Panel Data Models and Diff-In-Diff Methods

Zhiyuan Chen

Empirical Methods
Renmin Business School

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Outline

- Panel Data Models
  - Panel data
  - Random Effects vs. Fixed Effects
  - Fixed Effects vs. First Difference
- Difference-In-Differences Models
  - Two-By-Two Case
  - Dynamic Treatment Effects
  - Common Trend Assumption & Sensitivity Tests
  - Identification Tests
  - Inference

Panel Data

- Now we have data for N units (people, products, firms, counties, cities, provinces, countries ...)
- For each unit we have T_i (≥ 1) observations
  - T_i typically refers to time periods
  - Could be products of a firm, students in a classroom, counties in a province

We assume that:
  - N is large; consistency exists as N grows
  - T_i is small; T_i stays constant as N grows

Now let's consider the regression model:

$$Y_{it} = X_{it}'\beta + u_{it}$$

- *Assumption 1*: assume independence **across individuals** but **not across time**
- *Assumption 2:* $\mathbf{E}\left(X_{it}u_{it}\right) = 0$

Consistency:

$$\begin{aligned}\hat{\beta} &= \beta + \left(\frac{\sum_{i=1}^{N}\sum_{t=1}^{T_i} X_{it}X_{it}'}{\sum_{i=1}^{N} T_i}\right)^{-1}\left(\frac{\sum_{i=1}^{N}\sum_{t=1}^{T_i} X_{it}u_{it}}{\sum_{i=1}^{N} T_i}\right) \\ &\rightarrow_p \beta\end{aligned}$$

Serial Correlation

- The assumption of NO serial correlation is problematic so the asymptotic variance from before is not right
- Error terms are uncorrelated across individuals, but not within individuals
- Formally speaking, we assume that:

$$\mathbf{E}\left(u_{it}u_{jt}\right) = 0, \forall\, i \neq j$$
$$\mathbf{E}\left(u_{it}X_{it}\right) = 0$$

- However, the assumption of OLS is not satisfied because:

$$\mathbf{E}\left(u_{it}u_{is}\right) = 0$$

  is a CRAZY assumption!
- Ignoring the serial correlation tends to **underestimate** the size of standard errors

Clustered Standard Errors

- Recall that

$$\hat{\beta} - \beta = \left(\sum_i^N \sum_t^{T_i} X_{it} X_{it}' \right)^{-1} \sum_i^N \sum_t^{T_i} X_{it} u_{it}$$

  - Define $\eta_i \equiv \sum_{t=1}^{T_i} X_{it} u_{it}$, then η_i is iid
  - $var\left(\eta_i\right) = V_\eta$

- Then we get

$$\sqrt{N}\left(\hat{\beta} - \beta\right) = \left(\frac{1}{N} \sum_i \sum_t X_{it} X_{it}' \right)^{-1} \left(\frac{1}{\sqrt{N}} \sum_{i=1}^N \eta_i \right)$$

- Using the Central Limit Theorem we know

$$\sqrt{N}\left(\hat{\beta} - \beta\right) \sim \mathcal{N}\left(0, \left[\mathbf{E}\left(\sum_{t=1}^{T_i} X_{it} X_{it}'\right)^{-1}\right] V_\eta \left[\mathbf{E}\left(\sum_{t=1}^{T_i} X_{it} X_{it}'\right)\right]^{-1}\right)$$

We can approximate the variance of $\hat{\beta}$ as

$$Var\left(\hat{\beta}\right) \approx \left(\sum_i \sum_t X_{it} X'_{it}\right)^{-1} \left[\sum_i \left(\sum_t X_{it} \hat{u}_{it}\right) \left(\sum_t X'_{it} \hat{u}_{it}\right)\right] \left(\sum_i \sum_t X_{it} X'_{it}\right)^{-1}$$

- This is a generalization of the heteroskedastic robust standard errors
- We are allowing $[X_{i1} u_{i1}, X_{i2} u_{i2}, \cdots, X_{iT_i} u_{iT_i}]$ to have an arbitrary variance-covariance matrix

In STATA, this is done by coding `reg y x, cluster(i)`

- i is the id of the group in which the errors are serially correlated

Two-way Cluster (Cameron et al., 2011)

- Consider situations where each observation may belong to more than one "dimension" of groups.
  - E.g., firms belong to city group and industry group
- For errors belong to the same group, they can have an arbitrary correlation
- For two groups G and H. It turns out the variance $\hat{V}(\hat{\beta})$ can be calculated as

$$\hat{V}(\hat{\beta}) = \hat{V}^{G}(\hat{\beta}) + \hat{V}^{H}(\hat{\beta}) - \hat{V}^{G \cap H}(\hat{\beta})$$

- This can be computed by:
  1. Clustering on group G;
  2. Clustering on group H;
  3. Clustering on $G \cap H$

Random Effects vs. Fixed Effects

- Panel data enable us to take care of the idiosyncratic component in the error term
- Write the linear model as

$$Y_{it} = X_{it}'\beta + \theta_i + \varepsilon_{it}$$

  - In both of the models, we assume that

$$\mathbf{E}\left(\varepsilon_{it} X_{it}\right) = 0$$

  - In the Random Effects (RE) model, we assume that

$$\mathbf{E}\left(\theta_i X_{it}\right) = 0$$

  - In the Fixed Effects (FE) model, we do not assume anything about the relationship between θ_i and X_i! θ_i is an idiosyncratic constant.

Consistent Estimators for FE models

- Include individual dummies and run the regression:

$$Y_{it} = X_{it}\beta + D_{it}'\theta + \varepsilon_{it}$$

where $D_{it} = \left[D_{it}^{(j)}\right]$, $D_{it}^{(j)} = 1$ if $i = j$ and zero otherwise
  - Conceptually this is a different model, but technically it delivers consistent estimates for β
- **Standard FE (Mean-Differencing)** model:

$$(Y_{it} - \bar{Y}_i) = (X_{it} - \bar{X}_i)'\beta + (\varepsilon_{it} - \bar{\varepsilon}_i)$$

where $\bar{Z}_i \equiv \frac{1}{T_i}\sum_{t=1}^{T_i} Z_{it}$
- **First-Differencing (FD)** model:

$$Y_{it} - Y_{it-1} = (X_{it} - X_{it-1})'\beta + \varepsilon_{it} - \varepsilon_{it-1}$$

  - With 2 periods, this is equivalent to the standard FE model (verify it by yourself)

Fixed Effects vs. First Differencing

More generally, we consider the model

$$Y_{it} = \beta \tau_{it} + \theta_i + \varepsilon_{it}$$

Assume that $T_i = T$ for everyone, for everyone the only regressor τ_{it} is given by

$$\tau_{it} = \begin{cases} 0 & t \leq t_0 \\ 1 & t > t_0 \end{cases}$$

- τ_{it} can represent some macro-level program (trade liberalization, 5-year plan, expansion of college enrollment...) begins at $t_0 + 1$
- The FE and FD estimators are:

$$FE : \hat{\beta}_{FE} = \frac{\sum_{i=1}^{N} \sum_{t=t_0+1}^{T} Y_{it}}{N\left(T - t_0\right)} - \frac{\sum_{i=1}^{N} \sum_{t=1}^{t_0} Y_{it}}{N t_0}$$

$$FD : \hat{\beta}_{FD} = \frac{\sum_{i=1}^{N} \left(Y_{it_0+1} - Y_{it_0}\right)}{N}$$

Fixed Effects vs. Pooled Regression

The fixed effects estimator is NOT always better than pooled OLS regression

- The sample variance of the data is:

$$
\begin{aligned}
ss\left(X_{it}\right) &= \sum_i \sum_t \left(X_{it} - \bar{X}\right)^2 \\
&= \underbrace{\sum_i \sum_t \left(X_{it} - \bar{X}_i\right)^2}_{within\, variance} + \underbrace{\sum_i T_i \left(\bar{X}_i - \bar{X}\right)^2}_{between\, variance}
\end{aligned}
$$

  FE estimator only uses the within the variance of X_i:

1. It is inefficient. Standard errors are very large when X_{it} does not change
2. It can even lead to a worse bias:

$$
\begin{aligned}
\hat{\beta}_{POLS} &= \beta + \frac{cov\left(X_{it}, \theta_i + \varepsilon_{it}\right)}{var\left(X_{it}\right)} \\
\hat{\beta}_{FE} &= \beta + \frac{cov\left(X_{it} - \bar{X}_i, \varepsilon_{it} - \bar{\varepsilon}_i\right)}{var\left(X_{it} - \bar{X}_i\right)}
\end{aligned}
$$

Attenuation Bias of FE Estimates

- The year-to-year changes in explanatory variables may be mostly noise, especially when X_{it} varies a little over time, causing attenuation bias from measurement error
- More measurement error in the differenced regressors than in leveled variables
- **Attenuation Bias**: Measurement errors bias the estimates towards zero

$$\textit{True model: } y_i = \beta x_i + \varepsilon_i, \quad \mathbf{E}(x_i \varepsilon_i) = 0$$

$$\textit{Measurement error: } \tilde{x}_i = x_i + u_i$$

$$\textit{Orthogonality condition: } \mathbf{E}(u_i) = 0; \mathbf{E}(x_i u_i) = 0; \mathbf{E}(u_i \varepsilon_i) = 0$$

$$\Rightarrow \quad \hat{\beta}^{bias} = \frac{cov(\tilde{x}_i, y_i)}{var(\tilde{x}_i)} = \frac{cov(x_i + u_i, \beta x_i + \varepsilon_i)}{var(x_i + u_i)} = \frac{var(x_i)}{var(x_i) + var(u_i)} \beta$$

  - The estimate of β moves towards zero when $var(u_i)$ is relatively larger than $var(x_i)$.

Example: Almond, Chay, and Lee (QJE, 2005)

- Their goal is to estimate the effects of birth weight on health:

$$h_{ij} = \alpha + \beta bw_{ij} + X_i'\gamma + a_i + \varepsilon_{ij}$$

where

  - h_{ij}: health of newborn j of mother i
  - bw_{ij}: birth weight
  - a_i: mother specific effect

- The pooled OLS regression of h_{ij} on bw_{ij} gives us

$$\hat{\beta}_{POLS} = \beta + \frac{\operatorname{cov}(bw_{ij}, X_i'\gamma)}{\operatorname{var}(bw_{ij})} + \frac{\operatorname{cov}(bw_{ij}, a_i)}{\operatorname{var}(bw_{ij})}$$

- Their clever solution is to **use twins**:
  - Twins share the same mother, so a_i effectively controls for race, age, education, family background...
  - Estimate the model as

$$\Delta h_{ij} = \beta \Delta bw_{ij} + \Delta \varepsilon_{ij}$$

    where they assume that $\operatorname{cov}(\Delta bw_{ij}, \Delta \varepsilon_{ij}) = 0$
- Attenuation bias caused by measurement errors?

Difference-In-Differences

Simple Before-After Policy Evaluation: Two-by-One Case

- Data on individuals right before and after the policy intervention: *Pre* and *Post*
- Two years dated 0 and 1 and that the policy is enacted in between
- We can simply identify the effect as:

$$\hat{\alpha} = \bar{Y}_1 - \bar{Y}_0$$

We could justify this using a FE model:

$$Y_{it} = \alpha_0 + \alpha \tau_{it} + \theta_i + \varepsilon_{it}$$

where

$$\tau_{it} = \begin{cases} 0 & t = 0 \\ 1 & t = 1 \end{cases}$$

We assume that $\mathbf{E}(\tau_{it}\varepsilon_{it}) = 0$ but no particularly assumption on θ_i

In the two-period case, FE model is equivalent to FD model, which is

$$Y_{i1} - Y_{i0} = \alpha + u_{i1} - u_{i0}$$

The estimator for the policy effect is

$$\hat{\alpha} = \bar{Y}_{i1} - \bar{Y}_{i0}$$

- We assume no other changes in time between and attribute whatever that is to the program
- Add time dummies into the model the treatment effect is not separated from the policy's impact

After adding time dummy variables, the model becomes

$$Y_{it} = \alpha_0 + \alpha \tau_{it} + \delta t + \theta_i + \varepsilon_{it}$$

Then the difference estimator delivers

$$\begin{aligned} \mathbf{E}\left(Y_{i1} - Y_{i0}\right) &= \mathbf{E}\left[\left(\alpha_0 + \alpha + \delta + \theta_i + \varepsilon_{i1}\right) - \left(\alpha_0 + \theta_i + \varepsilon_{i0}\right)\right] \\ &= \alpha + \color{red}{\delta} \neq \alpha \end{aligned}$$

Using the first-order difference, we generally cannot separate the time trend (δ) from the treatment effects (α)

- The Diff-in-Diff estimator is designed to solve this problem

Difference-In-Differences: The Two-by-Two Case

Now we have Two periods for Two groups:

1. People who are affected by the policy changes (*treated*): Y_{it}^{1}
2. People who are not affected by the policy changes (*controls*): Y_{it}^{0}

We can think:

1. Using the treated to pick up the time changes and policy effects:
$$\hat{\alpha} + \hat{\delta} = \bar{Y}_{i1}^{1} - \bar{Y}_{i0}^{1}$$
2. Under the **Common Trend Assumption** controls pick up the time changes:
$$\hat{\delta} = \bar{Y}_{i1}^{0} - \bar{Y}_{i0}^{0}$$

We can then estimate the policy effect as a difference in difference

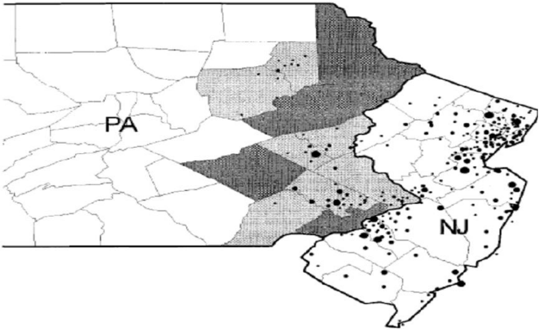
$$\hat{\alpha} = \left(\bar{Y}_{1}^{1} - \bar{Y}_{0}^{1}\right) - \left(\bar{Y}_{1}^{0} - \bar{Y}_{0}^{0}\right)$$

Example of Two-by-Two DID

Card and Krueger (1994)

- In 1992, New Jersey increased its minimum wage substantially while Pennsylvania kept its minimum wage constant.
- Card and Krueger compared fast-food restaurants in New Jersey ("treated group") with similar restaurants in nearby parts of Pennsylvania ("control group").

Location of Restaurants (Card and Krueger 2000)



Estimation using STATA

- data source: `http://dss.princeton.edu/training/Panel101.dta`
- Generate variables indicating treatment and time:

```
gen time=(year>=1994)&!missing(year)
gen treated=(countray>4)&!missing(country)
gen did=time*treated
```

- Regression: `reg y time treated did, r`

- An alternative is to use the hashtag command:
  `reg y time##treated, r`
- Or use the `diff` program in STATA:

```
ssc install diff
diff y, t(treated) p(time)
```

More General Formulation of DID Estimator

Formally, we can write the DGP (data generating process) for the DID estimator as

$$Y_{it} = \alpha_0 + \alpha \tau_{it}^{g_i} + \delta t + \theta_i + \varepsilon_{it}$$

where

$$\tau_{it}^{g_i} = \begin{cases} 1 & t = 1, g_i = 1 \\ 0 & otherwise \end{cases}$$

$\tau_{it}^{g_i}$ is usually written as $g_i \times t$

- Now we run a fixed effect regression and get a consistent estimate of the treatment effects α

Recall that the FE estimator for two-period data is equivalent to the FD estimator:

$$
\begin{aligned}
\hat{\alpha} &= \frac{\sum_{i=1}^{N}\left[\left(\tau_{i1}^{g_i}-\tau_{i0}^{g_i}\right)-\overline{\left(\tau_{i1}^{g_i}-\tau_{i0}^{g_i}\right)}\right]\left(Y_{i1}-Y_{i0}\right)}{\sum_{i=1}^{N}\left[\left(\tau_{i1}^{g_i}-\tau_{i0}^{g_i}\right)-\overline{\left(\tau_{i1}^{g_i}-\tau_{i0}^{g_i}\right)}\right]^2} \\
&= \left(\bar{Y}_1^1-\bar{Y}_0^1\right)-\left(\bar{Y}_1^0-\bar{Y}_0^0\right)
\end{aligned}
$$

- Notice that

$$
\begin{aligned}
\overline{\left(\tau_{i1}^{g_i}-\tau_{i0}^{g_i}\right)} &= \frac{1}{N_1+N_0}\sum_i\left(\tau_{i1}^{g_i}-\tau_{i0}^{g_i}\right) \\
&= \frac{1}{N_1+N_0}\left[\sum_{\{i:\,g_i=1\}}\left(\tau_{i1}^{1}-\tau_{i0}^{1}\right)+\sum_{\{i:\,g_i=0\}}\left(\tau_{i1}^{0}-\tau_{i0}^{0}\right)\right] \\
&= \frac{N_1}{N_1+N_0}
\end{aligned}
$$

"In principle, you don't need panel data to implement DID regression; repeated cross-section data are fine!"

- In general, we can write the DID regression as

$$Y_{t_i} = \alpha_0 + \alpha \tau_{t_i}(g_i) + \delta t_i + \gamma g_i + \varepsilon_i$$

  - where g_i is the group indicator of person i and t_i is the time period in which i exists in the data
  - $\tau_{t_i}(g_i) = g_i \times t_i$

- We have 4 categories of people: (before, treated), (before, controls), (after, treated), (after, controls)
- We end up with having 4 groups of *moment conditions*:

$$\begin{aligned}
\mathbf{E}(\varepsilon_i) &= 0 \\
\mathbf{E}(\tau_{t_i}(g_i)\varepsilon_i) &= 0 \\
\mathbf{E}(t_i\varepsilon_i) &= 0 \\
\mathbf{E}(g_i\varepsilon_i) &= 0
\end{aligned}$$

Using

$$Y_i = \hat{\alpha}_0 + \hat{\alpha}\tau_{t_i}(g_i) + \hat{\delta}t_i + \hat{\gamma}g_i + \hat{\varepsilon}_i$$

We can rewrite the *sample analog* of the moment conditions as

$$\begin{aligned}
\bar{Y}_0^1 &= \hat{\alpha}_0 + \hat{\gamma} \\
\bar{Y}_1^1 &= \hat{\alpha}_0 + \hat{\alpha} + \hat{\delta} + \hat{\gamma} \\
\bar{Y}_0^0 &= \hat{\alpha}_0 \\
Y_1^0 &= \hat{\alpha}_0 + \hat{\delta}
\end{aligned}$$

We can solve for the parameters as

$$\begin{aligned}
\hat{\alpha}_0 &= \bar{Y}_0^0 \\
\hat{\gamma} &= \bar{Y}_0^1 - \bar{Y}_0^0 \\
\hat{\delta} &= \bar{Y}_0^1 - \bar{Y}_0^0 \\
\hat{\alpha} &= \left(Y_1^1 - \bar{Y}_0^1\right) - \left(\bar{Y}_1^0 - \bar{Y}_0^0\right)
\end{aligned}$$

More generally, we can add more control variables and specify the DID model as

$$Y_i = \alpha \tau_{t_i}(g_i) + \mathbf{X}_{it}'\beta + \delta_{t_i} + \theta_{g_i} + \varepsilon_i$$

Question: What is $\mathbf{X}_{it}$ actually picking up?

This setting is simple yet powerful! There are many papers that do this basic stuff.

- Eissa and Liebman (QJE, 1996): Estimate the effect of the earned income tax credit on the labor supply of women
- Dohahue and Levitt (QJE, 2001): Impact of legalized abortion on crime

Multiple Periods: Event Studies

- The treatment effects could be dynamic, with short-run effects differing from long-run effects
- We can easily extend the baseline model to allow for this:

$$Y_i = \beta_0 + \sum_{j=0}^{J} \alpha_j \tau_{t_i - j}(g_i) + \delta_{g_i} + \gamma_{t_i} + \varepsilon_i$$

where

$$\tau_t(g_i) = \begin{cases} 1 & g_i = 1 \text{ and policy started in year } t \\ 0 & \text{otherwise} \end{cases}$$

Common Trend Assumption

- Recall that the model we specified for DID is:

$$Y_i = \beta_0 + \alpha \tau_{t_i}(g_i) + \delta t_i + \gamma g_i + \varepsilon_i$$

The DID estimator is

$$\hat{\alpha}_{DID} = \alpha + \left(\bar{\varepsilon}_1^1 - \bar{\varepsilon}_0^1\right) - \left(\bar{\varepsilon}_1^0 - \bar{\varepsilon}_0^0\right)$$

To obtain a consistent estimator, we require that

$$\mathbf{E}\left[\left(\bar{\varepsilon}_1^1 - \bar{\varepsilon}_0^1\right) - \left(\bar{\varepsilon}_1^0 - \bar{\varepsilon}_0^0\right)\right] = 0$$

- The treated units can have different *levels* of the error term, but the *change* in the error term must be random
- Two approaches to validate the common trend assumption: **placebo policies** and **add group-specify time trends**

Placebo Policies

- *A popular strategy for robustness check*: if a policy was enacted in say 2010 you could pretend it was enacted in 2005 in the same place and then only use data through 2009
- The easiest (and most common) is in the Event framework: include leads as well as lags in the model (Bertrand, Duflo, Mullainathan, 2004, QJE)
- To implement it you can run a regression like:

$$Y_i = \beta_0 + \sum_{j=-\tilde{J}, j \neq -1}^{J} \alpha_j \tau_{t_i - j}(g_i) + \delta_{g_i} + \rho_{t_i} + \varepsilon_i$$

where $t_i = -\tilde{J}, \cdots, J$ and the period of enactment to be zero

  - $\tau^1_{t_i - j} = 1$ whenever $t_i - j = 0$
  - Note $\sum_{j=-\tilde{J}}^{J} \tau_{t_i - j}(g_i) = \delta_{g_i}$, so we drop one period to avoid perfect co-linearity

If we normalize $\alpha_{-1} = 0$, α_{-2} is estimated as

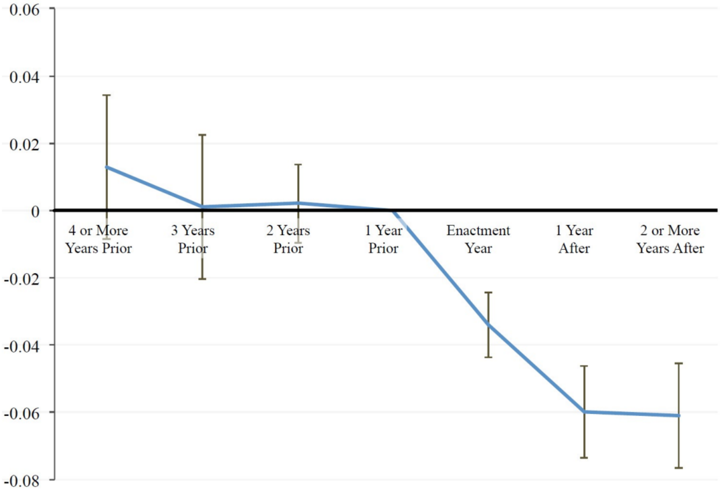
$$\hat{\alpha}_{-2} = \left(\bar{Y}^1_{-2} - \bar{Y}^1_{-1}\right) - \left(\bar{Y}^0_{-2} - \bar{Y}^0_{-1}\right)$$

where

$$\begin{aligned}
\bar{Y}^1_{-2} &= \hat{\beta}_0 + \hat{\alpha}_{-2} + \hat{\delta} + \hat{\rho}_{-2} \\
\bar{Y}^1_{-1} &= \hat{\beta}_0 + \hat{\delta} + \hat{\rho}_{-1} \\
\bar{Y}^0_{-2} &= \hat{\beta}_0 + \hat{\rho}_{-2} \\
\bar{Y}^0_{-1} &= \hat{\beta}_0 + \hat{\rho}_{-1}
\end{aligned}$$

- $\hat{\alpha}_{-2}$ should be zero under the common trend assumption
- $\hat{\alpha}_{-j} (j \geq 2)$ should also be zero under the common trend assumption

Figure 1: Typical event studies for the placebo policies



Group-Specific Time Trends

- One might be worried that units that are trending up or trending down are more likely to change policy
- One can include group×time dummy variables in the model to fix this problem
- Now let's consider the three-period case where the policy happens between period 1 and 2, the model becomes

$$Y_i = \beta_0 + \alpha \tau_{t_i}(g_i) + \delta_0 t_i \times (1 - g_i) + \delta_1 t_i \times g_i + \delta_2 \mathbb{I}(t_i = 2) + \gamma g_i + \varepsilon_i$$

- We can write the estimator of α as a Triple Difference (DDD):

$$\begin{aligned}\hat{\alpha}_{DDD} &= \left(\bar{Y}_2^1 - \bar{Y}_1^1\right) - \left(\bar{Y}_2^0 - \bar{Y}_1^0\right) - \left[\left(\bar{Y}_1^1 - \bar{Y}_0^1\right) - \left(\bar{Y}_1^0 - \bar{Y}_0^0\right)\right] \\ &\approx (\alpha + \delta_1 + \delta_2) - (\delta_0 + \delta_2) - (\delta_1 - \delta_0) \\ &= \alpha\end{aligned}$$

If we do not add the group-specific time trends, the error term is a composite:

$$\tilde{\varepsilon}_i = \varepsilon_i + \delta_0 t_i \times (1 - g_i) + \delta_1 t_i \times g_i - \delta t_i$$

We go back to the common trend assumption and get

$$\begin{aligned}
\mathbf{E}\left(\left(\bar{\tilde{\varepsilon}}_1^1 - \bar{\tilde{\varepsilon}}_1^0\right) - \left(\bar{\tilde{\varepsilon}}_1^0 - \bar{\tilde{\varepsilon}}_0^0\right)\right) &= \mathbf{E}\left(\left(\bar{\varepsilon}_1^1 - \bar{\varepsilon}_1^0\right) - \left(\bar{\varepsilon}_1^0 - \bar{\varepsilon}_0^0\right)\right) \\
&\quad + (\delta_1 - \delta) - (\delta_0 - \delta) \\
&= \mathbf{E}\left(\left(\bar{\varepsilon}_1^1 - \bar{\varepsilon}_1^0\right) - \left(\bar{\varepsilon}_1^0 - \bar{\varepsilon}_0^0\right)\right) + \delta_1 - \delta_0 \\
&\approx \delta_1 - \delta_0 \neq 0
\end{aligned}$$

Thus the common trend assumption is likely to fail!

Inference: Get the Right Standard Errors

- In applications, we often have individual data (people, firms...) and the policy is enacted at more aggregated level (cities, provinces)
- It seems that we have more data than we need

Consider the individual-level model

$$Y_i = \alpha \tau_{t_i}(g_i) + Z_i' \delta + X_{g_i t_i}' \beta + \theta_{g_i} + \gamma_{t_i} + u_i$$

One could aggregate the data by group and year:

$$\bar{Y}_{gt} = \alpha \bar{\tau}_{gt} + Z_{gt}' \delta + X_{gt}' \beta + \theta_g + \gamma_t + \bar{u}_{gt}$$

The second regression also gives consistent estimates for the treatment effects

- HOWEVER, two regressions yield different standard errors: which one should we use?

- The error term for the individual level model is

$$u_i = \eta_{g_i t_i} + \varepsilon_i$$

  - The i.i.d assumption for error term u_i is violated is $\eta_{g_i t_i}$ exists
  - Standard solution: *Cluster the standard error by group$\times$year* to allow for arbitrary correlation within a group
- Bertrand, Duflo, and Mullainathan (QJE, 2004):
  - If there is serial correlation in η_{gt}, cluster by group$\times$year is problematic
- *Solutions*:
  - **# of groups is large**: block bootstrap by state works well
  - **Moderate # of states**: asymptotic approximation of the variance-covariance matrix
  - **Small # of states**: collapse the data into a "pre"- and "post"-period and account for the effective sample size
- A practioner's guide is offered by Cameron and Miller (2015, JHR)