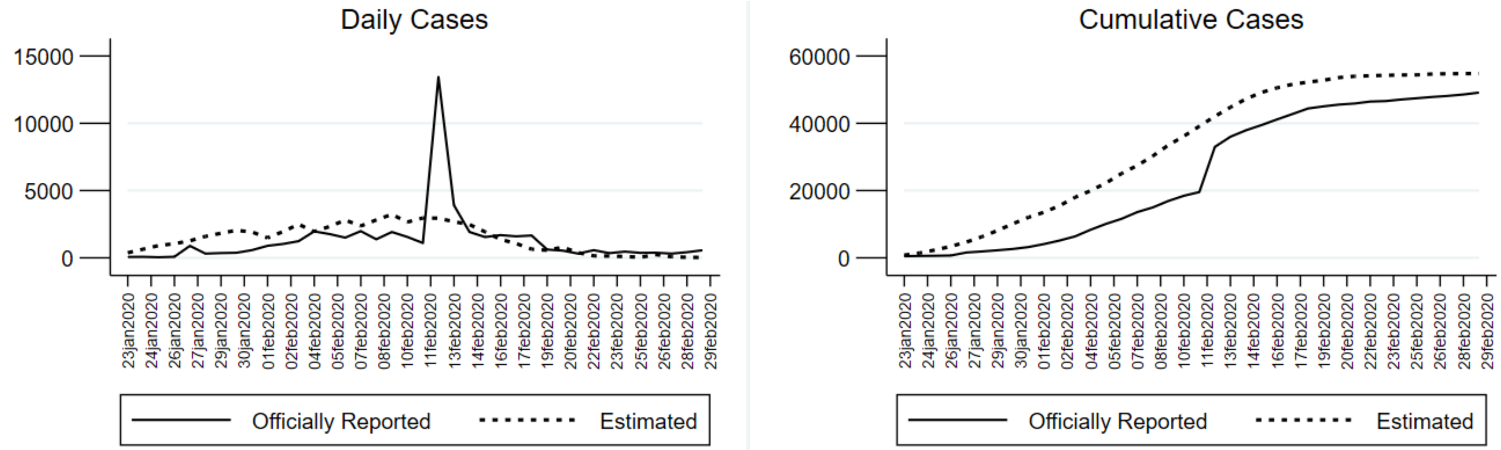




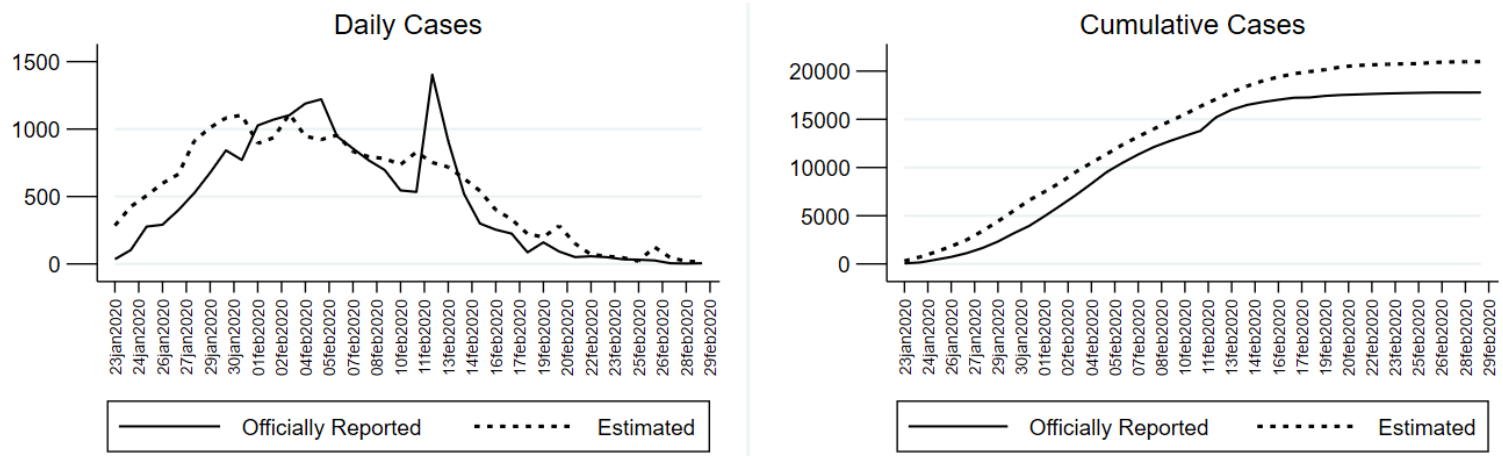
Notes: Panel A plots the dynamic lagged effects of past inflows from Wuhan pre (left figure) and post (right figure) destination cities' lockdown policy, if any. Panel B plots the dynamic lagged effects of past inflows from non-Wuhan Cities of Hubei pre (left figure) and post (right figure) destination cities' lockdown policy, if any. The coefficient estimates are obtained from estimating Equation (4). We add spline smoothing fit curves (in red) using the *rcspline* function and plot the 90% (the vertical gray whiskers) and 95% (the vertical black whiskers) confidence intervals.

Figure A5. Estimation on the “Actual” Number of Infected Cases in Wuhan and other Cities of Hubei

Panel A: Wuhan

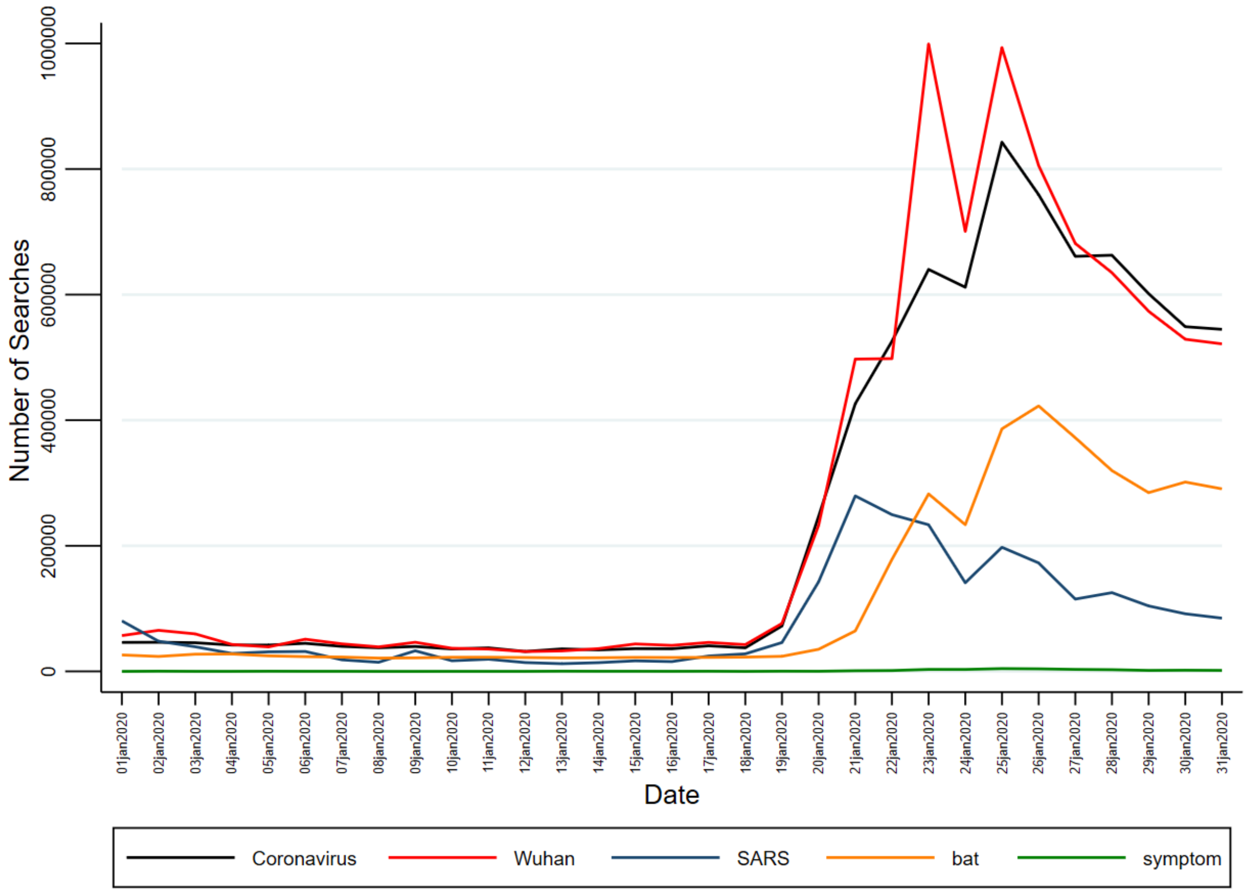


Panel B: 16 other Cities of Hubei



Notes: This figure compares the estimated COVID-19 cases (in the dotted curve) with the officially reported confirmed cases (in the solid curve) in Wuhan (top) and in 16 non-Wuhan cities in Hubei Province (bottom) from January 23 to February 29 in 2020. The left panel plots the estimated new COVID cases on each date t from 23 (January 23, 2020) to 60 (February 29, 2020). The right panel plots the estimated cumulative cases each day.

Figure A6: Daily Search Frequencies of COVID-19 Related Keywords



Notes: This figure graphs the daily search frequency of COVID-19 related keywords, including "Coronavirus", "Wuhan", "Bat", "SARS", and "symptom" (in Chinese). It shows a clear and abrupt spike in the search frequencies on January 20, the day of the public confirmation of human-to-human transmission of the Novel Coronavirus by Dr. Zhong Nanshan on Chinese national TV.

Appendix B. The Conversion of Baidu Mobility Indices into Number of Population Movements

We obtain three migration intensity indicators (the daily *in-migration* index (IMI) of a city, the daily *out-migration* index (OMI) of a city, and the daily *within-city* migration index (WCMI)) from Baidu Migration for 364 Chinese cities. Baidu Migration[16] uses Baidu Maps Location Based Service (LBS) open platform and Baidu Tianyan to calculate and analyze the LBS data, and provides visual presentation to show the trajectory and characteristics of the population migration. Baidu has been the dominant search engine in China because all Google search sites have been banned in mainland China since 2010.

Specifically, Baidu Migration provides the following information: (1), the top 100 origination cities (OC) for the population moving *into* the city and the corresponding percentages of inflow population that originated from each of the top 100 OC; and (2), the top 100 destination cities (DC) for the population moving *out of* the city, together with the corresponding percentages of the outflow population that go into each of the top DC. In the data, the cumulative percentages of the inflow population from the top 100 origination cities, and the cumulative percentages of the outflow population into the top 100 destination cities, reach 97% per city on average, which ensures that the Baidu Migration data capture near complete inflows and outflows for each of the 364 cities in the data.

We convert the mobility index unit into the number of population movements by taking the daily inflow of people into Shanghai by airplanes, trains, buses and cars, the daily within-city trips in Shanghai by subways, buses and expressways (provided by NESSDC), and the corresponding inflow index and within-city mobility index in Shanghai (provided by Baidu). Based on the definition of inter-city mobility indices provided by Baidu, the inter-city indices are comparable both across cities and time. We first divide the actual number of inflow/outflow population by the inflow/outflow index in a day to obtain population number per unit of inter-city index. For instance, given that the actual inflow population of 302,6000 on February 6, 2020 into Shanghai corresponds to the inflow index of 3.72, the population number per unit inflow index is 302,600/3.72=81344.08 on February 6, 2020. Since the NESSDC provides the actual number of inflow population between February 6 and February 22, 2020, we can then calculate population per unit inflow index for each day of this period and obtain an average population per inflow index, which equals to 90,848. To convert the inter-city flow indices into the total inter-city population flows for all cities, we multiply the indices by 90,848.

To convert the within-city mobility index to actual population flows, we weight the index by the number of the city's base population called"*regular residents*" in 2019 (i.e., people who had stayed in the city for at least six months during the year). For instance, given that the actual within-city population flows of 4,339,451 on February 6, 2020 in Shanghai corresponds to the within-city mobility index of 1.6 and the base population in Shanghai in 2019 is 24,237,800, the per unit within-city index is (4,339,451/24,237,800)/1.6)*24,237,800=2,712,156. Similarly, we calculate

[16]Source: http://qianxi.baidu.com/

the population per within-city mobility index for each day of this period to determine an average population per within-city flow index, which is 2,182,264. We then convert the within-city mobility indices into the number of within-city population flows for all cities by multiplying the indices by 2,182,264 and the ratio of a city's base population in 2019 over Shanghai's base population in 2019, 24,237,800. For instance, if the within-city mobility index in Wuhan on February 6, 2020 is 0.6 and Wuhan's base population in 2019 is 9,785,388, then the actual number of within-city population flows in Wuhan on February 6, 2020 is 2,182,264*0.6*(9,785,388/24,237,800)=528,620.

Appendix C. Estimating the "Actual" Number of Infection Cases in Wuhan and Other Cities in Hubei

Anecdotal evidence suggests the official statistics of COVID-19 cases in Wuhan may have been under-reported due to the shortages of testing equipment and other medical resources. With the estimated dynamic effects shown in Figure 1, which is estimated under the plausible assumption that the reported cases outside Hubei are reliable, we can estimate the "actual"' number of infection cases in Wuhan and other cities in Hubei.

To estimate the "actual" number of infections in Wuhan using the estimates from Eq. (3), we technically need to impute a value for $\mathit{Inflow}_{WH,WH,t-\kappa}$, that is "inflows from Wuhan to Wuhan." We proxy these inflows by the daily *within-Wuhan* population movement from January 1 to February 29, i.e., by $\mathit{WithinCityFlow}_{WH,t-\kappa}$. Similarly, to estimate the "actual" number of infection cases in other cities in Hubei, we need to replace the inflow from Wuhan to itself by the corresponding daily within-city-j population movements.

However, we do not have the city fixed effects for cities in Hubei because they were not included in the estimation sample for Eq. (3). Therefore, we cannot directly predict the "actual" number of infections in Wuhan and other cities in Hubei using Eq. (6). Instead, we use the estimated $\hat{\beta}_{1\kappa}$ coefficient as a measure of the *elasticity* of the new cases outside of Hubei at date t with respect to inflows from Wuhan κ days ago. We then calculate the percentage difference between the within-Wuhan population flow $\mathit{Inflow}_{WH,WH,t-\kappa}$ and the average inflows from Wuhan to cities outside Hubei, i.e., $\left(\sum_{i=1}^{347} \mathit{Inflow}_{i,WH,t-\kappa}\right)/347$, together with the average new daily cases outside of Hubei at date t and $\hat{\beta}_{1\kappa}$, to impute what Wuhan new cases would have been at date t, *under the assumption that* the relationship dictating the within-Wuhan population movements and Wuhan's "actual" new cases at date t is similar to that estimated for cities outside Hubei in Eq. (3). We follow the same method to estimate the "actual" number of new infections in 16 other cities of Hubei.

In Appendix Figure A5, we plot the estimated daily new cases according to the above-described method using the estimated Eq. (3), as well as the corresponding cumulative cases for Wuhan (Panel A) and 16 other cities of Hubei (Panel B) for the period of January 23 to February 29, 2020. We also plotted the corresponding daily and cumulative officially reported (i.e., documented) cases.

We find a persistent gap between the estimated and reported laboratory-confirmed cases in Wuhan before February 11, 2020, just before the announcement of a new Party Secretary for Hubei on February 12, 2020. The estimated "actual" number of infection cases is 2.81 times the reported cases during the first 20 days after the Wuhan lockdown, on average. In particular, we estimate that on January 23, 2020, the day of the Wuhan lockdown, 38.29% of our estimated infections in Wuhan were undocumented in the sense that the number of officially reported cases on that day was only 61.71% of our estimated infection cases. This undocumented-real gap widened over time, possibly due to the overwhelmed health care system, and peaked at 79.57% on January 26. The proportion of undocumented infections started to decline gradually, when more medical support and resources were mobilized across China to support Wuhan. As of February 29, we estimate that there were 54,797 total COVID-19 infections in Wuhan, which is 11.55% higher than the official reported statistics for Wuhan - a total of 49,122 cases. The 11.55% discrepancy can be plausibly be explained by the unaccounted for self-healing and death that might have occurred during the early periods of the outbreak between January 23 and early February. Thus, we are led to conclude that the almost all infection cases in Wuhan were able to be treated over time as the stress on the health system was relieved, and moreover, the official statistics were mostly accurate, as can be seen from the left figure on the daily new cases in Panel A in Figure A5.

In the bottom panel of Figure A5, we plot our estimated daily new confirmed cases and total infection case for 16 cities (other than Wuhan) in Hubei, together with the officially reported series. We find that in the 16 cities, infections were more seriously under-reported in the first week after the Wuhan lockdown when our estimated infected cases are 1.87 times the reported cases. Our estimate reveals a very high rate of undocumented infections on the first day of Wuhan lockdown: 81.02%. The gap narrowed gradually with more medical resources provided and more stringent control measures implemented in those cities. By the end of our study period on February 29, 2020, the estimated "actual" number of infections is 20,981 cases in 16 other cities in Hubei, which is 17.97% higher than the officially reported cumulative cases (17,785). The discrepancy between the estimated and officially reported cumulative cases could at least be partially attributed to the unaccounted for self-healing and death that might have occurred during the early periods of the outbreak.