Assessing the Impact of Non-Pharmaceutical Interventions on Consumer Mobility Patterns and COVID-19 Transmission in the US

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Draper Scholars Program
SM Data Science

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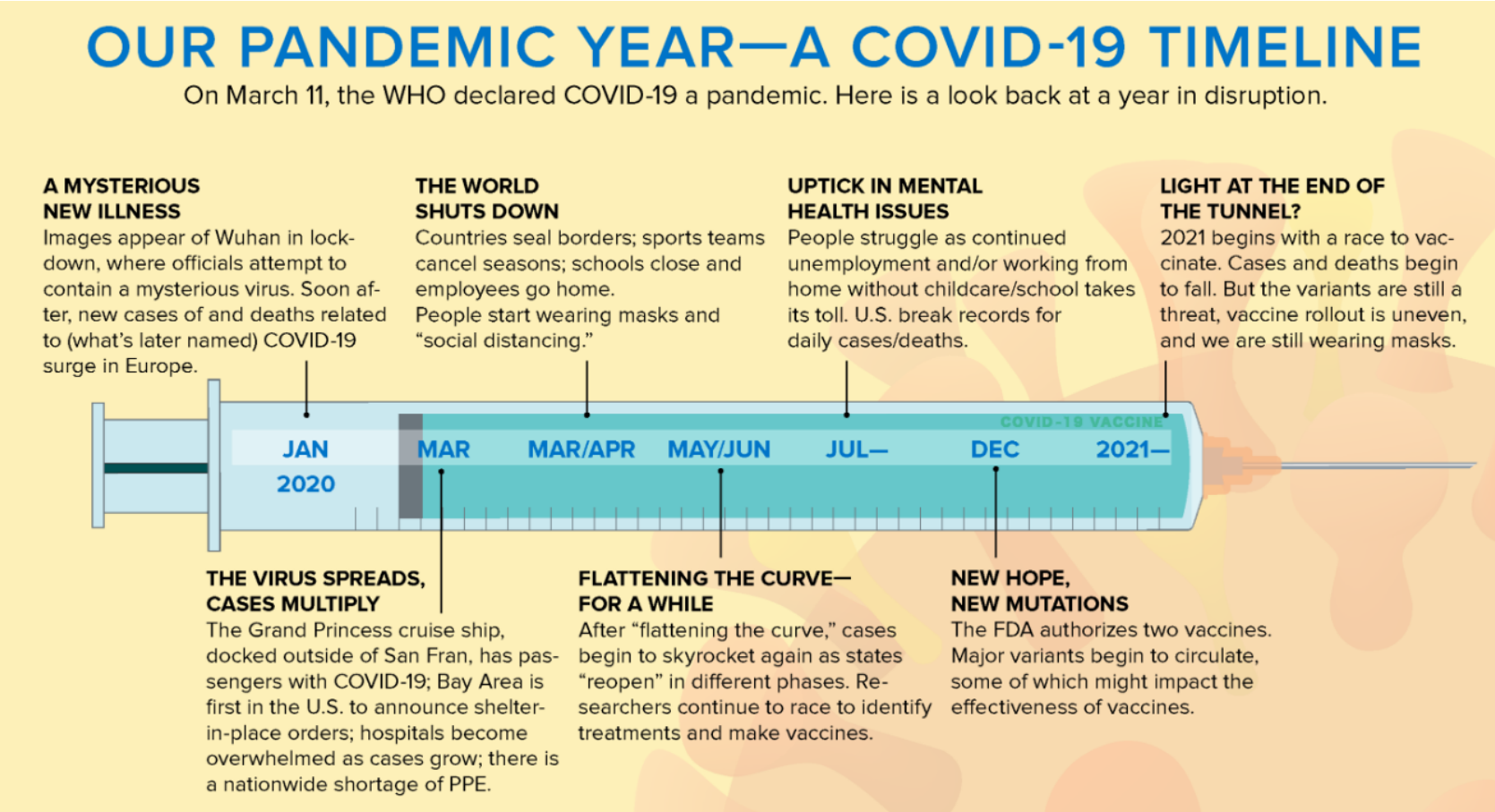
Background


OUR PANDEMIC YEAR—A COVID-19 TIMELINE
On March 11, the WHO declared COVID-19 a pandemic. Here is a look back at a year in disruption.
A MYSTERIOUS NEW ILLNESS
Images appear of Wuhan in lockdown, where officials attempt to contain a mysterious virus. Soon after, new cases of and deaths related to (what's later named) COVID-19 surge in Europe.
THE WORLD SHUTS DOWN
Countries seal borders; sports teams cancel seasons; schools close and employees go home.
People start wearing masks and "social distancing."
UPTICK IN MENTAL HEALTH ISSUES
People struggle as continued unemployment and/or working from home without childcare/school takes its toll. U.S. break records for daily cases/deaths.
LIGHT AT THE END OF THE TUNNEL?
2021 begins with a race to vaccinate. Cases and deaths begin to fall. But the variants are still a threat, vaccine rollout is uneven, and we are still wearing masks.
COVID-19 VACCINE
JAN 2020
MAR
MAR/APR
MAY/JUN
JUL—
DEC
2021—
THE VIRUS SPREADS, CASES MULTIPLY
The Grand Princess cruise ship, docked outside of San Fran, has passengers with COVID-19; Bay Area is first in the U.S. to announce shelter-in-place orders; hospitals become overwhelmed as cases grow; there is a nationwide shortage of PPE.
FLATTENING THE CURVE—FOR A WHILE
After "flattening the curve," cases begin to skyrocket again as states "reopen" in different phases. Researchers continue to race to identify treatments and make vaccines.
NEW HOPE, NEW MUTATIONS
The FDA authorizes two vaccines. Major variants begin to circulate, some of which might impact the effectiveness of vaccines.

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Previous Studies

Data

Government NPIs, Human Mobility Data (e.g., Google, SafeGraph, Teralytics, Unacast), COVID-19 Cases & Deaths (State & County-Level)

Methods

Event Study, Correlational Analyses, Mixed Effects Modeling

Findings

Early NPIs (specifically workplace closures and stay-at-home orders) effectively reduced human mobility and slowed the COVID-19 spread

Limitations

Aggregation Bias, Limited Granularity, Unmeasured Confounding

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Study

Research Questions

1. How did initial NPIs impact consumer mobility patterns?
2. How did changes in consumer mobility patterns impact the early COVID-19 spread?
3. How can we group individuals based on pre-pandemic consumer behavior?

Raw Data

BDEX Data

Daily point-of-sale (POS) credit card transactions

Sample: 2,000 residents of Boston, MA, and 2,000 residents of Ann Arbor, MI

Date Range: 01JAN2020 - 30MAY2020

Aggregation: County and Individual Level

Methods Overview

Supervised Learning

Mixed Effects Models (Linear & Negative Binomial)

Autoregressive Covariance Structure

Unsupervised Learning

Agglomerative & Divisive Clustering

K-Means Clustering

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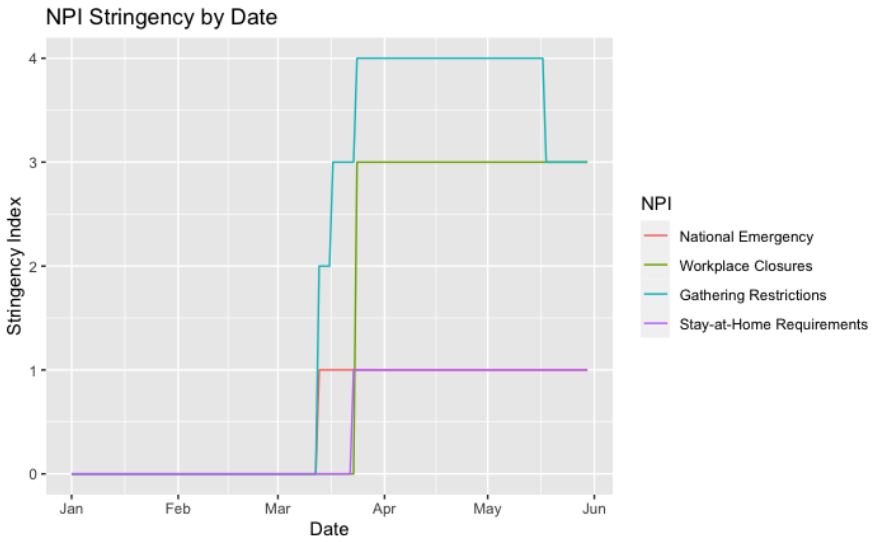
Non-Pharmaceutical Intervention Data

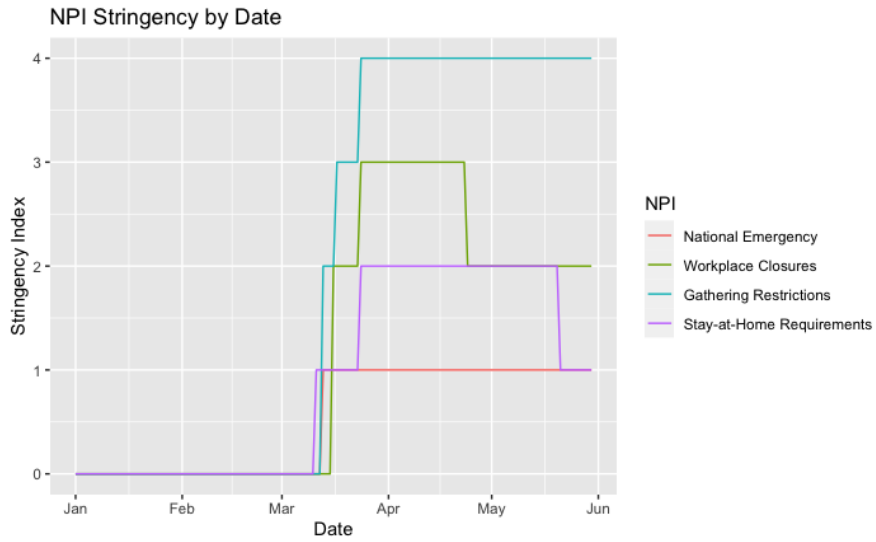
Policy	Description	Stringency Index
National Emergency	Record national emergency status	0 - not effective 1 - effective
Workplace Closures	Record closing of workplaces	0 - no measures 1 - recommend closing 2 - require closing (some sectors) 3 - require closing (all but essential)
Stay-at-Home Reqs.	Record orders to "shelter in place"	0 - no measures 1 - recommend not leaving home 2 - require not leaving home (with exceptions) 3 - require not leaving home (minimal exceptions)
Gathering Restrictions	Record limits on gatherings	0 - no measures 1 - restrict gatherings $>$ 1000 people 2 - restrict gatherings 101-1000 people 3 - restrict gatherings 11-100 people 4 - restrict gatherings $\leq$ 10 people

Table: Non-Pharmaceutical Intervention Data

Non-Pharmaceutical Intervention Data



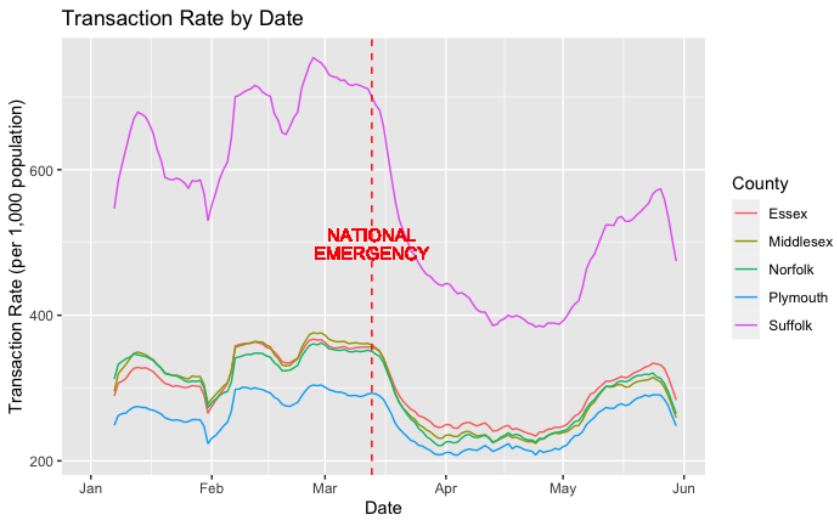
(a) Massachusetts



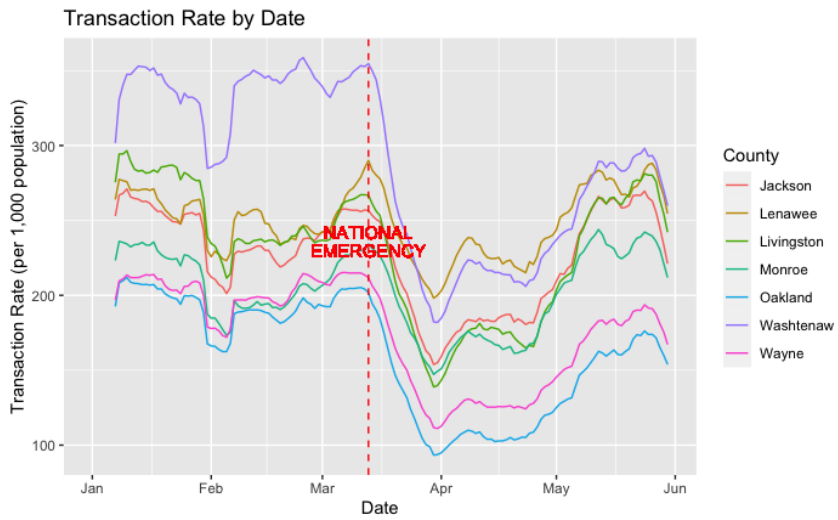
(b) Michigan

Figure: Non-Pharmaceutical Intervention Stringency by Date

Point-of-Sale Transaction Data



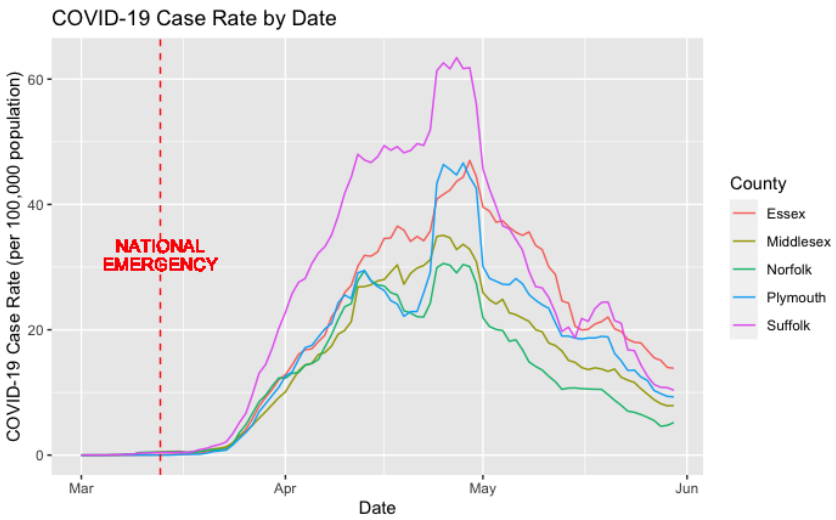
(a) Massachusetts



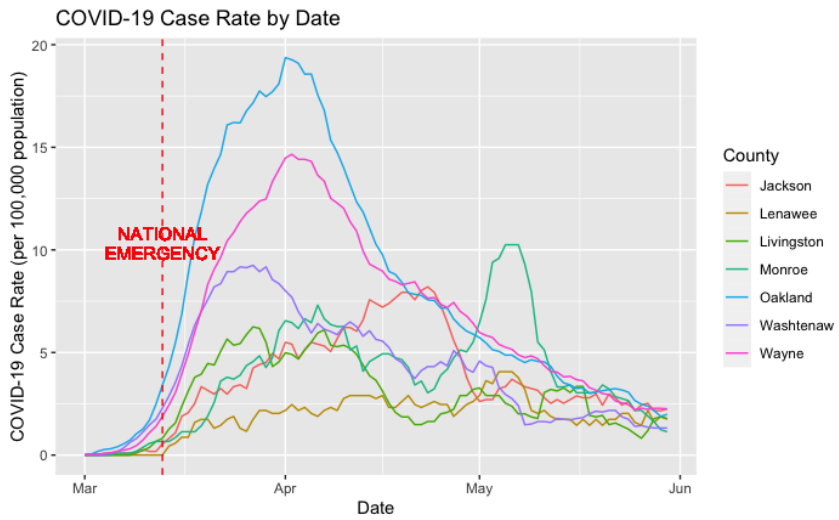
(b) Michigan

Figure: Transaction Rate (per 1k population) by Date

COVID-19 Case Data



(a) Massachusetts



(b) Michigan

Figure: COVID-19 Case Rate (per 100k population) by Date

Mobility Modeling

Modeling Approach

Method: Negative Binomial Mixed Effects Models (Autoregressive Covariance Structure)

Response: POS Transaction Rate (per 1k population)

Predictor: NPIs (i.e., National Emergency, Workplace Closures, Stay-at-Home Requirements, Gathering Restrictions)

Controls: Seasonality, Political Affiliation, Demographic Makeup, State

Mobility Modeling

Model 1 (Baseline)

$$\log\left(\frac{1000 \times transactions_{ij}}{population_{ij}}\right) = \beta_0 + \beta NPI_{ij} + \beta weekend_{ij} + \gamma_{0j} \quad (1)$$

$$i \equiv date$$

$$j \equiv county$$

Mobility Modeling

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	353.28	(279.49,446.56)	0.00***
	Effective	0.86	(0.80,0.93)	0.00***
	Weekend	0.87	(0.86,0.88)	0.00***
Workplace Closure	Intercept	345.31	(273.19,436.47)	0.00***
	Recommended	NA	NA	NA
	Required (some)	NA	NA	NA
	Required (all)	0.89	(0.82,0.96)	0.00**
	Weekend	0.87	(0.85,0.88)	0.00***
Stay-at-Home Reqs.	Intercept	347.44	(274.89,439.13)	0.00***
	Recommended	0.88	(0.81,0.95)	0.00**
	Required (some ex.)	NA	NA	NA
	Required (min ex.)	NA	NA	NA
	Weekend	0.87	(0.85,0.88)	0.00***
Gathering Restrictions	Intercept	371.96	(295.58,469.66)	0.00***
	Restrict $>$ 1,000	NA	NA	NA
	Restrict 101-1,000	0.92	(0.86,0.99)	0.03*
	Restrict 11-100	0.80	(0.74,0.86)	0.00***
	Restrict $<$ 10	0.77	(0.71,0.84)	0.00***
	Weekend	0.87	(0.85,0.88)	0.00***

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	237.06	(205.53,273.43)	0.00***
	Effective	0.89	(0.83,0.96)	0.00**
	Weekend	0.82	(0.81,0.83)	0.00***
Workplace Closure	Intercept	254.76	(221.02,293.65)	0.00***
	Recommended	NA	NA	NA
	Required (some)	0.84	(0.79,0.90)	0.00***
	Required (all)	0.68	(0.64,0.73)	0.00***
	Weekend	0.81	(0.80,0.82)	0.00***
Stay-at-Home Reqs.	Intercept	239.41	(207.41,276.35)	0.00***
	Recommended	0.97	(0.90,1.03)	0.32
	Required (some ex.)	0.82	(0.76,0.89)	0.00***
	Required (min ex.)	NA	NA	NA
	Weekend	0.82	(0.80,0.83)	0.00***
Gathering Restrictions	Intercept	284.98	(242.80,334.49)	0.00***
	Restrict $>$ 1,000	NA	NA	NA
	Restrict 101-1,000	0.94	(0.88,1.01)	0.08·
	Restrict 11-100	0.79	(0.72,0.86)	0.00***
	Restrict $<$ 10	0.64	(0.57,0.71)	0.00***
	Weekend	0.82	(0.80,0.83)	0.00***

Table: Model 1 (Baseline) Results (MA & MI)

Mobility Modeling

Model 2 (Political)

$$\log\left(\frac{1000 \times transactions_{ij}}{population_{ij}}\right) = \beta_0 + \beta_1 NPI_{ij} + \beta_2 political_{ij} + \beta_3 NPI_{ij} political_{ij} + \beta_4 weekend_{ij} + \gamma_{0j} \quad (2)$$

$$i \equiv date$$

$$j \equiv county$$

Mobility Modeling

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	193.92	(131.34,286.31)	0.00****
	Emergency	0.97	(0.82,1.15)	0.73
	Political	7.41	(2.85,19.24)	0.00***
	Emergency × Political	0.72	(0.47,1.10)	0.13
	Weekend	0.87	(0.86,0.88)	0.00***
Workplace Closure	Intercept	203.09	(137.06,300.93)	0.00***
	Closure	0.94	(0.78,1.13)	0.50
	Political	5.70	(2.13,15.25)	0.00***
	Closure × Political	0.85	(0.53,1.36)	0.49
	Weekend	0.87	(0.85,0.88)	0.00***
Stay-at-Home Reqs.	Intercept	208.44	(140.87,308.44)	0.00***
	Requirements	0.92	(0.77,1.11)	0.38
	Political	5.52	(2.06,14.76)	0.00****
	Reqs. × Political	0.87	(0.55,1.38)	0.55
	Weekend	0.87	(0.85,0.88)	0.00***
Gathering Restrictions	Intercept	199.49	(144.48,275.45)	0.00***
	Restrictions	0.97	(0.91,1.03)	0.35
	Political	6.34	(2.88,13.95)	0.00***
	Restrict × Political	0.87	(0.74,1.01)	0.06·
	Weekend	0.87	(0.85,0.88)	0.00***

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	265.92	(223.63,316.20)	0.00***
	Emergency	0.89	(0.83,0.96)	0.00**
	Political	1.25	(0.68,2.27)	0.47
	Emergency × Political	0.81	(0.65,1.03)	0.08·
	Weekend	0.82	(0.81,0.83)	0.00***
Workplace Closure	Intercept	311.65	(268.38,361.90)	0.00***
	Closure	0.83	(0.80,0.85)	0.00***
	Political	1.04	(0.62,1.77)	0.87
	Closure × Political	0.92	(0.82,1.04)	0.19
	Weekend	0.81	(0.80,0.82)	0.00***
Stay-at-Home Reqs.	Intercept	274.73	(235.69,320.23)	0.00***
	Requirements	0.90	(0.86,0.93)	0.00***
	Political	1.04	(0.60,1.79)	0.89
	Reqs. × Political	0.93	(0.82,1.07)	0.32
	Weekend	0.82	(0.80,0.83)	0.00***
Gathering Restrictions	Intercept	328.19	(276.71,389.25)	0.00***
	Restrictions	0.86	(0.83,0.90)	0.00***
	Political	1.07	(0.60,1.91)	0.82
	Restrict × Political	0.93	(0.83,1.04)	0.20
	Weekend	0.82	(0.80,0.83)	0.00***

Table: Model 2 (Political) Results (MA & MI)

Mobility Modeling

Model 3 (Race)

$$\log\left(\frac{1000 \times transactions_{ij}}{population_{ij}}\right) = \beta_0 + \beta_1 NPI_{ij} + \beta_2 minority_{ij} + \beta_3 NPI_{ij} minority_{ij} + \beta_4 weekend_{ij} + \gamma_{0j} \quad (3)$$

$$i \equiv date$$

$$j \equiv county$$

Mobility Modeling

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	175.27	(121.62,252.59)	0.00***
	Emergency	0.97	(0.81,1.17)	0.79
	Minority	44.36	(9.70,202.79)	0.00***
	Emergency × Minority	0.57	(0.26,1.24)	0.16
	Weekend	0.87	(0.86,0.88)	0.00***
Workplace Closure	Intercept	184.67	(127.61,267.25)	0.00***
	Closure	0.94	(0.77,1.15)	0.53
	Minority	27.84	(5.76,134.64)	0.00***
	Closure × Minority	0.77	(0.32,1.81)	0.54
	Weekend	0.87	(0.85,0.88)	0.00***
Stay-at-Home Reqs.	Intercept	188.00	(130.20,271.46)	0.00***
	Requirements	0.93	(0.76,1.13)	0.46
	Minority	27.46	(5.73,131.75)	0.00***
	Reqs. × Minority	0.77	(0.33,1.81)	0.55
	Weekend	0.87	(0.85,0.88)	0.00***
Gathering Restrictions	Intercept	180.90	(136.90,239.05)	0.00***
	Restrictions	0.97	(0.91,1.04)	0.41
	Minority	33.89	(10.66,107.72)	0.00***
	Restrict × Minority	0.78	(0.59,1.04)	0.09·
	Weekend	0.87	(0.85,0.88)	0.00***

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	270.51	(209.80,348.81)	0.00***
	Emergency	0.95	(0.85,1.05)	0.33
	Minority	0.93	(0.30,2.84)	0.89
	Emergency × Minority	0.70	(0.44,1.12)	0.14
	Weekend	0.82	(0.81,0.83)	0.00***
Workplace Closure	Intercept	333.46	(268.00,414.92)	0.00***
	Closure	0.85	(0.80.0.89)	0.00***
	Minority	0.69	(0.26,1.79)	0.45
	Closure × Minority	0.86	(0.68,1.09)	0.23
	Weekend	0.81	(0.80,0.82)	0.00***
Stay-at-Home Reqs.	Intercept	292.95	(233.96,366.83)	0.00***
	Requirements	0.92	(0.86,0.97)	0.00**
	Minority	0.70	(0.26,1.90)	0.48
	Reqs. × Minority	0.87	(0.67,1.13)	0.30
	Weekend	0.82	(0.80,0.83)	0.00***
Gathering Restrictions	Intercept	345.19	(268.93,443.07)	0.00***
	Restrictions	0.89	(0.84,0.94)	0.00***
	Minority	0.72	(0.25,2.14)	0.56
	Restrict × Minority	0.87	(0.69,1.10)	0.25
	Weekend	0.82	(0.80,0.83)	0.00****

Table: Model 3 (Race) Results (MA & MI)

Mobility Modeling

Model 4 (State)

$$\log\left(\frac{1000 \times transactions_{ij}}{population_{ij}}\right) = \beta_0 + \beta_1 NPI_{ij} + \beta_2 state_{ij} + \beta_3 NPI_{ij} state_{ij} + \beta_4 weekend_{ij} + \gamma_{0j} \tag{4}$$

$$i \equiv date$$

$$j \equiv county$$

Mobility Modeling

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	406.69	(324.07,510.37)	0.00***
	Emergency	0.87	(0.81,0.94)	0.00***
	State (MI)	0.65	(0.49,0.88)	0.00**
	Emergency × State (MI)	1.02	(0.92,1.12)	0.71
	Weekend	0.84	(0.83,0.85)	0.00***
Workplace Closure	Intercept	409.90	(328.94,510.79)	0.00***
	Closure	0.87	(0.81,0.93)	0.00***
	State (MI)	0.73	(0.55,0.97)	0.03*
	Closure × State (MI)	0.96	(0.89,1.04)	0.37
	Weekend	0.83	(0.82,0.84)	0.00***
Stay-at-Home Reqs.	Intercept	410.42	(328.06,513.47)	0.00***
	Requirements	0.86	(0.80,0.93)	0.00***
	State (MI)	0.66	(0.50,0.88)	0.00**
	Reqs. × State (MI)	1.04	(0.96,1.13)	0.36
	Weekend	0.84	(0.83,0.85)	0.00***
Gathering Restrictions	Intercept	400.21	(325.29,492.39)	0.00***
	Restrictions	0.92	(0.89,0.95)	0.00***
	State (MI)	0.75	(0.56,1.00)	0.05·
	Restrict × State (MI)	0.97	(0.92,1.02)	0.20
	Weekend	0.84	(0.83,0.85)	0.00***

Table: Model 4 (State) Results

Discussion

Findings

1. Statistically significant negative association between NPIs and daily POS transaction rates (dose-response relationship)
2. Stringent workplace closures and gathering restrictions exhibited strongest negative association with daily POS transaction rates
3. Association between NPIs and daily POS transaction rates did not differ significantly by political affiliation, racial makeup, or state of county

Limitations

1. Difficult to isolate the impact of each NPI
2. Aggregation bias
3. Omitted variable bias
4. Generalizability

COVID-19 Modeling

Modeling Approach

Method: Linear Mixed Effects Models (Autoregressive Covariance Structure)

Response: COVID-19 Case Growth Rate

Predictor: Lagged Δ Transactions (vs. Pre-Pandemic Baseline Days)

Controls: Seasonality, Testing Rate, State

COVID-19 Modeling

Model 5 (COVID-19)

$$\begin{aligned} \textit{case growth rate}_{ij} = \beta_0 + \beta_1 \Delta \textit{transactions}_{ij} + \beta_2 \textit{test rate}_{ij} \\ + \beta_3 \textit{weekend}_{ij} + \gamma_{0j} \end{aligned} \tag{5}$$

$$i \equiv \textit{date}$$

$$j \equiv \textit{county}$$

COVID-19 Modeling

Lag Period	Fixed Effects	β	95% CI	*p*-value
06 Days	Intercept	31.95	(22.66,41.24)	0.00***
	Δ Transactions	0.11	(-0.11,0.35)	0.33
	Test Rate	-11.29	(-16.22,-6.36)	0.00***
	Weekend	-33.78	(-42.97,-24.60)	0.00***
08 Days	Intercept	31.83	(22.87,40.79)	0.00***
	Δ Transactions	0.17	(-0.06,0.40)	0.15
	Test Rate	-10.57	(-15.67,-5.48)	0.00***
	Weekend	-33.10	(-42.35,-23.85)	0.00***
10 Days	Intercept	31.39	(22.61,40.17)	0.00***
	Δ Transactions	0.23	(-0.01,0.47)	0.06·
	Test Rate	-9.57	(-14.89,-4.26)	0.00***
	Weekend	-32.61	(-41.86,-23.36)	0.00***
12 Days	Intercept	30.46	(21.77,39.15)	0.00***
	Δ Transactions	0.30	(0.06,0.54)	0.02*
	Test Rate	-8.25	(-13.81,-2.68)	0.00***
	Weekend	-31.42	(-40.76,-22.07)	0.00***
14 Days	Intercept	28.47	(19.70,37.24)	0.00***
	Δ Transactions	0.39	(0.13,0.65)	0.00**
	Test Rate	-6.08	(-12.17,0.01)	0.05*
	Weekend	-29.49	(-39.06,-19.93)	0.00***
16 Days	Intercept	27.58	(18.53,36.63)	0.00***
	Δ Transactions	0.33	(0.05,0.60)	0.02*
	Test Rate	-6.38	(-12.97,0.21)	0.06·
	Weekend	-29.46	(-39.37,-19.55)	0.00***

Lag Period	Fixed Effects	β	95% CI	*p*-value
06 Days	Intercept	17.08	(8.88,25.28)	0.00***
	Δ Transactions	0.13	(-0.05,0.31)	0.17
	Test Rate	-10.43	(-16.47,-4.40)	0.00***
	Weekend	-22.38	(-31.18,-13.58)	0.00***
08 Days	Intercept	18.22	(10.36,26.08)	0.00***
	Δ Transactions	0.19	(0.01,0.37)	0.03*
	Test Rate	-10.30	(-16.12,-4.47)	0.00***
	Weekend	-23.02	(-31.83,-14.21)	0.00***
10 Days	Intercept	16.54	(8.98,24.10)	0.00***
	Δ Transactions	0.14	(-0.04,0.32)	0.12
	Test Rate	-9.50	(-15.26,-3.75)	0.00***
	Weekend	-22.43	(-31.22,-13.64)	0.00***
12 Days	Intercept	15.94	(8.61,23.26)	0.00***
	Δ Transactions	0.13	(-0.05,0.31)	0.15
	Test Rate	-9.27	(-15.02,-3.52)	0.00***
	Weekend	-21.62	(-30.44,-12.80)	0.00***
14 Days	Intercept	15.32	(7.98,22.65)	0.00***
	Δ Transactions	0.09	(-0.08,0.27)	0.31
	Test Rate	-9.03	(-14.79,-3.27)	0.00***
	Weekend	-22.46	(-31.29,-13.64)	0.00***
16 Days	Intercept	15.81	(8.66,22.97)	0.00***
	Δ Transactions	0.15	(-0.03,0.33)	0.10·
	Test Rate	-8.62	(-14.39,-2.84)	0.00***
	Weekend	-22.14	(-30.92,-13.35)	0.00***

Table: Model 5 (COVID-19) Results (MA & MI)

Discussion

Findings

1. Statistically significant positive association between lagged changes in consumer mobility patterns and daily COVID-19 case growth rates
2. Optimal lag period undefined (differed by state)
3. POS transactions serve as a limited mobility metric

Limitations

1. Omitted variable bias
2. Reporting error
3. Data granularity/availability

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Point-of-Sale Transaction Data

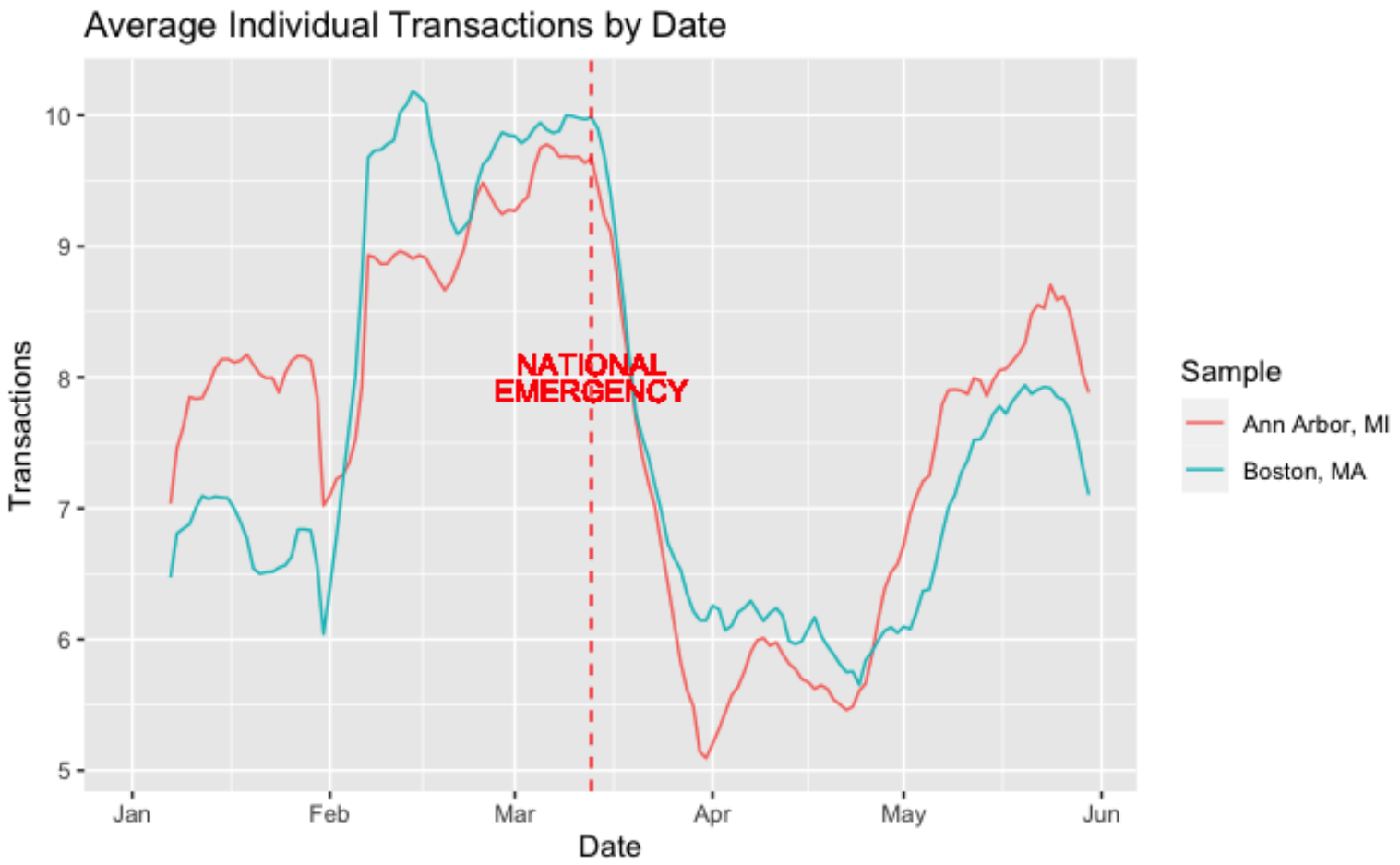


Figure: Average Individual Transactions by Date

Clustering

Modeling Approach

Feature Selection: Avg. Daily Transactions, Avg. Daily AM Transactions, Avg. Daily PM Transactions, Time Ratio (AM vs. PM), Avg. Daily Weekend Transactions, Avg. Daily Weekday Transactions, Day Ratio (Weekend vs. Weekday)

Algorithm Selection: Hierarchical Clustering (Agglomerative & Divisive), Partitional Clustering (K-Means Clustering)

Cluster Validation: Dendrograms, PCA Plots

Results Interpretation: Numerical Summaries and Plots by Cluster

K-Means Clustering

Figure: PCA Plot (K-Means Clustering)

Cluster Interpretation

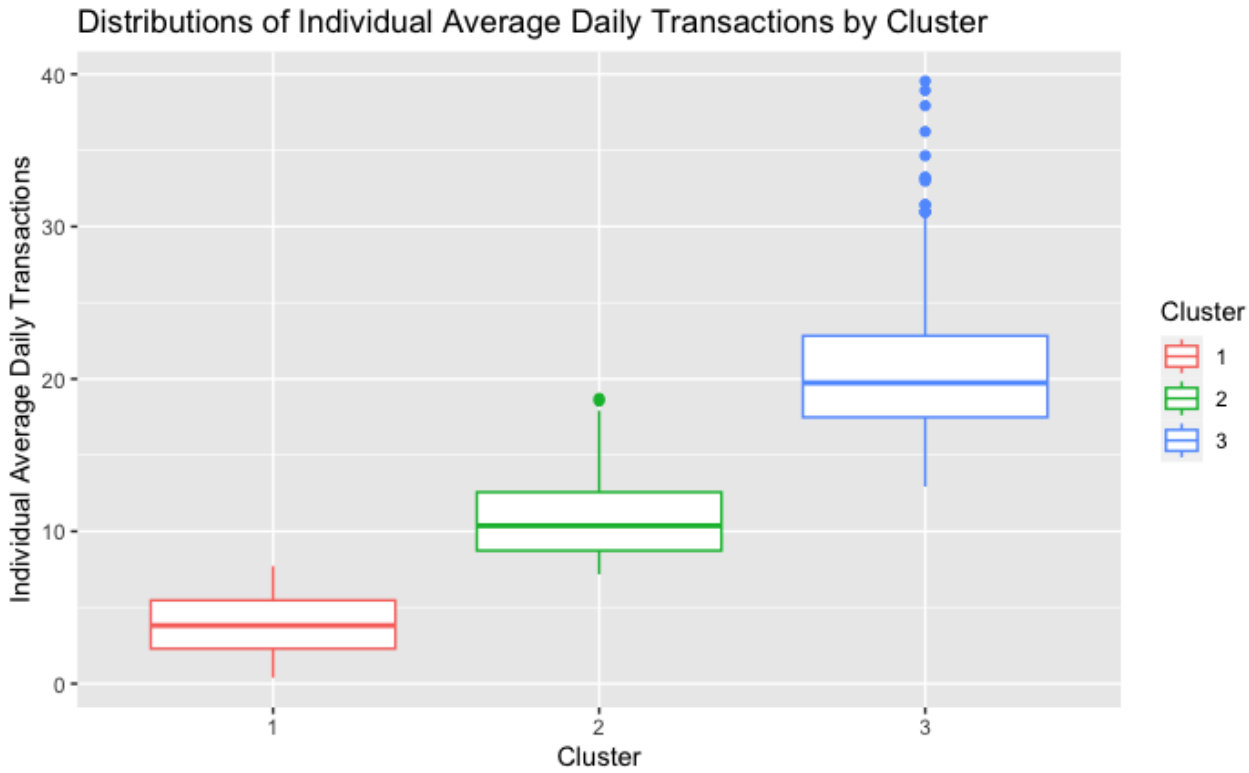
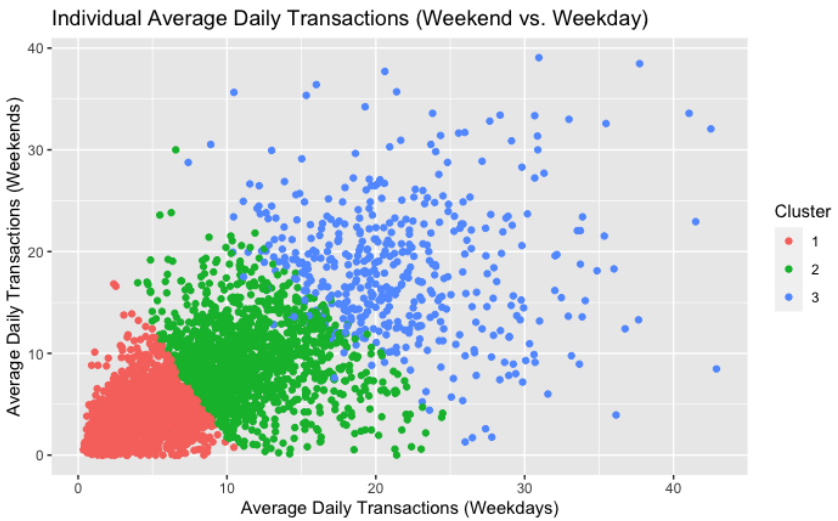
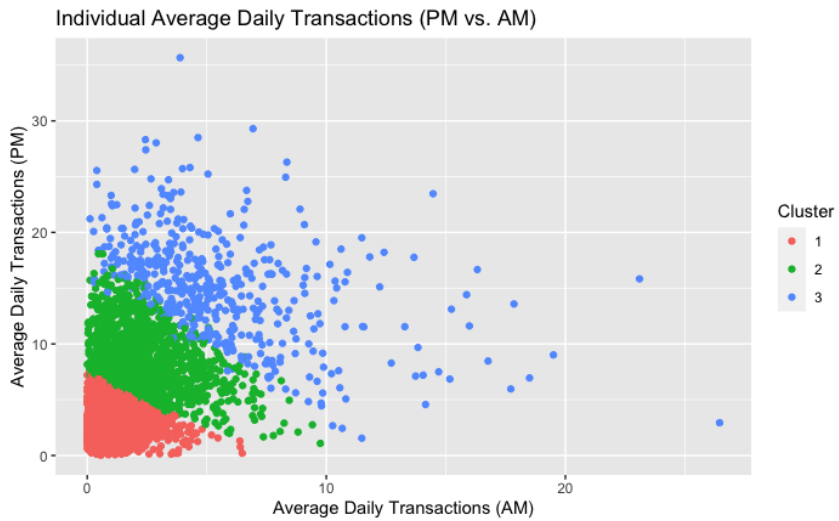


Figure: Distribution of Individual Average Transactions by Cluster

Cluster Interpretation



(a) Weekend vs. Weekday



(b) PM vs. AM

Figure: Individual Average Daily Transactions by Cluster

Mobility Modeling

Modeling Approach

Method: Negative Binomial Mixed Effects Models (Autoregressive Covariance Structure)

Response: POS Transaction Count

Predictor: NPIs (i.e., National Emergency, Workplace Closures, Stay-at-Home Requirements, Gathering Restrictions)

Controls: Seasonality, Consumer Type, State

Mobility Modeling

Model 6 (Baseline)

$$\log(transactions_{ij}) = \beta_0 + \beta NPI_{ij} + \beta weekend_{ij} + \gamma_{0j} \tag{6}$$

$$i \equiv date$$

$$j \equiv individual$$

Mobility Modeling

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	3.30	(3.14,3.47)	0.00***
	Effective	0.88	(0.85,0.91)	0.00***
	Weekend	0.86	(0.85,0.87)	0.00***
Workplace Closure	Intercept	3.29	(3.13,3.46)	0.00***
	Recommended	NA	NA	NA
	Required (some)	NA	NA	NA
	Required (all)	0.87	(0.84,0.91)	0.00***
	Weekend	0.85	(0.85,0.86)	0.00***
Stay-at-Home Reqs.	Intercept	3.30	(3.14,3.47)	0.00***
	Recommended	0.87	(0.84,0.91)	0.00***
	Required (some ex.)	NA	NA	NA
	Required (min ex.)	NA	NA	NA
	Weekend	0.85	(0.84,0.86)	0.00***
Gathering Restrictions	Intercept	3.42	(3.25,3.60)	0.00***
	Restrict $>$ 1,000	NA	NA	NA
	Restrict 101-1,000	0.93	(0.89,0.97)	0.00***
	Restrict 11-100	0.82	(0.78,0.86)	0.00***
	Restrict $<$ 10	0.82	(0.77,0.86)	0.00***
	Weekend	0.86	(0.85,0.87)	0.00***

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	4.80	(4.62,4.99)	0.00***
	Effective	0.87	(0.84,0.90)	0.00***
	Weekend	0.84	(0.83,0.85)	0.00***
Workplace Closure	Intercept	5.13	(4.94,5.34)	0.00***
	Recommended	NA	NA	NA
	Required (some)	0.84	(0.82,0.87)	0.00***
	Required (all)	0.62	(0.59,0.65)	0.00***
	Weekend	0.83	(0.82,0.84)	0.00***
Stay-at-Home Reqs.	Intercept	4.91	(4.72,5.11)	0.00***
	Recommended	0.94	(0.91,0.97)	0.00***
	Required (some ex.)	0.77	(0.74,0.80)	0.00***
	Required (min ex.)	NA	NA	NA
	Weekend	0.83	(0.83,0.84)	0.00***
Gathering Restrictions	Intercept	5.40	(5.19,5.63)	0.00***
	Restrict $>$ 1,000	NA	NA	NA
	Restrict 101-1,000	1.03	(0.99,1.07)	0.15
	Restrict 11-100	0.87	(0.83,0.91)	0.00***
	Restrict $<$ 10	0.67	(0.64,0.70)	0.00***
	Weekend	0.83	(0.82,0.84)	0.00***

Table: Model 6 (Baseline) Results (MA & MI)

Mobility Modeling

Model 7 (Consumer Type)

$$\begin{aligned}\log(transactions_{ij}) = \beta_0 + \beta_1 NPI_{ij} + \beta_2 consumer_{ij} \\ + \beta_3 NPI_{ij} consumer_{ij} + \beta_4 weekend_{ij} + \gamma_{0j}\end{aligned} \tag{7}$$

$$i \equiv date$$

$$j \equiv individual$$

Mobility Modeling

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	12.89	(11.52,14.41)	0.00***
	Emergency	0.66	(0.60,0.74)	0.00***
	Consumer (Low)	0.13	(0.12,0.15)	0.00***
	Consumer (Medium)	0.50	(0.43,0.56)	0.00***
	Emergency × Cons. (Low)	1.59	(1.42,1.78)	0.00***
	Emergency × Cons. (Med)	1.15	(1.02,1.30)	0.02*
	Weekend	0.86	(0.85,0.87)	0.00***
Workplace Closure	Intercept	18.27	(15.21,21.96)	0.00***
	Closure	0.68	(0.61,0.76)	0.00***
	Consumer (Low)	0.09	(0.08,0.12)	0.00***
	Consumer (Medium)	0.45	(0.36,0.55)	0.00***
	Closure × Cons. (Low)	1.50	(1.33,1.68)	0.00***
	Closure × Cons. (Med)	1.13	(1.00,1.28)	0.05*
	Weekend	0.85	(0.85,0.86)	0.00***
Stay-at-Home Reqs.	Intercept	20.18	(16.79,24.26)	0.00***
	Reqs.	0.64	(0.57,0.71)	0.00***
	Consumer (Low)	0.09	(0.07,0.10)	0.00***
	Consumer (Medium)	0.39	(0.32,0.49)	0.00***
	Reqs. × Cons. (Low)	1.60	(1.42,1.80)	0.00***
	Reqs. × Cons. (Med)	1.23	(1.09,1.39)	0.00***
	Weekend	0.85	(0.84,0.86)	0.00***
Gathering Restrictions	Intercept	16.87	(14.62,19.47)	0.00***
	Restrict	0.81	(0.78,0.85)	0.00***
	Consumer (Low)	0.10	(0.08,0.12)	0.00***
	Consumer (Medium)	0.45	(0.38,0.53)	0.00***
	Restrict × Cons. (Low)	1.26	(1.20,1.33)	0.00***
	Restrict × Cons. (Med)	1.08	(1.02,1.14)	0.02*
	Weekend	0.86	(0.85,0.87)	0.00***

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	14.68	(13.36,16.14)	0.00***
	Emergency	0.61	(0.56,0.68)	0.00***
	Consumer (Low)	0.19	(0.17,0.21)	0.00***
	Consumer (Medium)	0.52	(0.47,0.58)	0.00***
	Emergency × Cons. (Low)	1.66	(1.50,1.85)	0.00***
	Emergency × Cons. (Med)	1.25	(1.12,1.40)	0.00***
	Weekend	0.84	(0.83,0.85)	0.00***
Workplace Closure	Intercept	20.81	(18.34,23.62)	0.00***
	Closure	0.70	(0.66,0.74)	0.00***
	Consumer (Low)	0.18	(0.16,0.21)	0.00***
	Consumer (Medium)	0.55	(0.47,0.63)	0.00***
	Closure × Cons. (Low)	1.20	(1.13,1.28)	0.00***
	Closure × Cons. (Med)	1.05	(0.98,1.12)	0.17
	Weekend	0.83	(0.82,0.84)	0.00***
Stay-at-Home Reqs.	Intercept	19.52	(17.12,22.25)	0.00***
	Reqs.	0.75	(0.71,0.79)	0.00***
	Consumer (Low)	0.16	(0.14,0.18)	0.00***
	Consumer (Medium)	0.52	(0.45,0.60)	0.00***
	Reqs. × Cons. (Low)	1.27	(1.19,1.35)	0.00***
	Reqs. × Cons. (Med)	1.07	(1.01,1.15)	0.03*
	Weekend	0.83	(0.83,0.84)	0.00***
Gathering Restrictions	Intercept	23.04	(20.25,26.22)	0.00***
	Restrict	0.75	(0.72,0.78)	0.00***
	Consumer (Low)	0.13	(0.12,0.15)	0.00***
	Consumer (Medium)	0.47	(0.41,0.54)	0.00***
	Restrict × Cons. (Low)	1.28	(1.22,1.34)	0.00***
	Restrict × Cons. (Med)	1.10	(1.05,1.15)	0.00***
	Weekend	0.84	(0.83,0.84)	0.00***

Table: Model 7 (Consumer Type) Results (MA & MI)

Mobility Modeling

Model 8 (State)

$$\log(transactions_{ij}) = \beta_0 + \beta_1 NPI_{ij} + \beta_2 state_{ij} + \beta_3 NPI_{ij} state_{ij} + \beta_4 weekend_{ij} + \gamma_{0j} \quad (8)$$

$$i \equiv date$$

$$j \equiv individual$$

Mobility Modeling

NPI	Fixed Effects	e^{β}	95% CI	p-value
National Emergency	Intercept	3.50	(3.35,3.66)	0.00***
	Emergency	0.88	(0.85,0.91)	0.00***
	State (MI)	1.30	(1.23,1.39)	0.00***
	Emergency × State (MI)	1.00	(0.95,1.06)	0.89
	Weekend	0.85	(0.84,0.85)	0.00***
Workplace Closure	Intercept	4.04	(3.78,4.32)	0.00***
	Closure	0.87	(0.84,0.90)	0.00***
	State (MI)	1.60	(1.47,1.74)	0.00***
	Closure × State (MI)	0.89	(0.86,0.94)	0.00***
	Weekend	0.84	(0.83,0.85)	0.00***
Stay-at-Home Reqs.	Intercept	4.07	(3.81,4.36)	0.00***
	Requirements	0.86	(0.83,0.90)	0.00***
	State (MI)	1.36	(1.24,1.48)	0.00***
	Reqs. × State (MI)	1.01	(0.97,1.05)	0.74
	Weekend	0.84	(0.84,0.85)	0.00***
Gathering Restrictions	Intercept	3.79	(3.59,4.00)	0.00***
	Restrictions	0.94	(0.92,0.95)	0.00***
	State (MI)	1.57	(1.45,1.69)	0.00***
	Restrict × State (MI)	0.93	(0.91,0.95)	0.00***
	Weekend	0.85	(0.84,0.85)	0.00***

Table: Model 8 (State) Results

Discussion

Findings

1. Statistically significant negative association between NPIs and daily POS transaction counts (dose-response relationship)
2. Stringent workplace closures and gathering restrictions exhibited strongest negative association with daily POS transaction rates
3. Association between NPIs and transaction rates differed significantly by consumer type and state

Limitations

1. Difficult to isolate the impact of each NPI
2. Inclusion of personal and business credit lines
3. Omitted variable bias

COVID-19 Modeling

Modeling Approach

Method: Linear Models (Autoregressive Covariance Structure)

Response: COVID-19 Case Growth Rate

Predictor: Lagged Δ Transactions (vs. Pre-Pandemic Baseline Days)

Controls: Seasonality, Testing Rate, State

COVID-19 Modeling

Model 9 (COVID-19)

$$\begin{aligned} \textit{case growth rate}_i = \beta_0 + \beta_1 \Delta \textit{transactions}_i + \beta_2 \textit{test rate}_i \\ + \beta_3 \textit{weekend}_i \end{aligned} \tag{9}$$

$$i \equiv \textit{date}$$

COVID-19 Modeling

Lag Period	Fixed Effects	β	95% CI	p-value
06 Days	Intercept	28.99	(12.05,45.93)	0.00***
	Δ Transactions	0.38	(0.00,0.75)	0.05*
	Test Rate	-0.09	(-0.19,0.01)	0.08·
	Weekend	-33.82	(-52.33,-15.31)	0.00***
08 Days	Intercept	30.36	(12.89,47.83)	0.00***
	Δ Transactions	0.16	(-0.20,0.52)	0.39
	Test Rate	-0.10	(-0.21,-0.00)	0.05*
	Weekend	-38.10	(-56.45,-19.76)	0.00***
10 Days	Intercept	29.40	(11.58,47.22)	0.00***
	Δ Transactions	0.20	(-0.20,0.59)	0.33
	Test Rate	-0.09	(-0.20,0.02)	0.12
	Weekend	-40.68	(-58.35,-23.02)	0.00***
12 Days	Intercept	25.40	(5.97,44.83)	0.01**
	Δ Transactions	0.27	(-0.11,0.64)	0.17
	Test Rate	-0.07	(-0.19,0.05)	0.24
	Weekend	-34.71	(-53.95,-15.47)	0.00***
14 Days	Intercept	17.32	(-4.14,38.79)	0.11
	Δ Transactions	0.45	(0.03,0.86)	0.04*
	Test Rate	-0.02	(-0.15,0.10)	0.71
	Weekend	-25.63	(-47.56,-3.69)	0.02*
16 Days	Intercept	24.51	(4.22,44.81)	0.02*
	Δ Transactions	0.28	(-0.13,0.68)	0.18
	Test Rate	-0.06	(-0.19,0.07)	0.38
	Weekend	-38.61	(-56.27,-20.94)	0.00***

Lag Period	Fixed Effects	β	95% CI	p-value
06 Days	Intercept	18.15	(1.33,34.97)	0.04*
	Δ Transactions	0.32	(-0.12,0.76)	0.16
	Test Rate	-0.12	(-0.25,0.01)	0.07
	Weekend	-20.40	(-39.75,-1.04)	0.04*
08 Days	Intercept	13.77	(-2.42,29.95)	0.09·
	Δ Transactions	0.15	(-0.28,0.58)	0.50
	Test Rate	-0.10	(-0.23,0.02)	0.11
	Weekend	-19.91	(-39.51,-0.30)	0.05*
10 Days	Intercept	13.80	(-2.04,29.65)	0.09·
	Δ Transactions	0.15	(-0.26,0.57)	0.47
	Test Rate	-0.10	(-0.22,0.03)	0.13
	Weekend	-20.83	(-40.63,-1.04)	0.04*
12 Days	Intercept	25.40	(5.97,44.83)	0.01*
	Δ Transactions	0.27	(-0.11,0.64)	0.17
	Test Rate	-0.07	(-0.19,0.05)	0.24
	Weekend	-34.71	(-53.95,-15.47)	0.00***
14 Days	Intercept	12.21	(-2.05,26.48)	0.09·
	Δ Transactions	0.12	(-0.27,0.51)	0.54
	Test Rate	-0.09	(-0.21,0.03)	0.16
	Weekend	-19.57	(-39.22,0.08)	0.05*
16 Days	Intercept	11.36	(-2.85,25.57)	0.12
	Δ Transactions	0.06	(-0.33,0.44)	0.77
	Test Rate	-0.09	(-0.21,0.03)	0.16
	Weekend	-19.92	(-39.64,-0.20)	0.05*

Table: Model 9 (COVID-19) Results (MA & MI)

Discussion

Findings

1. Statistically significant positive association between lagged changes in residents' consumer mobility patterns and daily COVID-19 case growth rates (Suffolk County, MA)
2. Optimal lag period undefined
3. POS transactions serve as a limited mobility metric

Limitations

1. Omitted variable bias
2. Reporting error
3. Data granularity/availability

Table of Contents

Key Takeaways

Highlights

1. Results from both studies support previous findings that NPIs (especially workplace closures and gathering restrictions) reduced human mobility during the initial COVID-19 outbreak
2. Unlike previous studies, which often uncovered strong relationships between changes in human mobility patterns and the early COVID-19 spread, our results suggest POS transactions serve as a limited mobility metric
3. Future studies should explore more complete mobility metrics across more states over a longer duration

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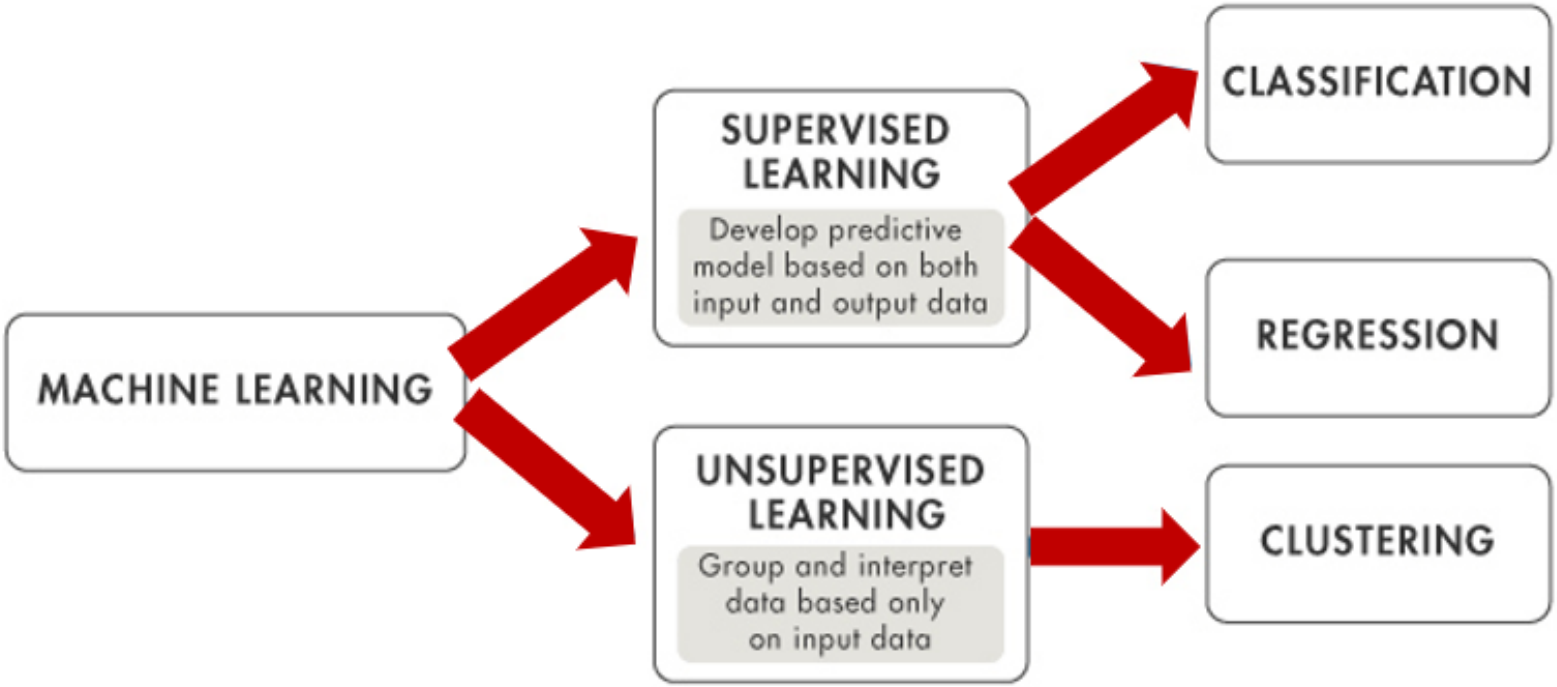
Supervised Learning Methods



Linear Regression

Linear Regression Model

$$y = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p + \epsilon,$$

where y is the response variable, $x_1, \ldots, x_p$ are predictor variables, and ϵ is normally distributed (i.e., $\mathcal{N} \sim (0, \sigma_y^2)$).

Poisson Regression

What about non-normal response variables?

Suppose Y_i represents a sample of n count responses $y_1, y_2, \ldots, y_n$ such that $Y_i \sim \text{Pois}(\mu_i)$.

Assumption: $\mathbb{E}(Y) = \mathbb{V}(Y)$

Poisson Regression Model

$$\log(\frac{\mu}{A}) = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p,$$

where μ is the expected value of the response variable, $x_1, \ldots, x_p$ are predictor variables, A is an offset term.

Negative Binomial Regression

What about over-dispersed count data?

Suppose Y_i represents a sample of n count responses $y_1, y_2, \ldots, y_n$ such that $Y_i \sim \mathrm{NB}(\mu_i, \mu_i[1 + \alpha\mu_i])$.

Assumption: $\mathbb{E}(Y) = \Phi\mathbb{V}(Y)$, where Φ represents the dispersion parameter

Negative Binomial Regression Model

$$\log(\frac{\mu}{A}) = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p,$$

where μ is the expected value of the response variable, $x_1, \ldots, x_p$ are predictor variables, A is an offset term.

Mixed Effects Models

What about multiple sources of variance?
Suppose there exists a correlation structure in the error term, ϵ (e.g., grouped, nested, hierarchical data).

Mixed Effects Model

$$y_{ij} = \beta_1 x_{1ij} + \cdots + \beta_n x_{nij} + \gamma_{i1} z_{1ij} + \cdots + \gamma_{in} z_{nij} + \epsilon_{ij},$$

where y_{ij} represents the response variable for observation i from group j, β_1 through β_n are the fixed effect regression coefficients, γ_{i1} through γ_{in} are the random effect regression coefficients, and ϵ_{ij} represents the error term for observation i from group j.

Autoregressive Covariance Structure

What about time-series data?

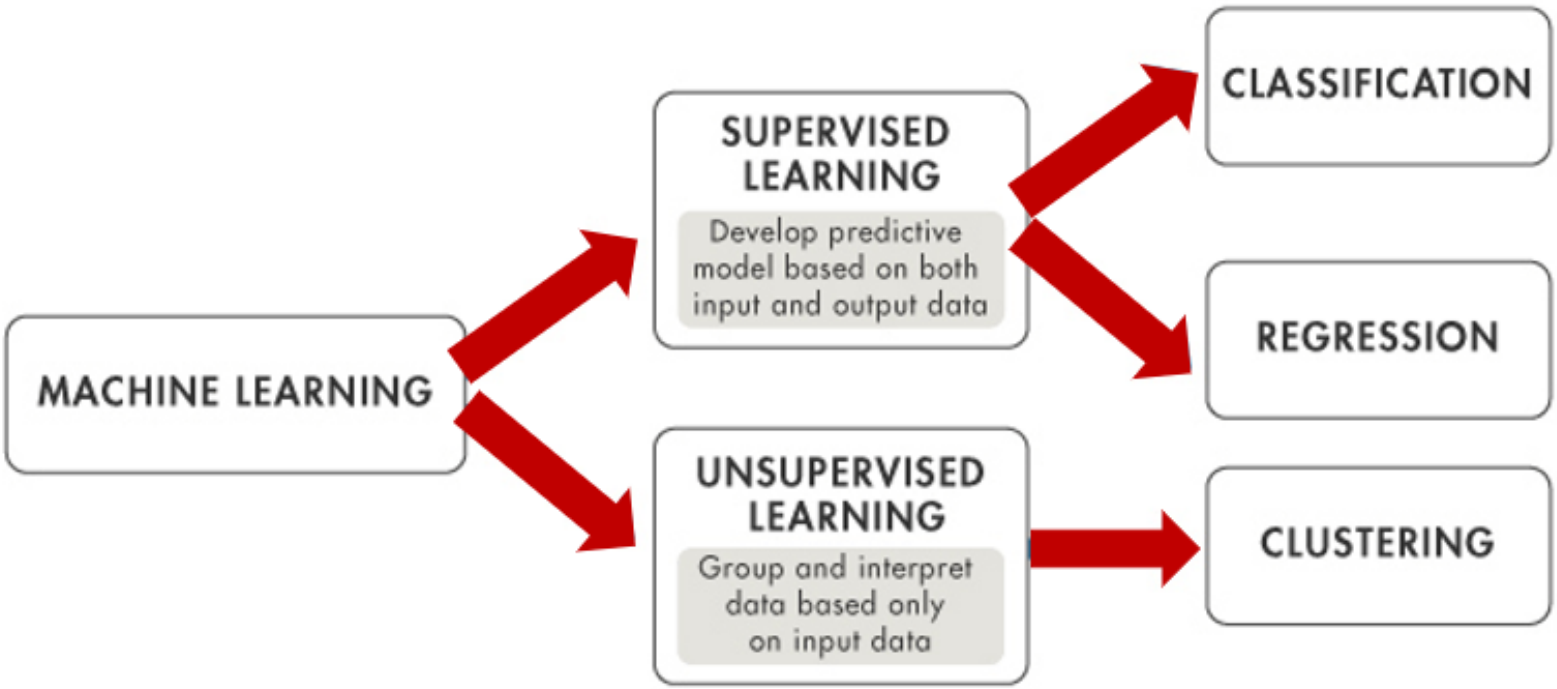
Suppose there exists serial correlation within groups.

Autoregressive Covariance Structure

$$\sigma^2 \begin{bmatrix} 1 & \rho & \rho^2 & \rho^3 \\ \rho & 1 & \rho & \rho^2 \\ \rho^2 & \rho & 1 & \rho \\ \rho^3 & \rho^2 & \rho & 1 \end{bmatrix},$$

where the variance-covariance matrix specifies homogeneous variances and correlations that decline exponentially with time.

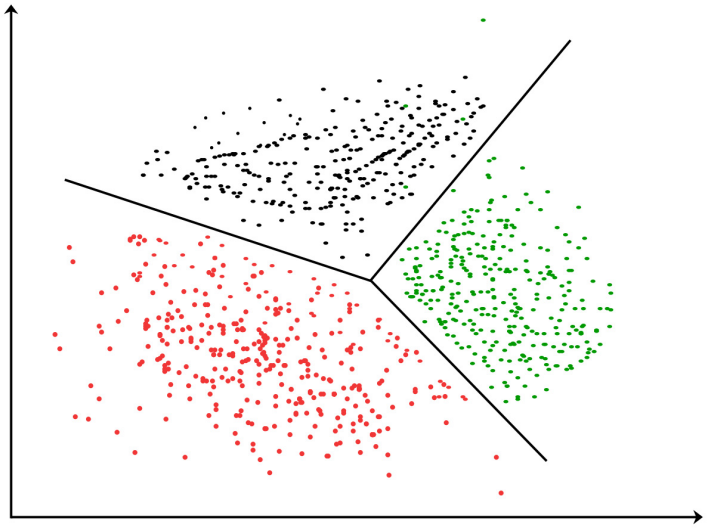
Unsupervised Learning Methods



Clustering

Steps

1. Feature Selection
2. Algorithm Selection
3. Cluster Validation
4. Results Interpretation



Proximity Measures

Euclidean Distance

$$d_{ij}(x_{ik}, x_{jk}) = \sqrt{\sum_{k=1}^{p}(x_{ik} - x_{jk})^2}$$

Manhattan Distance

$$d_{ij}(x_{ik}, x_{jk}) = \sum_{k=1}^{p}|x_{ik} - x_{jk}|$$

where x_{ik} and x_{jk} represent, respectively, the kth feature value of the p-dimensional observations for individuals i and j.

Determining Optimal Number of Clusters

Direct Methods

Elbow Method: Minimize total within-cluster variation

Silhouette Method: Maximize average silhouette score

Testing Methods

Gap Statistic Method: Detect whether clustering of data into K groups is significantly better than random generation

Clustering Algorithms

Hierarchical Algorithms

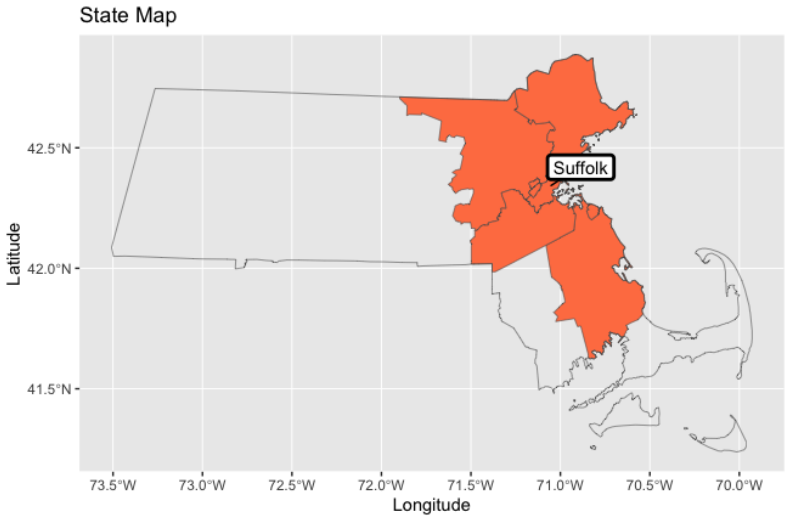
Agglomerative Clustering: Bottom-up approach that is particularly effective for identifying large clusters

Divisive Clustering: Top-down approach that is particularly effective for identifying small clusters

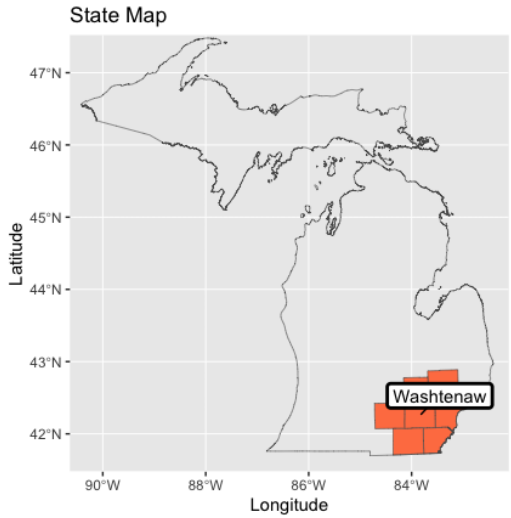
Partitional Algorithms

K-Means Clustering: Assign observations to clusters such that total within-cluster variation is minimized

Point-of-Sale Transaction Data



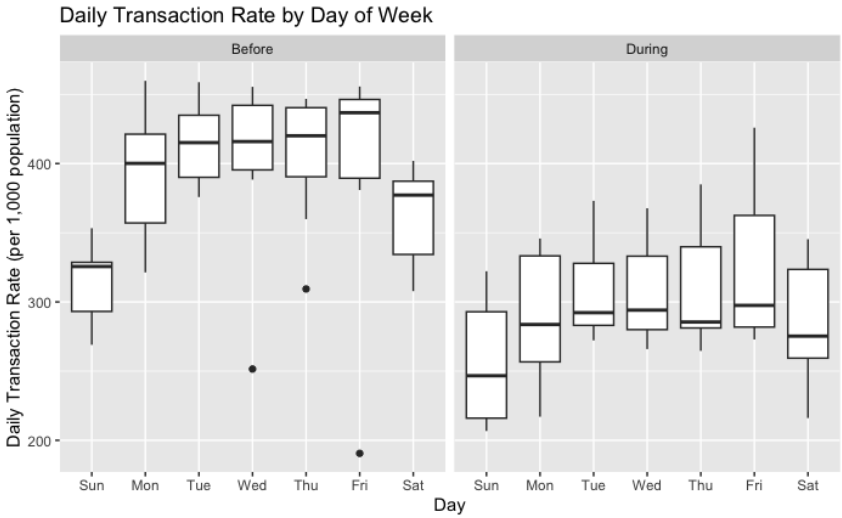
(a) Massachusetts



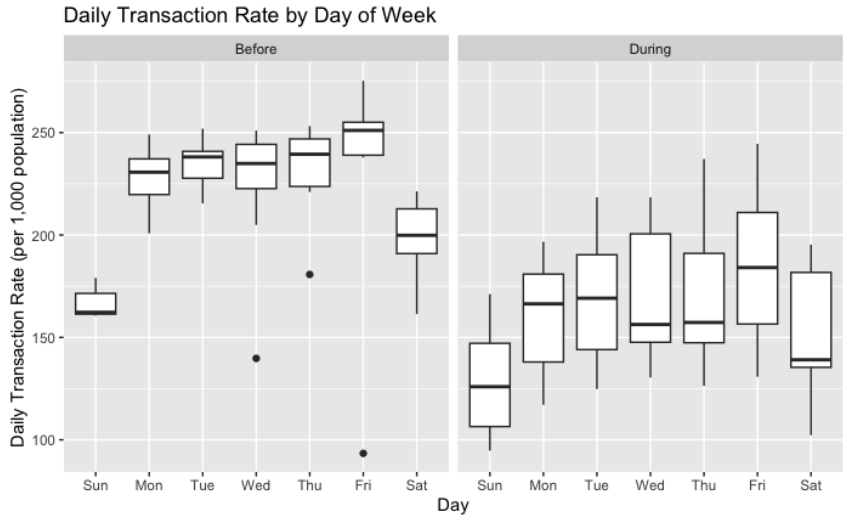
(b) Michigan

Figure: State Maps with Counties of Interest

Point-of-Sale Transaction Data



(a) Massachusetts



(b) Michigan

Figure: Daily Transaction Rate (per 1k population) by Day of Week

Point-of-Sale Transaction Data

County (MA)	Avg. Daily Transaction Rate		
	Before	*During*	*% Change*
Suffolk	657	462	-29.72
Middlesex	339	260	-23.25
Norfolk	332	261	-21.51
Essex	331	274	-17.34
Plymouth	276	239	-13.51

County (MI)	Avg. Daily Transaction Rate		
	Before	*During*	*% Change*
Oakland	194	132	-32.02
Washtenaw	336	244	-27.53
Wayne	203	151	-25.67
Livingston	257	209	-18.80
Jackson	242	212	-12.57
Monroe	212	196	-07.82
Lenawee	255	244	-04.27

Table: Average Daily Transaction Rate (per 1k population) by County

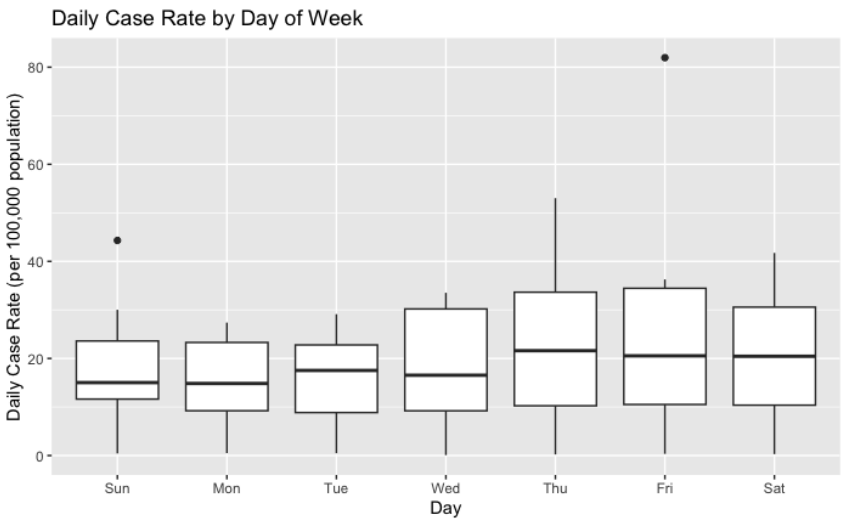
COVID-19 Case Data

County (MA)	Avg. Case Rate
Suffolk	28.11
Essex	22.62
Plymouth	18.99
Middlesex	16.55
Norfolk	14.31

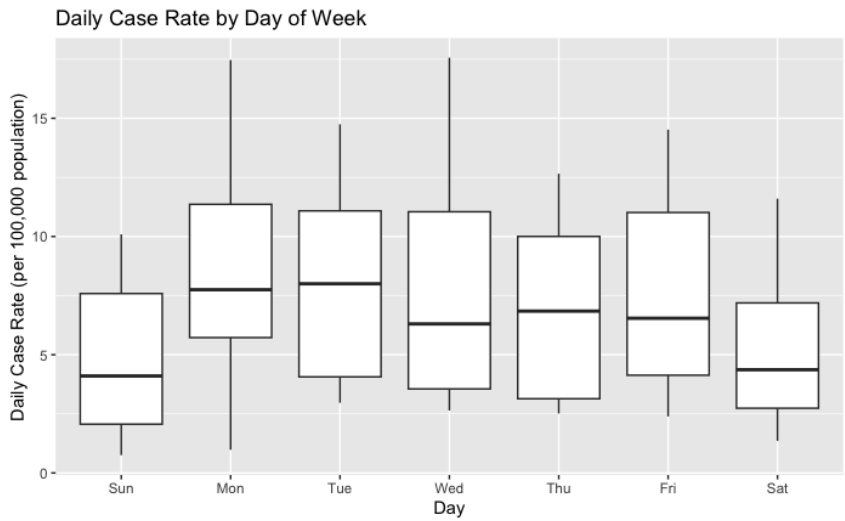
County (MI)	Avg. Case Rate
Oakland	8.86
Wayne	7.39
Washtenaw	4.57
Monroe	4.57
Jackson	4.24
Livingston	3.27
Lenawee	2.21

Table: Average Daily COVID-19 Case Rate (per 100k population) by County

COVID-19 Case Data



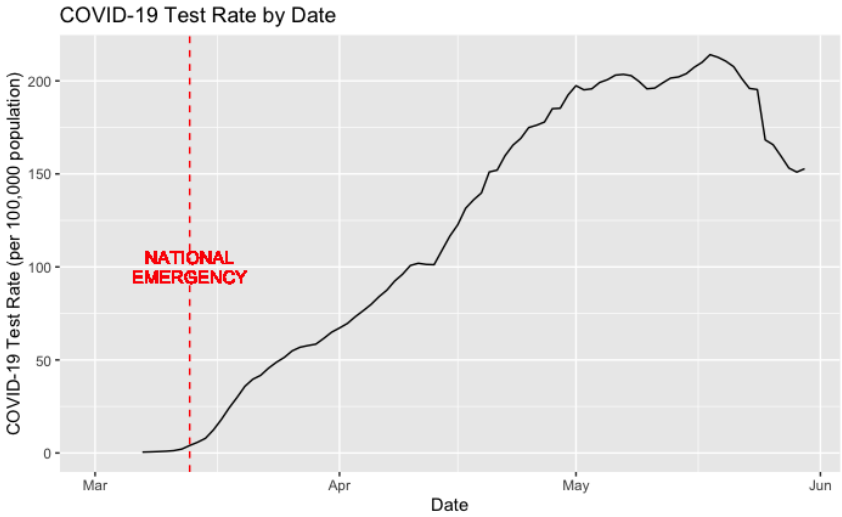
(a) Massachusetts



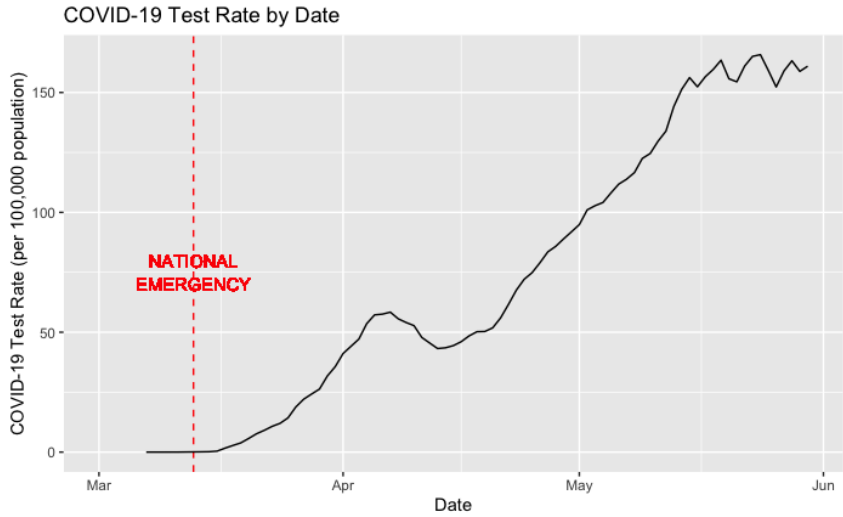
(b) Michigan

Figure: Daily COVID-19 Case Rate (per 100k population) by Day of Week

COVID-19 Testing Data



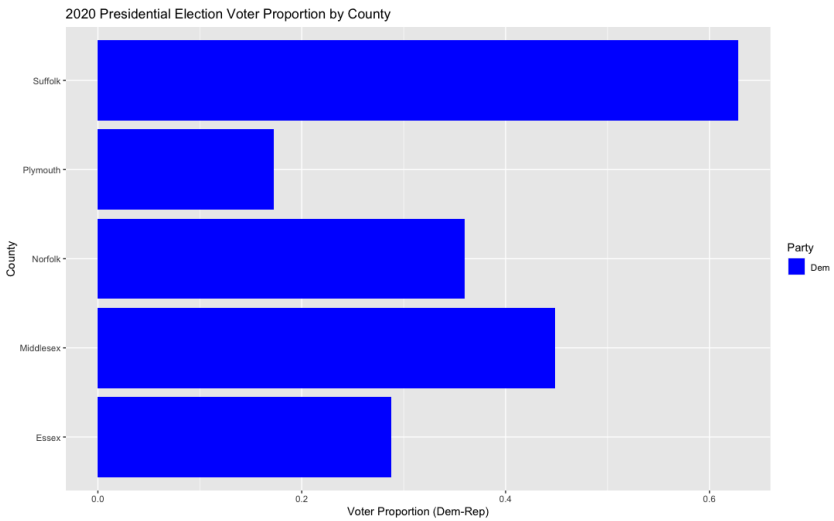
(a) Massachusetts



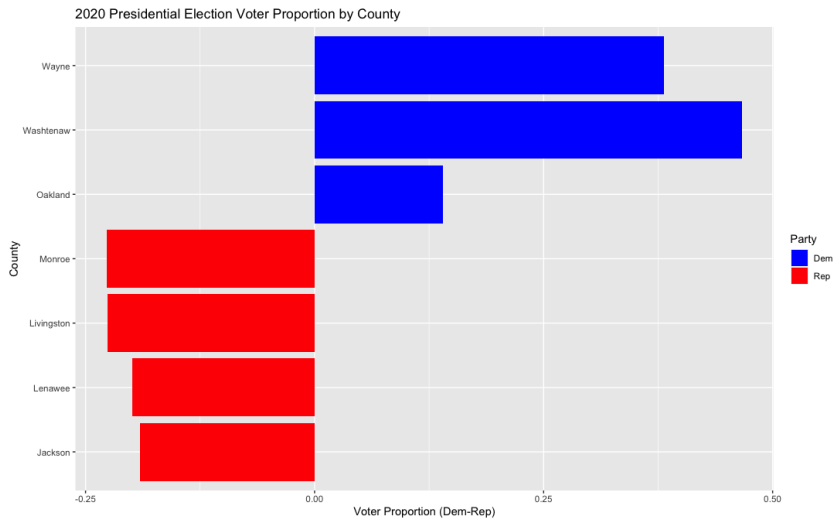
(b) Michigan

Figure: COVID-19 Test Rate (per 100k population) by Date

Political Data



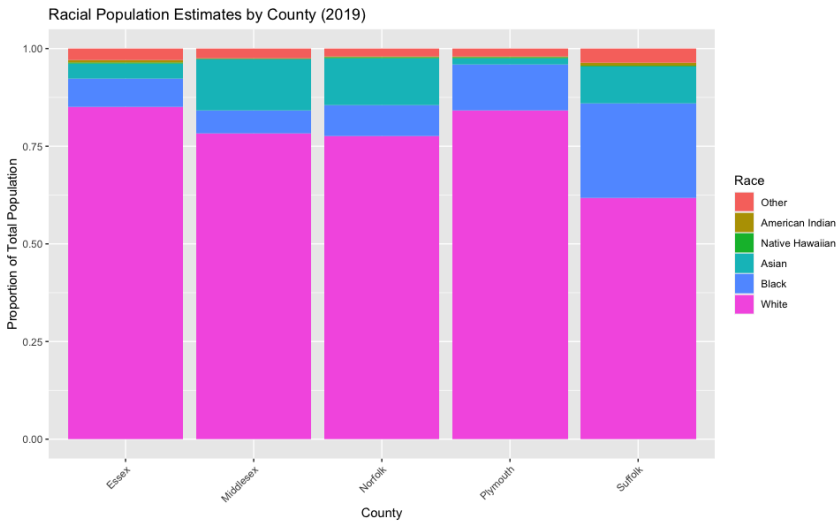
(a) Massachusetts



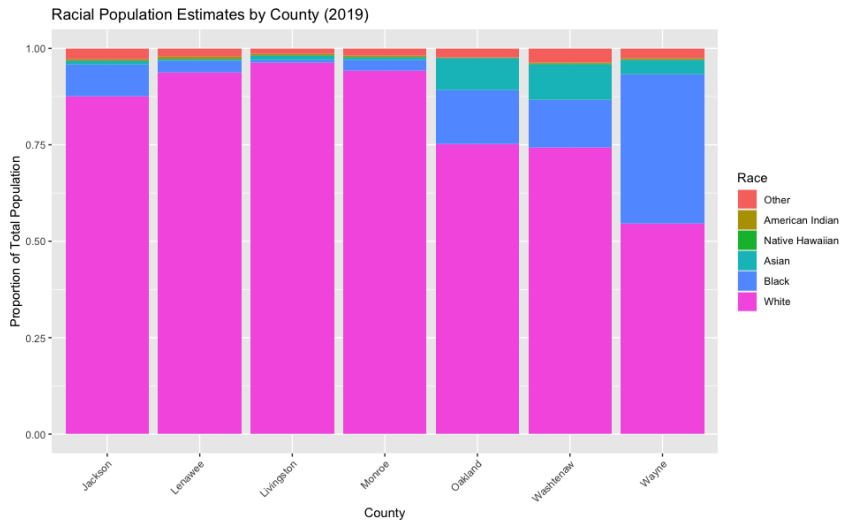
(b) Michigan

Figure: 2020 Presidential Election Voter Proportion by County

Demographic Data



(a) Massachusetts



(b) Michigan

Figure: Racial Population Estimates by County (2019)

Data Summary

Variable (MA)	Before ($n = 360$)	During ($n = 395$)	Total ($n = 755$)
NPIs			
Workplace Closures			
-*None*	360 (100%)	55 (13.9%)	415 (55.0%)
-*Recommended*	0 (0%)	0 (0%)	0 (0%)
-*Required (some)*	0 (0%)	0 (0%)	0 (0%)
-*Required (all)*	0 (0%)	340 (86.1%)	340 (45.0%)
Stay-at-Home Reqs.			
-*None*	360 (100%)	50 (12.7%)	410 (54.3%)
-*Recommended*	0 (0%)	345 (87.3%)	345 (45.7%)
-*Required (some ex.)*	0 (0%)	0 (0%)	0 (0%)
-*Required (min ex.)*	0 (0%)	0 (0%)	0 (0%)
Gathering Restrictions			
-*None*	360 (100%)	0 (0%)	360 (47.7%)
-*Restrict* $>$ *1,000 people*	0 (0%)	0 (0%)	0 (0%)
-*Restrict 101-1,000 people*	0 (0%)	20 (5.1%)	20 (2.6%)
-*Restrict 11-100 people*	0 (0%)	100 (25.3%)	100 (13.2%)
-*Restrict* $<$ *10 people*	0 (0%)	275 (69.6%)	275 (36.4%)
Daily Transaction Rates (per 1,000 population)			
Total	387 ± 150	299 ± 96.5	341 ± 133
Grocery	6.70 ± 3.50	6.42 ± 3.68	6.56 ± 3.59
Convenience	7.16 ± 2.45	5.96 ± 2.02	6.53 ± 2.31
Restaurants	38.5 ± 19.0	24.3 ± 9.56	31.1 ± 16.4
Health	38.2 ± 16.9	26.7 ± 8.67	32.2 ± 14.4
Hotels	15.1 ± 10.8	9.85 ± 4.81	12.3 ± 8.65
Daily COVID-19 Rates (per 100,000 population)			
Case	0.0265 ± 0.154	20.1 ± 16.4	10.5 ± 15.5
Test	0.225 ± 0.837	137 ± 77.5	71.6 ± 88.2

Table: NPIs, Transaction & COVID-19 Rates Before/During National Emergency

Data Summary

Variable (MI)	Before ($n = 504$)	During ($n = 553$)	Total ($n = 1057$)
NPIs			
Workplace Closures			
-*None*	504 (100%)	21 (3.8%)	525 (49.7%)
-*Recommended*	0 (0%)	0 (0%)	0 (0%)
-*Required (some)*	0 (0%)	315 (57.0%)	315 (29.8%)
-*Required (all)*	0 (0%)	217 (39.2%)	217 (20.5%)
Stay-at-Home Reqs.			
-*None*	490 (97.2%)	0 (0%)	490 (46.4%)
-*Recommended*	14 (2.8%)	147 (26.6%)	161 (15.2%)
-*Required (some ex.)*	0 (0%)	406 (73.4%)	406 (38.4%)
-*Required (min ex.)*	0 (0%)	0 (0%)	0 (0%)
Gathering Restrictions			
-*None*	504 (100%)	0 (0%)	504 (47.7%)
-*Restrict $>$ 1,000 people*	0 (0%)	0 (0%)	0 (0%)
-*Restrict 101-1,000 people*	0 (0%)	28 (5.1%)	28 (2.6%)
-*Restrict 11-100 people*	0 (0%)	49 (8.9%)	49 (4.6%)
-*Restrict $<$ 10 people*	0 (0%)	476 (86.1%)	476 (45.0%)
Daily Transaction Rates (per 1,000 population)			
Total	243 $\pm$ 59.9	198 $\pm$ 57.1	219 $\pm$ 62.6
Grocery	6.06 $\pm$ 2.59	6.08 $\pm$ 2.87	6.07 $\pm$ 2.74
Convenience	5.37 $\pm$ 3.14	4.63 $\pm$ 2.96	4.98 $\pm$ 3.07
Restaurants	31.30 $\pm$ 7.57	22.0 $\pm$ 6.76	26.4 $\pm$ 8.52
Health	29.30 $\pm$ 11.1	22.6 $\pm$ 8.63	25.8 $\pm$ 10.4
Hotels	6.51 $\pm$ 2.07	5.14 $\pm$ 1.65	5.79 $\pm$ 1.99
Daily COVID-19 Rates (per 100,000 population)			
Case	0.108 $\pm$ 0.478	5.00 $\pm$ 4.21	2.67 $\pm$ 3.92
Test	0.000406 $\pm$ 0.0295	85.1 $\pm$ 59.3	44.5 $\pm$ 60.4

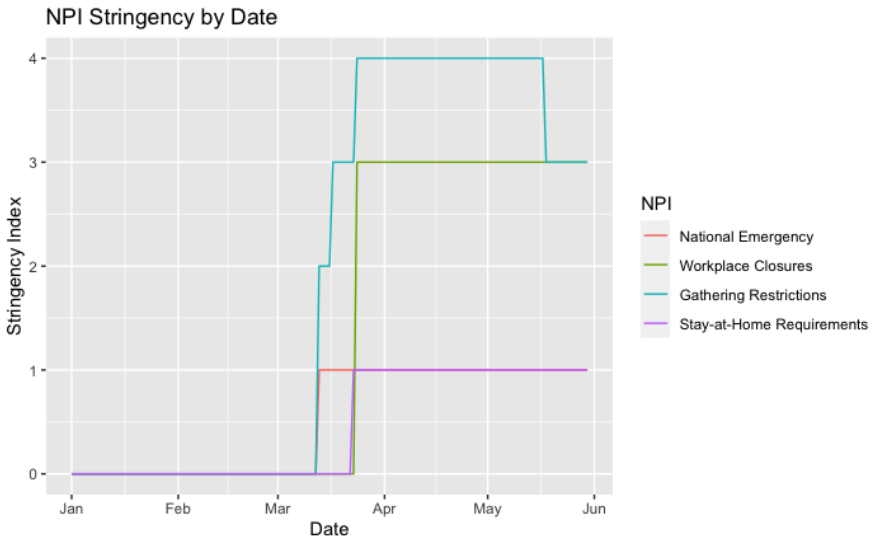
Table: NPIs, Transaction & COVID-19 Rates Before/During National Emergency

Non-Pharmaceutical Intervention Data

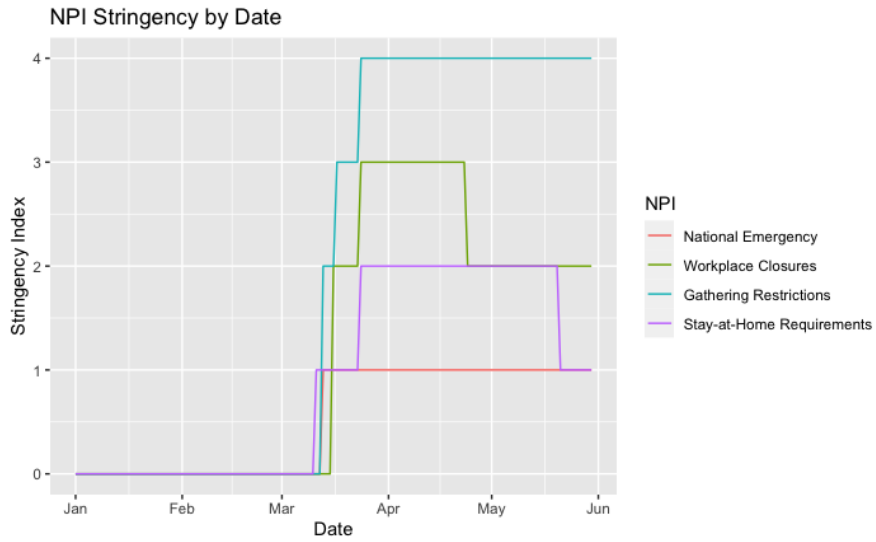
Policy	Description	Stringency Index
National Emergency	Record national emergency status	0 - not effective 1 - effective
Workplace Closures	Record closing of workplaces	0 - no measures 1 - recommend closing 2 - require closing (some sectors) 3 - require closing (all but essential)
Stay-at-Home Reqs.	Record orders to "shelter in place"	0 - no measures 1 - recommend not leaving home 2 - require not leaving home (with exceptions) 3 - require not leaving home (minimal exceptions)
Gathering Restrictions	Record limits on gatherings	0 - no measures 1 - restrict gatherings $>$ 1000 people 2 - restrict gatherings 101-1000 people 3 - restrict gatherings 11-100 people 4 - restrict gatherings $\leq$ 10 people

Table: Non-Pharmaceutical Intervention Data

Non-Pharmaceutical Intervention Data



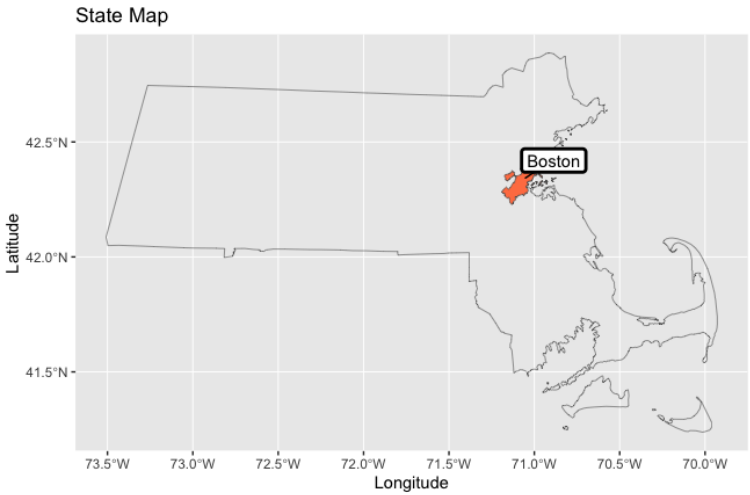
(a) Massachusetts



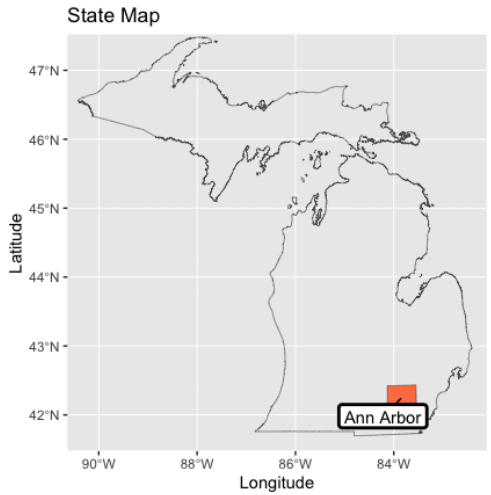
(b) Michigan

Figure: Non-Pharmaceutical Intervention Stringency by Date

Point-of-Sale Transaction Data



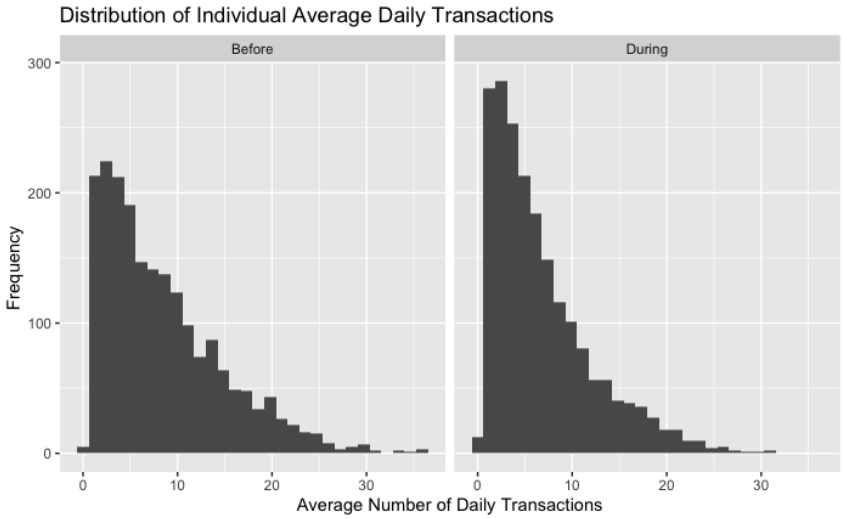
(a) Massachusetts



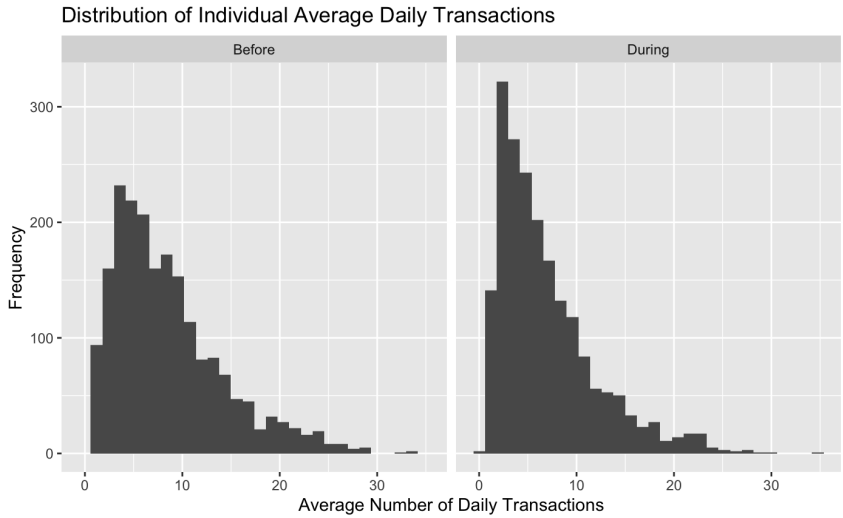
(b) Michigan

Figure: State Maps with Cities of Interest

Point-of-Sale Transaction Data



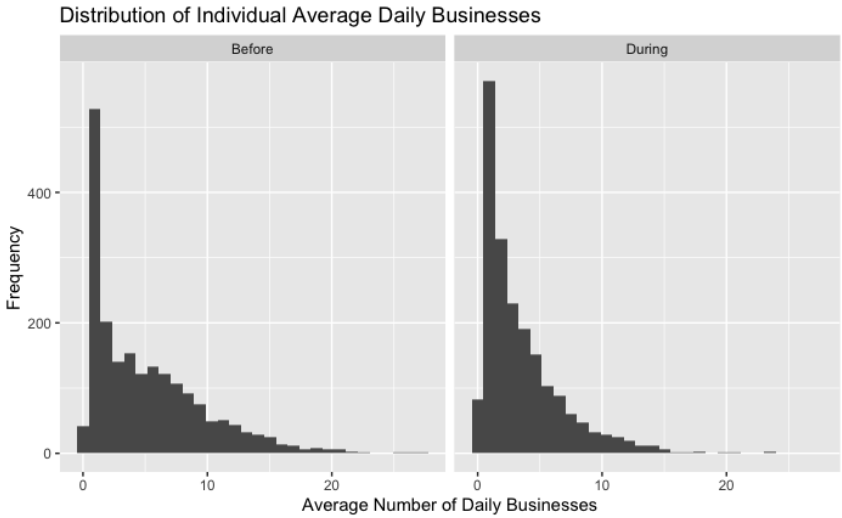
(a) Massachusetts



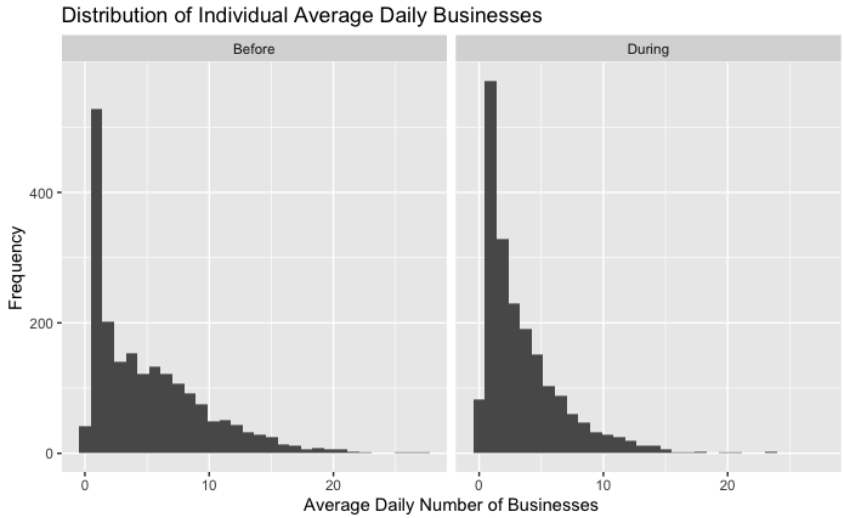
(b) Michigan

Figure: Distribution of Individual Average Daily Transactions

Point-of-Sale Transaction Data



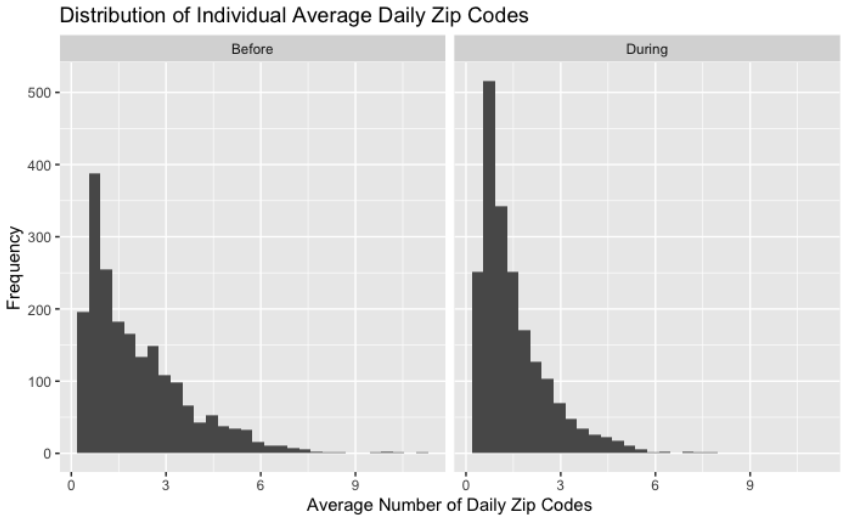
(a) Massachusetts



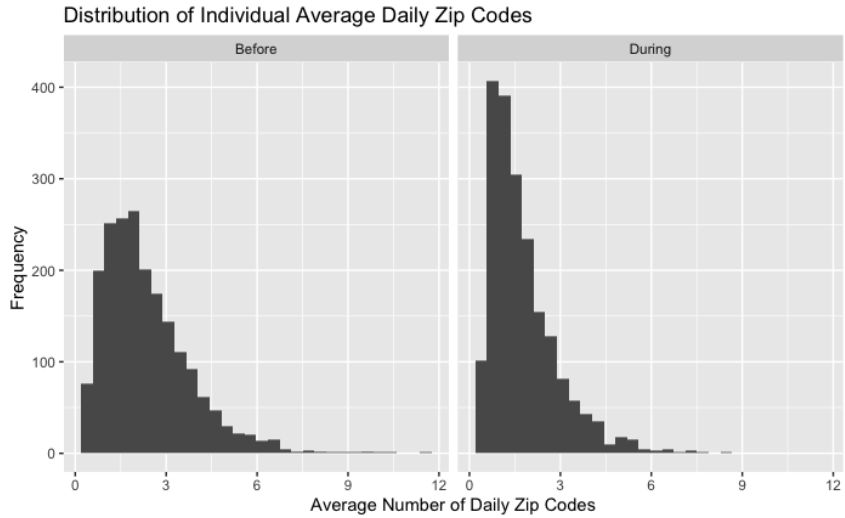
(b) Michigan

Figure: Distribution of Individual Average Daily Businesses

Point-of-Sale Transaction Data



(a) Massachusetts



(b) Michigan

Figure: Distribution of Individual Average Daily Zip Codes

Point-of-Sale Transaction Data

UUID	Avg. Daily Transactions			Avg. Daily Businesses			Avg. Daily Zip Codes		
	Before	*During*	*% Change*	*Before*	*During*	*% Change*	*Before*	*During*	*% Change*
MA1	27.44	1.01	-96.31	16.10	0.41	-97.48	3.03	0.34	-88.71
MA2	15.67	0.92	-94.10	11.06	0.67	-93.93	3.60	0.53	-85.22
MA3	11.82	0.75	-93.68	1.58	0.47	-70.42	0.88	0.42	-52.26
MA4	12.75	0.92	-92.75	1.00	0.35	-64.56	0.57	0.33	-42.20
MA5	10.18	0.77	-92.42	1.49	0.51	-65.93	1.40	0.46	-67.51
MA6	24.46	1.96	-91.98	18.63	1.51	-91.91	5.19	0.75	-85.62
MA7	2.32	15.72	+577.81	0.67	1.78	+167.72	0.47	1.22	+157.33
MA8	3.90	27.72	+610.30	1.93	5.05	+161.62	1.26	2.85	+125.34
MA9	1.53	12.33	+707.00	0.94	2.32	+145.27	0.89	1.49	+68.04
MA10	3.14	26.44	+742.43	1.19	3.06	+156.46	0.88	1.59	+82.28
MA11	1.29	17.01	+1217.11	0.60	12.63	+2015.28	0.60	3.08	+415.04
MA12	0.71	18.67	+2535.89	0.46	1.56	+217.61	0.42	0.42	+103.54

UUID	Avg. Daily Transactions			Avg. Daily Businesses			Avg. Daily Zip Codes		
	Before	*During*	*% Change*	*Before*	*During*	*% Change*	*Before*	*During*	*% Change*
MI1	14.17	0.84	-94.10	5.97	0.66	-88.98	0.97	0.56	-42.71
MI2	20.10	1.44	-92.81	15.28	1.32	-91.38	2.24	0.58	-73.96
MI3	9.83	0.76	-92.28	6.15	0.39	-93.62	1.78	0.39	-77.93
MI4	22.82	2.13	-90.68	14.75	1.62	-89.02	2.56	0.65	-74.74
MI5	23.87	2.35	-90.13	2.58	1.03	-60.31	1.86	0.84	-55.11
MI6	20.08	2.04	-89.85	17.33	1.67	-90.36	3.65	0.84	-77.13
MI7	2.08	16.09	+672.25	1.63	9.03	+455.40	0.83	1.71	+105.06
MI8	1.22	9.47	+674.68	0.96	3.90	+306.82	0.81	2.68	+233.13
MI9	1.19	10.34	+765.82	0.76	1.30	+70.68	0.64	1.25	+96.15
MI10	1.11	11.54	+938.99	1.04	2.87	+175.85	0.43	0.65	+49.94
MI11	0.78	11.86	+1424.95	0.47	1.09	+130.53	0.46	0.73	+60.18
MI12	1.49	26.92	+1711.71	1.42	17.32	1122.34	0.57	0.87	+53.38

Table: Consumer Behavior Before/During National Emergency (MA & MI)

Point-of-Sale Transaction Data

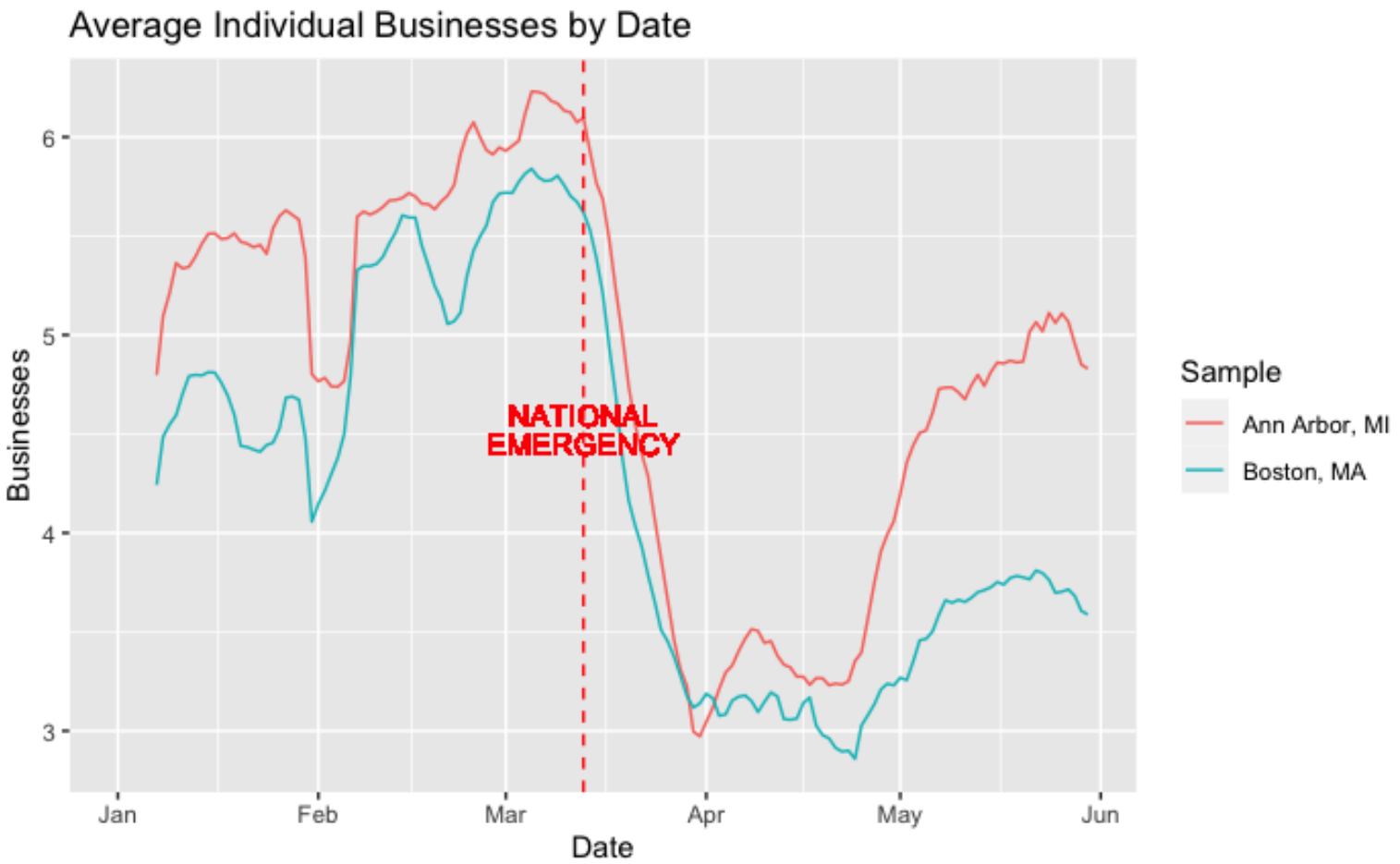


Figure: Average Individual Businesses by Date

Point-of-Sale Transaction Data

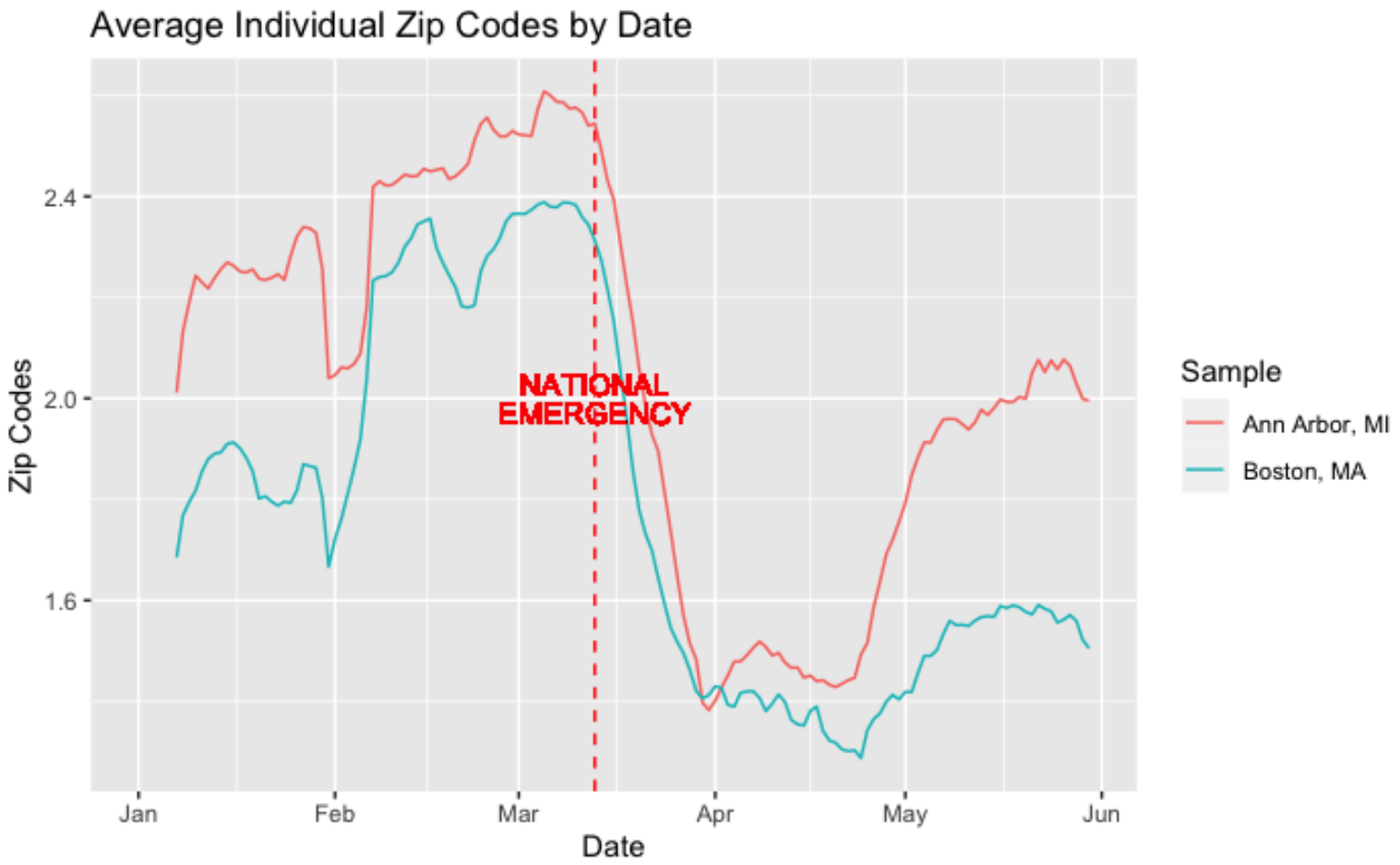
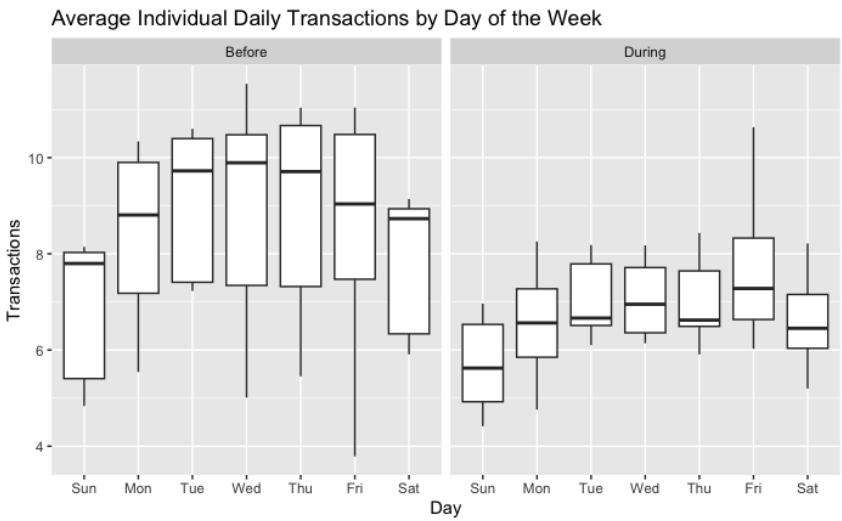
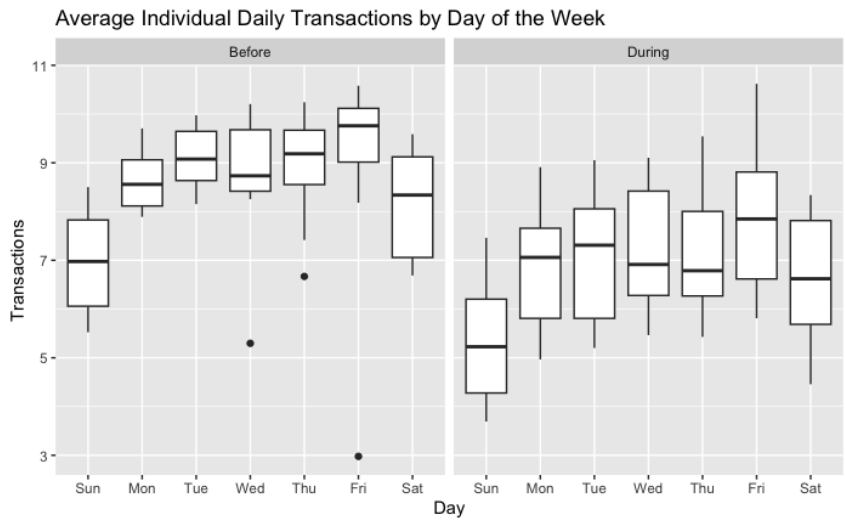


Figure: Average Individual Zip Codes by Date

Point-of-Sale Transaction Data



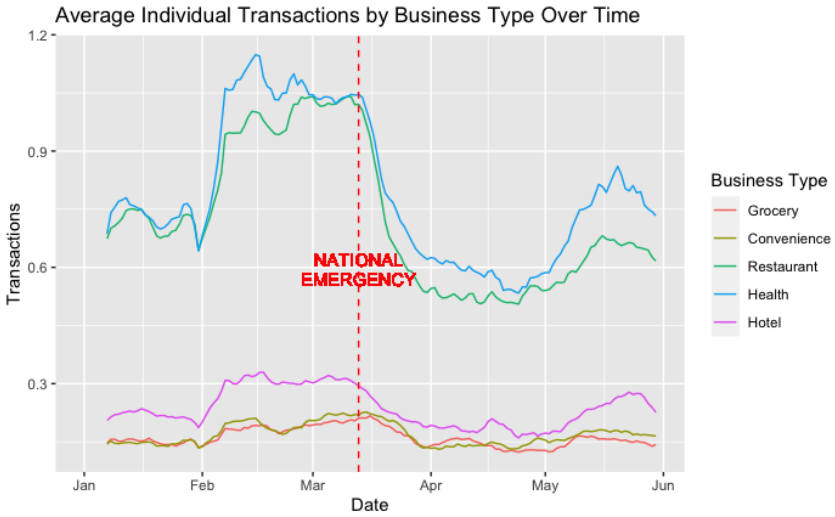
(a) Massachusetts



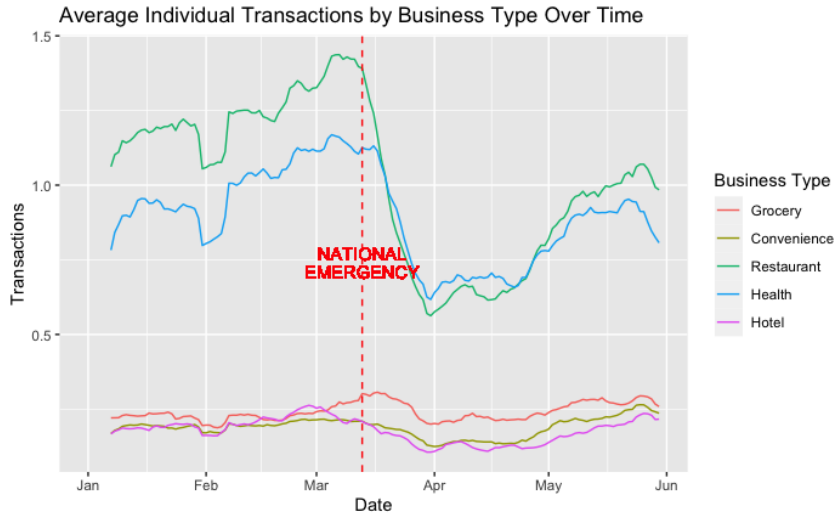
(b) Michigan

Figure: Distribution of Average Individual Daily Transactions by Day of the Week

Point-of-Sale Transaction Data



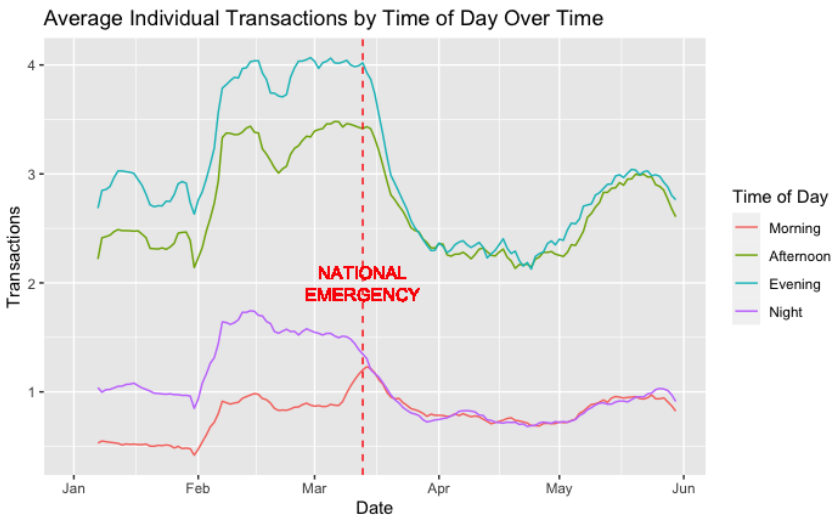
(a) Massachusetts



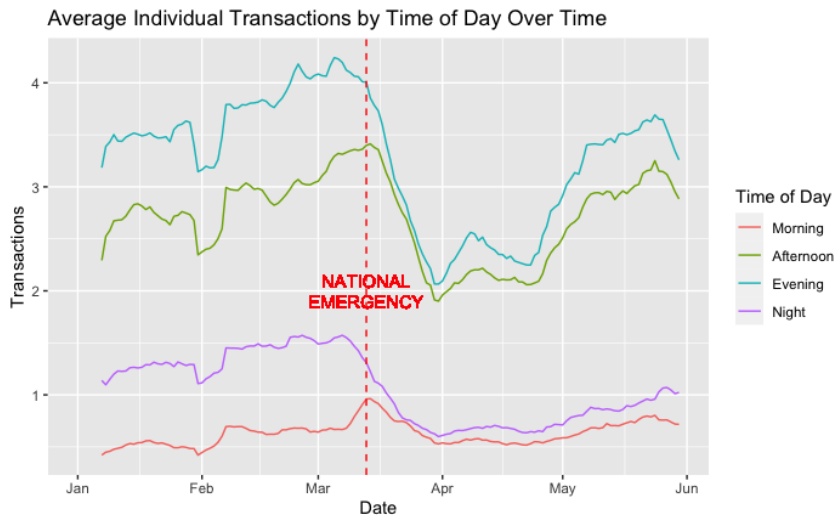
(b) Michigan

Figure: Average Individual Transactions by Business Type Over Time

Point-of-Sale Transaction Data



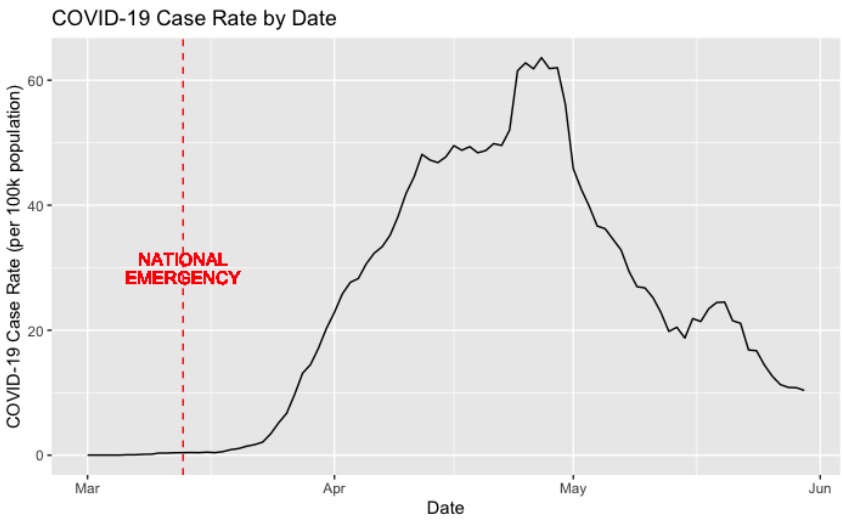
(a) Massachusetts



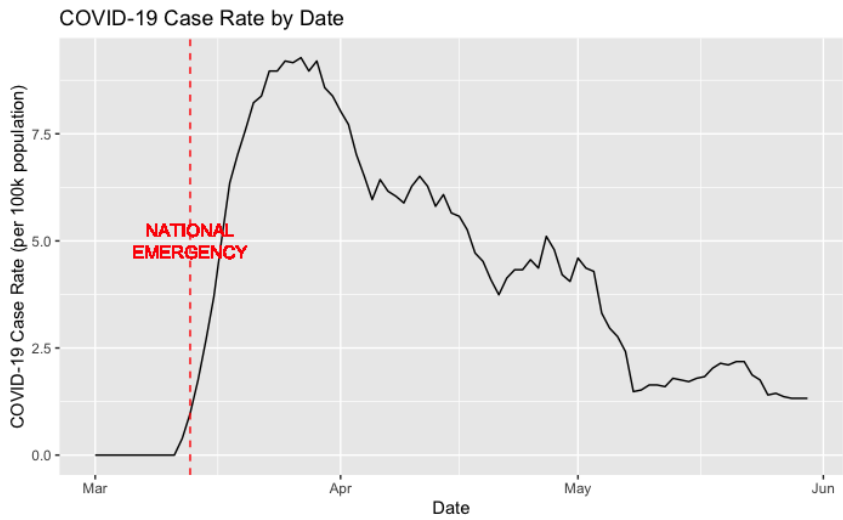
(b) Michigan

Figure: Average Individual Transactions by Time of Day Over Time

COVID-19 Case Data



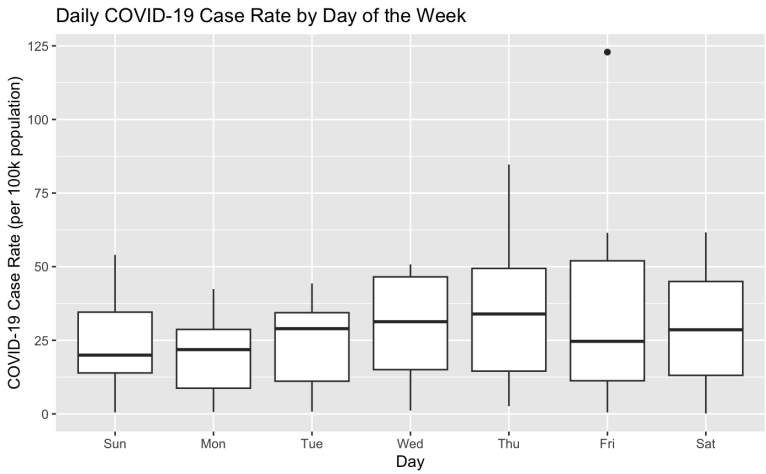
(a) Suffolk County, Massachusetts



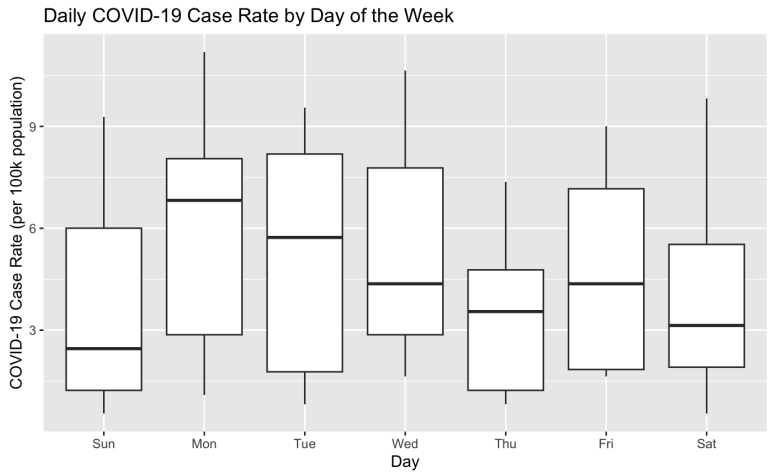
(b) Washtenaw County, Michigan

Figure: COVID-19 Case Rate (per 100k population) by Date

COVID-19 Case Data



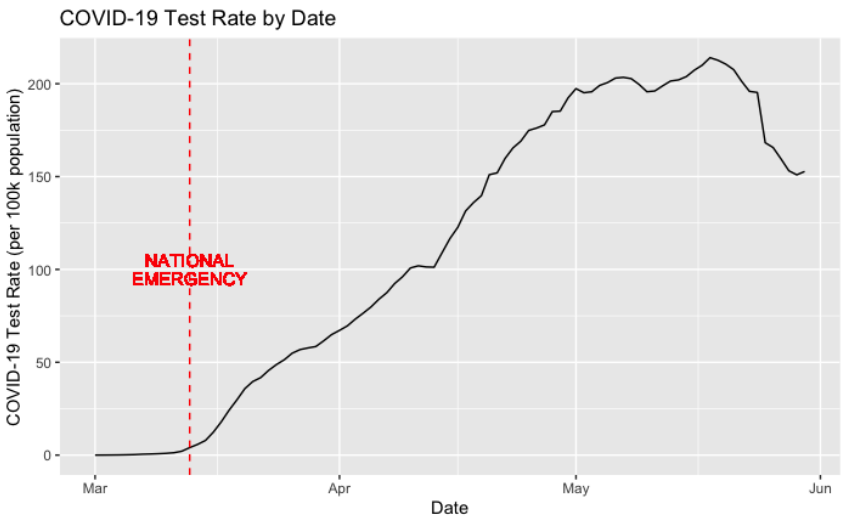
(a) Suffolk County, Massachusetts



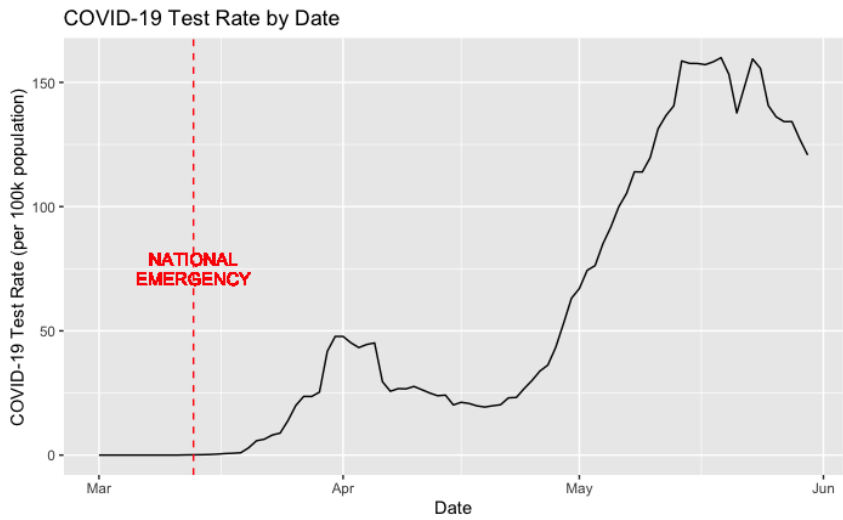
(b) Washtenaw County, Michigan

Figure: Daily COVID-19 Case Rate (per 100k population) by Day of the Week

COVID-19 Testing Data



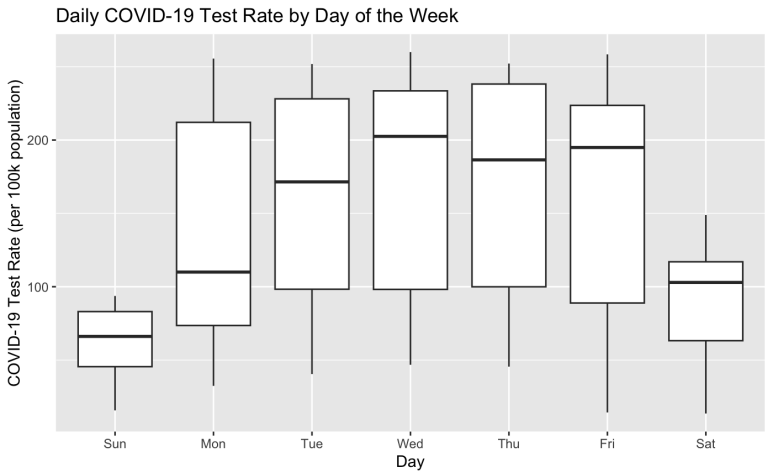
(a) Suffolk County, Massachusetts



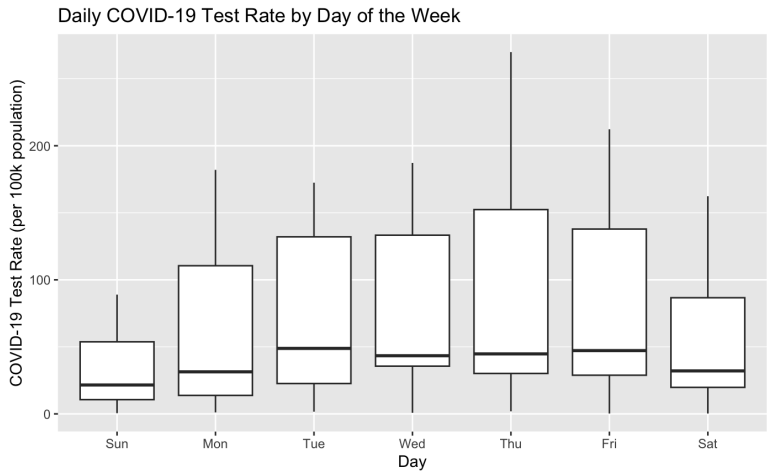
(b) Washtenaw County, Michigan

Figure: Daily COVID-19 Testing Rate (per 100k population) by Date

COVID-19 Testing Data



(a) Suffolk County, Massachusetts



(b) Washtenaw County, Michigan

Figure: Daily COVID-19 Testing Rate (per 100k population) by Day of the Week

Data Summary

Variable (MA)	Before ($n = 144,000$)	During ($n = 158,000$)	Total ($n = 302,000$)
NPIs			
Workplace Closures			
-None	144,000 (100%)	22,000 (13.9%)	166,000 (55.0%)
-Recommended	0 (0%)	0 (0%)	0 (0%)
-Required (some)	0 (0%)	0 (0%)	0 (0%)
-Required (all)	0 (0%)	136,000 (86.1%)	136,000 (45.0%)
Stay-at-Home Reqs.			
-None	144,000 (100%)	20,000 (12.7%)	164,000 (54.3%)
-Recommended	0 (0%)	138,000 (87.3%)	138,000 (45.7%)
-Required (some ex.)	0 (0%)	0 (0%)	0 (0%)
-Required (min ex.)	0 (0%)	0 (0%)	0 (0%)
Gathering Restrictions			
-None	144,000 (100%)	0 (0%)	144,000 (47.7%)
-Restrict > 1,000 people	0 (0%)	0 (0%)	0 (0%)
-Restrict 101-1,000 people	0 (0%)	8,000 (5.1%)	8,000 (2.6%)
-Restrict 11-100 people	0 (0%)	40,000 (25.3%)	40,000 (13.2%)
-Restrict < 10 people	0 (0%)	110,000 (69.6%)	110,000 (36.4%)
Transactions			
Total	8.40 ± 12.3	6.80 ± 10.9	7.57 ± 11.6
Unique Businesses	5.05 ± 7.31	3.47 ± 5.53	4.22 ± 6.48
Unique Zip Codes	2.08 ± 2.65	1.50 ± 1.99	1.78 ± 2.35
Grocery	0.17 ± 0.88	0.15 ± 0.83	0.16 ± 0.86
Convenience	0.18 ± 0.81	0.16 ± 0.97	0.17 ± 0.891
Restaurants	0.86 ± 2.28	0.60 ± 2.06	0.72 ± 2.17
Health	0.91 ± 2.98	0.68 ± 2.79	0.79 ± 2.89
Hotels	0.27 ± 1.30	0.21 ± 1.46	0.24 ± 1.39
Morning	0.75 ± 2.95	0.83 ± 2.97	0.79 ± 2.96
Afternoon	2.89 ± 5.49	2.53 ± 5.37	2.70 ± 5.43
Evening	3.44 ± 6.02	2.61 ± 5.32	3.01 ± 5.68
Night	1.32 ± 3.78	0.83 ± 2.88	1.06 ± 3.35
COVID-19 Rates (per 100,000 population)			
Case	0.040 ± 0.172	28.2 ± 21.6	14.8 ± 21.0
Test	0.221 ± 0.837	137 ± 77.4	71.6 ± 88.2

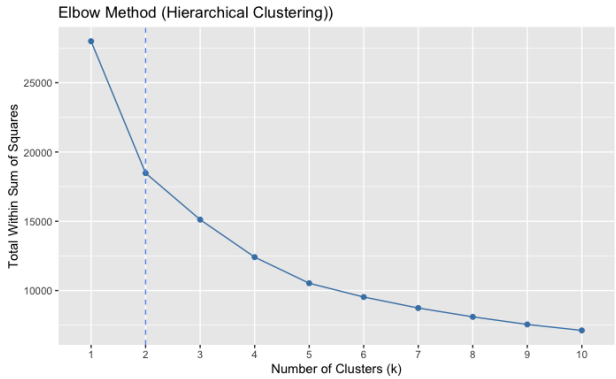
Table: NPIs, Transaction & COVID-19 Rates Before/During National Emergency

Data Summary

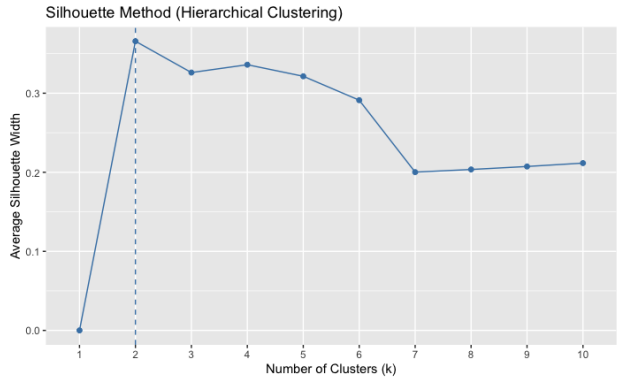
Variable (MI)	Before ($n = 144,000$)	During ($n = 158,000$)	Total ($n = 302,000$)
NPIs			
Workplace Closures			
-*None*	144,000 (100%)	6,000 (3.8%)	150,000 (49.7%)
-*Recommended*	0 (0%)	0 (0%)	0 (0%)
-*Required (some)*	0 (0%)	90,000 (57.0%)	90,000 (29.8%)
-*Required (all)*	0 (0%)	62,000 (39.2%)	62,000 (20.5%)
Stay-at-Home Reqs.			
-*None*	140,000 (97.2%)	0 (0%)	140,000 (46.4%)
-*Recommended*	4,000 (2.8%)	42,000 (26.6%)	46,000 (15.2%)
-*Required (some ex.)*	0 (0%)	116,000 (73.4%)	116,000 (38.4%)
-*Required (min ex.)*	0 (0%)	0 (0%)	0 (0%)
Gathering Restrictions			
-*None*	144,000 (100%)	0 (0%)	144,000 (47.7%)
-*Restrict > 1,000 people*	0 (0%)	0 (0%)	0 (0%)
-*Restrict 101-1,000 people*	0 (0%)	8,000 (5.1%)	8,000 (2.6%)
-*Restrict 11-100 people*	0 (0%)	14,000 (8.9%)	14,000 (4.6%)
-*Restrict < 10 people*	0 (0%)	136,000 (86.1%)	136,000 (45.0%)
Transactions			
Total	8.53 ± 11.4	6.90 ± 10.7	7.67 ± 11.1
Unique Businesses	5.58 ± 7.08	4.14 ± 6.01	4.83 ± 6.58
Unique Zip Codes	2.35 ± 2.66	1.77 ± 2.27	2.05 ± 2.48
Grocery	0.23 ± 0.97	0.25 ± 1.10	0.24 ± 1.04
Convenience	0.20 ± 0.74	0.18 ± 0.92	0.19 ± 0.84
Restaurants	1.23 ± 2.65	0.83 ± 2.14	1.02 ± 2.41
Health	0.99 ± 2.75	0.80 ± 2.75	0.89 ± 2.75
Hotels	0.20 ± 1.12	0.16 ± 1.06	0.18 ± 1.09
Morning	0.61 ± 2.67	0.64 ± 2.68	0.63 ± 2.67
Afternoon	2.86 ± 5.24	2.56 ± 5.23	2.71 ± 5.24
Evening	3.70 ± 5.70	2.90 ± 5.39	3.28 ± 5.56
Night	1.36 ± 3.53	0.80 ± 2.73	1.06 ± 3.15
COVID-19 Rates (per 100,000 population)			
Case	0.038 ± 0.319	4.58 ± 3.01	2.42 ± 3.15
Test	0.008 ± 0.064	68.8 ± 62.9	36.0 ± 57.0

Table: NPIs, Transaction & COVID-19 Rates Before/During National Emergency

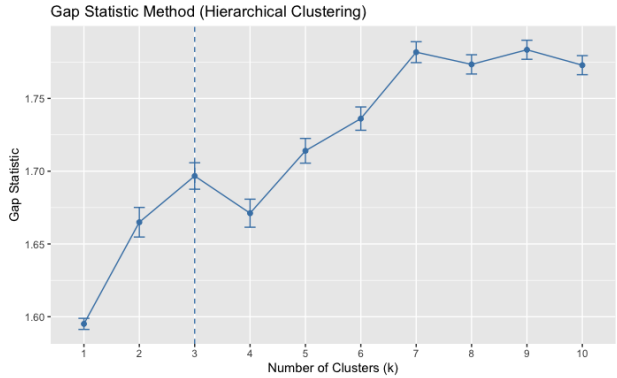
Hierarchical Clustering



(a) Elbow Method



(b) Silhouette Method



(c) Gap Statistic Method

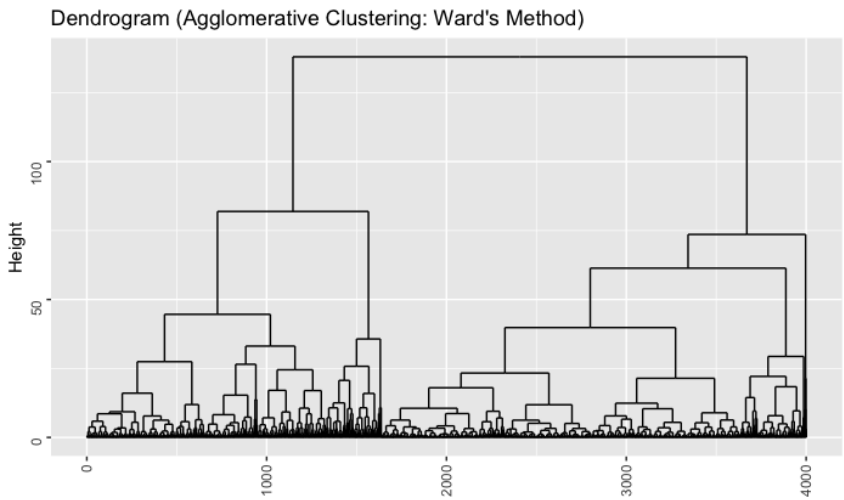
Figure: Optimal Number of Clusters (Hierarchical Clustering)

Agglomerative Clustering

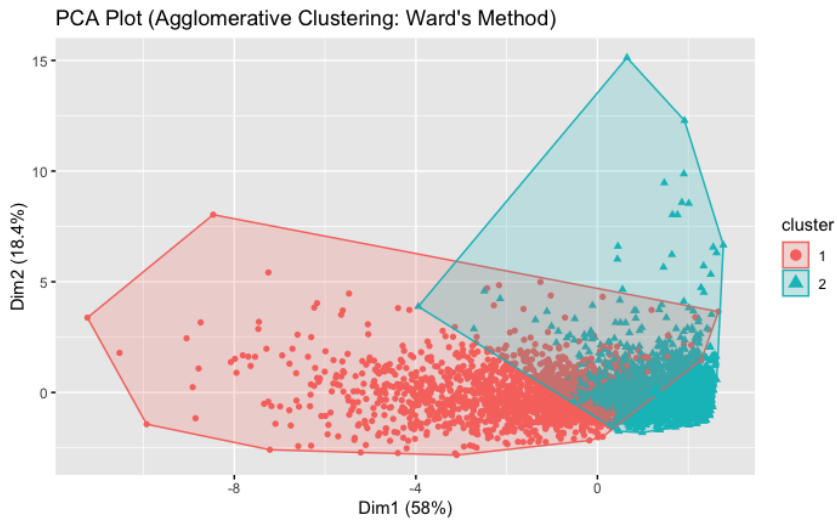
Method	**AC**
Complete	0.9928
Single	0.9772
Average	0.9873
Ward	0.9985

Table: Agglomerative Clustering Results

Agglomerative Clustering



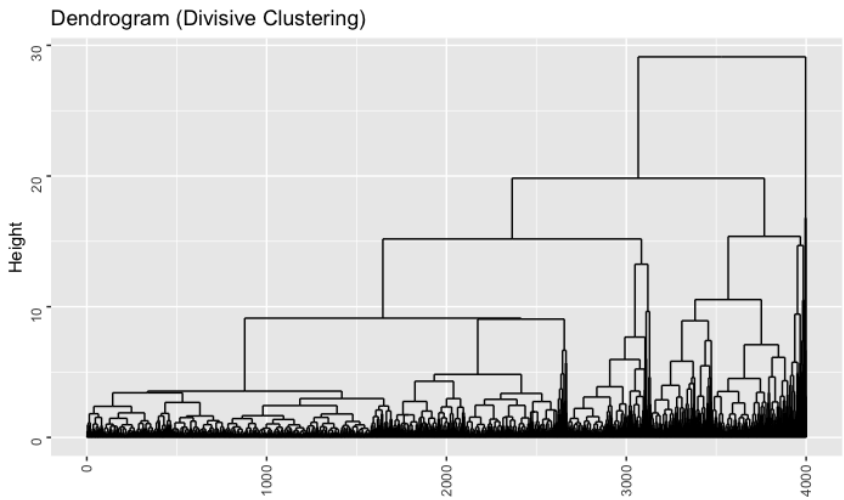
(a) Dendrogram



(b) PCA Plot

Figure: Agglomerative Clustering Results (Ward's Method)

Divisive Clustering

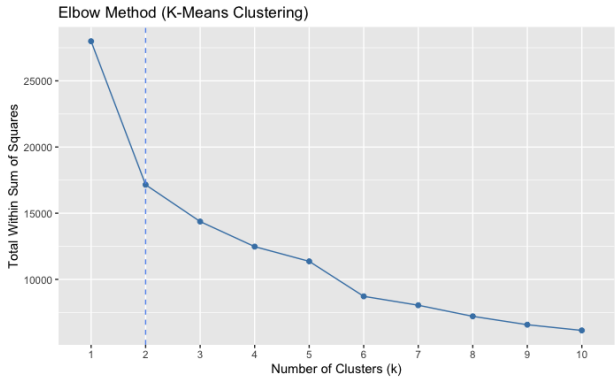


(a) Dendrogram

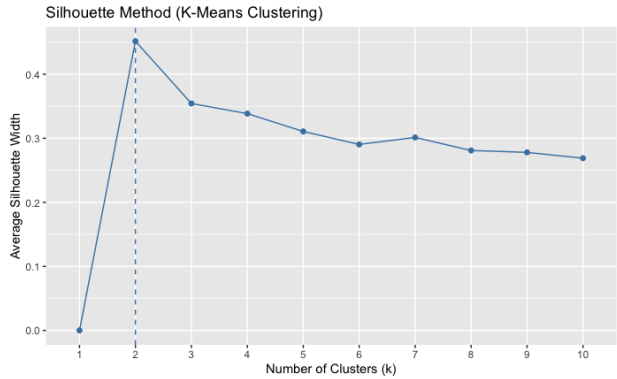
(b) PCA Plot

Figure: Divisive Clustering Results

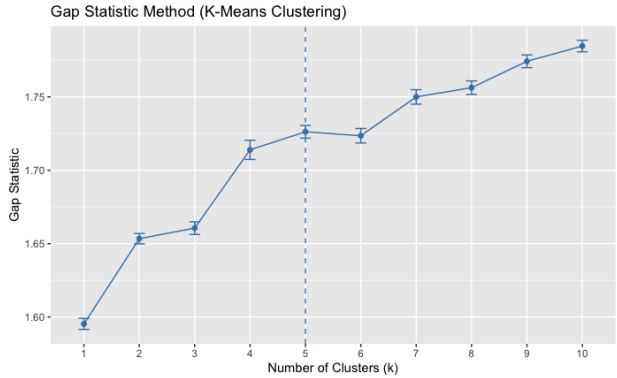
K-Means Clustering



(a) Elbow Method



(b) Silhouette Method



(c) Gap Statistic Method

Figure: Optimal Number of Clusters (K-Means Clustering)

K-Means

Measure	**Cluster 1**	**Cluster 2**	**Cluster 3**
Size	2157	1385	458
Within Cluster SS	7869.647	3320.855	3179.931

Table: K-Means Clustering Results

Cluster Interpretation

Variable	Cluster 1 ($n = 2157$)	Cluster 2 ($n = 1385$)	Cluster 3 ($n = 458$)	Overall ($n = 4000$)
Avg. Daily Total Transactions				
-Mean ($\pm$ SD)	3.87 ($\pm$ 1.85)	10.80 ($\pm$ 2.52)	20.60 ($\pm$ 4.42)	8.20 ($\pm$ 6.04)
-Median (Min,Max)	3.82 (0.40,7.72)	10.40 (7.18,18.70)	19.70 (12.90,39.60)	6.65 (0.40,39.60)
Avg. Daily AM Transactions				
-Mean ($\pm$ SD)	0.95 ($\pm$ 0.84)	2.33 ($\pm$ 1.52)	5.51 ($\pm$ 3.54)	1.95 ($\pm$ 2.16)
-Median (Min,Max)	0.73 (0.00,6.48)	2.08 (0.00,9.75)	4.72 (0.12,26.50)	1.28 (0.00,26.50)
Avg. Daily PM Transactions				
-Mean ($\pm$ SD)	2.92 ($\pm$ 1.62)	8.51 ($\pm$ 2.70)	15.10 ($\pm$ 4.77)	6.25 ($\pm$ 4.82)
-Median (Min,Max)	2.75 (0.03,7.37)	8.10 (1.08,18.10)	15.20 (1.55,35.70)	5.03 (0.03,35.70)
Avg. Daily Ratio (AM vs. PM) Transactions				
-Mean ($\pm$ SD)	0.56 ($\pm$ 1.58)	0.35 ($\pm$ 0.46)	0.50 ($\pm$ 0.72)	0.48 ($\pm$ 1.22)
-Median (Min,Max)	0.28 (0.00,32.40)	0.24 (0.00,9.00)	0.33 (0.01,9.02)	0.27 (0.00,32.4)
Avg. Daily Weekend Transactions				
-Mean ($\pm$ SD)	3.62 ($\pm$ 2.39)	9.36 ($\pm$ 3.88)	18.30 ($\pm$ 6.42)	7.29 ($\pm$ 5.97)
-Median (Min,Max)	3.18 (0.00,16.80)	9.06 (0.00,30.00)	17.90 (1.29,39.10)	5.76 (0.00,39.10)
Avg. Daily Weekday Transactions				
-Mean ($\pm$ SD)	3.96 ($\pm$ 2.05)	11.40 ($\pm$ 3.37)	21.50 ($\pm$ 5.82)	8.56 ($\pm$ 6.60)
-Median (Min,Max)	3.79 (0.35,10.50)	10.80 (4.00,24.50)	20.70 (7.40,42.90)	6.81 (0.35,42.90)
Avg. Daily Ratio (Weekend vs. Weekday) Transactions				
-Mean ($\pm$ SD)	1.05 ($\pm$ 0.78)	0.91 ($\pm$ 0.52)	0.93 ($\pm$ 0.46)	0.98 ($\pm$ 0.67)
-Median (Min,Max)	0.89 (0.00,9.73)	0.82 (0.00,4.57)	0.88 (0.05,3.89)	0.86 (0.00,9.73)

Table: Consumer Behavior by Cluster