Advanced DiD Mixtape Workshop
Multiple Periods & Staggered Treatment Timing

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Staggered Timing

- Remember that in the canonical DiD model we had:
  - Two periods and a common treatment date
  - Identification from parallel trends and no anticipation
  - A large number of clusters for inference
- A very active recent literature has focused on relaxing the first assumption: **what if there are multiple periods and units adopt treatment at different times?**
- This literature typically maintains the remaining ingredients: parallel trends and many clusters

Overview of Staggered Timing Literature

1. Negative results: TWFE OLS doesn't give us what we want with treatment effect heterogeneity
2. New estimators: perform better under treatment effect heterogeneity

Staggered timing set-up

- Suppose units adopt a binary treatment at different dates $G_i \in \{1, ..., T\} \cup \infty$ (where $G_i = \infty$ means "never-treated")
  - Literature is now starting to consider cases with continuous treatment & treatments that turn on/off – that lit is still developing (see Section 3.4 of review paper)

- Potential outcomes $Y_{it}(g)$ – depend on time and time you were first-treated

Extending the Identifying Assumptions

- The key identifying assumptions from the canonical model are extended in the natural way
- **Parallel trends:** Intuitively, says that if treatment hadn't happened, all "adoption cohorts" would have parallel average outcomes in all periods

$$E[Y_{it}(\infty) - Y_{i,t-1}(\infty)|G_i = g] = E[Y_{it}(\infty) - Y_{i,t-1}(\infty)|G_i = g'] \text{ for all } g, t, t'$$

  Note: can impose slightly weaker versions (e.g. only require PT post-treatment)

- **No anticipation:** Intuitively, says that treatment has no impact before it is implemented

$$Y_{it}(g) = Y_{it}(\infty) \text{ for all } t < g$$

Negative results

- Suppose we again run the regression

$$Y_{it} = \alpha_i + \phi_t + D_{it}\beta + \epsilon_{it},$$

  where $D_{it} = 1[t \geq G_i]$ is a treatment indicator

- And suppose we're willing to assume no anticipation and parallel trends across all adoption cohorts as described above

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- Good news: if treatment effects are constant across time and units, $Y_{it}(g) - Y_{it}(\infty) \equiv \tau$, then $\beta = \tau$

- Bad news: if treatment effects are not constant across time/units, then β may put negative weights on treatment effects for some units and time periods
  - E.g., if treatment effect depends on time since treatment, $Y_{it}(t-r) - Y_{it}(\infty) = \tau_r$, then some τ_rs may get negative weight

Where do these negative results come from?

- The intuition for these negative results is that the TWFE OLS specification combines two sources of comparisons:
  1. **Clean comparisons:** DiD's between treated and not-yet-treated units
  2. **Forbidden comparisons:** DiD's between two sets of already-treated units (who began treatment at different times)
- These forbidden comparisons can lead to negative weights: the "control group" is already treated, so we run into problems if their treatment effects change over time

Some intuition for forbidden comparisons

- Consider the two period model, except suppose now that our two groups are **always-treated** units (treated in both periods) and **switchers** (treated only in period 2)
- The TWFE OLS specification

$$Y_{it} = \alpha_i + \phi_t + D_{it}\beta + \epsilon_{it},$$

is still identified, with

$$\hat{\beta} = \underbrace{\left(\bar{Y}_{Switchers,2} - \bar{Y}_{Switchers,1}\right)}_{\text{Change for switchers}} - \underbrace{\left(\bar{Y}_{AT,2} - \bar{Y}_{AT,1}\right)}_{\text{Change for always treated}}$$

- Problem: if the treatment effect for the always-treated grows over time, that will enter $\hat{\beta}$ negatively!
- With multiple periods/staggered timing, $\hat{\beta}$ includes both this type of comparisons and clean comparisons

Not just negative but weird...

- The literature has placed a lot of emphasis on the fact that some treatment effects may get negative weights
- But even if the weights are non-negative, they might not give us the most intuitive parameter
- For example, suppose each unit i has treatment effect τ_i in every period if they are treated (no dynamics). Then β gives a weighted average of the τ_i where the weights are largest for units treated closest to the middle of the panel
- It is not obvious that these weights are relevant for policy, even if they are all non-negative!

Issues with dynamic TWFE

- Sun and Abraham (2021) show that similar issues arise with dynamic TWFE specifications:

$$Y_{i,t} = \alpha_i + \lambda_t + \sum_{k \neq 0} \gamma_k D^k_{i,t} + \varepsilon_{i,t},$$

where $D^k_{i,t} = 1\{t - G_i = k\}$ are "event-time" dummies.

- Like for the static spec, γ_k may put negative weight on treatment effects after k periods for some units
- SA also show that γ_k may be "contaminated" by treatment effects at lags $k' \neq k$

Dynamic TWFE - Continued

- The results in SA suggest that interpreting the $\hat{\gamma}_k$ for $k = 1, 2, ...$ as estimates of the dynamic effects of treatment may be misleading
- These results also imply that pre-trends tests of the γ_k for $k < 0$ may be misleading – could be non-zero even if parallel trends holds, since they may be "contaminated" by post-treatment effects!

Dynamic TWFE - Continued

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- The issues discussed in SA arise if dynamic path of treatment effects is heterogeneous across adoption cohorts
  - Biases may be less severe than for "static" specs if dynamic patterns are similar across cohorts

New estimators (and estimands!)

- Several new (closely-related) estimators have been proposed to try to address these negative weighting issues
- The key components of all of these are:
  1. Be precise about the target parameter (estimand) – i.e., how do we want to aggregate treatment effects across time/units
  2. Estimate the target parameter using only "clean-comparisons"

Example – Callaway and Sant'Anna (2020)

- Define $ATT(g,t)$ to be ATT in period t for units first treated at period g,

$$ATT(g,t) = E[Y_{it}(g) - Y_{it}(\infty)|G_i = g]$$

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$$ATT(g,t) = E[Y_{it}(g) - Y_{it}(\infty)|G_i = g]$$

- Under PT and No Anticipation, $ATT(g,t)$ is identified as

$$ATT(g,t) = \underbrace{E[Y_{it} - Y_{i,g-1}|G_i = g]}_{\text{Change for cohort g}} - \underbrace{E[Y_{it} - Y_{i,g-1}|G_i = \infty]}_{\text{Change for never-treated units}}$$

- Why?

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- Why? This is a two-group two-period comparison, so the argument is the same as in the canonical case!

Proof of Identification Argument

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- Add and subtract $E[Y_{it}(\infty)|G_i = g]$ to obtain:

$$E[Y_{it}(g) - Y_{it}(\infty)|G_i = g] +$$
$$[E[Y_{it}(\infty) - Y_{i,g-1}(\infty)|G_i = g] - E[Y_{ig}(\infty) - Y_{i,g-1}(\infty)|G_i = \infty]]$$

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- Kill the last term using PT to get $E[Y_{it}(g) - Y_{it}(\infty)|G_i = g] = ATT(g,t)$

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- We can then estimate this with sample analogs:

$$\widehat{ATT}(g,t) = \underbrace{\widehat{E}[Y_{it} - Y_{i,g-1}|G_i = g]}_{\text{Sample change for cohort g}} - \underbrace{\widehat{E}[Y_{it} - Y_{i,g-1}|G_i = \infty]}_{\text{Sample change for never-treated}}$$

where $\hat{E}$ denotes sample means.

Aggregation schemes

- If have a large number of observations and relatively few groups/periods, can report $\widehat{ATT}(g,t)$'s directly.
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- One of the most useful is to report event-study parameters which aggregate $\widehat{ATT}(g,t)$'s at a particular lag since treatment
  - E.g. $\hat{\theta}_k = \sum_g \widehat{ATT}(g, t+k)$ aggregates effects for cohorts in the kth period after treatment
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  - Can also construct for $k < 0$ to estimate "pre-trends"
- C&S discuss other sensible aggregations too – e.g., if interested in whether treatment effects differ across good/bad economies, may want to "calendar averages" that pool the $\widehat{ATT}(t,g)$ for the same year

Comparisons of new estimators

Several other estimators have been proposed based on related ideas:

- Callaway and Sant'Anna also propose an analogous estimator using *not-yet-treated* rather than never-treated units.
- Sun and Abraham (2021) propose a similar estimator but with different comparisons groups (e.g. using last-to-be treated rather than not-yet-treated)
- Borusyak et al. (2021), Wooldridge (2021), Gardner (2021) propose "imputation" estimators that estimate the counterfactual $\hat{Y}_{it}(0)$ using a TWFE model that is fit using only pre-treatment data
  - Main difference from C&S is that this uses more pre-treatment periods, not just period $g-1$
  - This can sometimes be more efficient (if outcome not too serially correlated), but also relies on a stronger PT assumption that may be more susceptible to bias
- Roth and Sant'Anna (2021) show that you can get even more precise estimates if you're willing to assume treatment timing is "as good as random"

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- The most important thing is to be precise about who you want the comparison group to be and to choose a method that only uses these "clean comparisons"
- In my experience, the difference between the new estimators is typically not that large – can report multiple new methods for robustness (to make your referees happy!)

Borusyak, Kirill, Xavier Jaravel, and Jann Spiess, "Revisiting Event Study Designs: Robust and Efficient Estimation," *arXiv:2108.12419 [econ]*, 2021.

Gardner, John, "Two-stage differences in differences," *Working Paper*, 2021.

Roth, Jonathan and Pedro H. C. Sant'Anna, "Efficient Estimation for Staggered Rollout Designs," *arXiv:2102.01291 [econ, math, stat]*, 2021.

Sun, Liyang and Sarah Abraham, "Estimating dynamic treatment effects in event studies with heterogeneous treatment effects," *Journal of Econometrics*, 2021, *225* (2), 175–199.

Wooldridge, Jeffrey M, "Two-Way Fixed Effects, the Two-Way Mundlak Regression, and Difference-in-Differences Estimators," *Working Paper*, 2021, pp. 1–89.