DiD for Big Data in R

Theoretical Background

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Notation and Identification (1/4)

Notation and Definition of Treatment:

- i: unit of observation.
  $\rightarrow$ We will often say "individual".
- t: calendar time. Sample time frame is $\mathcal{T}$.
  $\rightarrow$ We will often say "year".
- $D_{i,t}$: indicator for currently receiving treatment.
  $\rightarrow$ Permanent treatment: $D_{i,t} = 1 \implies D_{i,t+1} = 1,\ t \in \mathcal{T}$.
- $G_i \equiv \min\{t : D_{i,t} = 1\}$: time that i first receives treatment.
  $\rightarrow$ We will often say "cohort" or "onset time".
  $\rightarrow$ If i never receives treatment, we can write $G_i = \infty$.
  $\rightarrow$ Note: $D_{i,t} \equiv 1\{t \geq G_i\}$.
- $E_{i,t} \equiv (t - G_i)$: time since first treatment.
  $\rightarrow$ We will often say "event time".
  $\rightarrow$ Sometimes we will consider fixing an event time e years after treatment versus b years before treatment.
- Potential outcomes: Let $Y_{i,t}(g)$ denote the outcome that is experienced if treated at g.
- Observed outcome:
  $Y_{i,t} = Y_{i,t}(\infty) + \sum_g 1\{G_i = g\}(Y_{i,t}(g) - Y_{i,t}(\infty))$.

Notation and Identification (2/4)

Goal: Identify ATT at an event time. We assume throughout that the goal is to identify the average treatment effect on the treated (ATT) at event time e. Formally, we seek to identify,

$$\mathrm{ATT}_e \equiv \mathbb{E}[Y_{i,t}(g) - Y_{i,t}(\infty) | E_{i,t} = e]$$

The identification challenge is that $\mathbb{E}[Y_{i,t}(\infty) | E_{i,t} = e]$ is a counterfactual object – it is the average outcome that *would have been experienced* by those receiving treatment for e years *if they had not received treatment*.

Decomposition into cohort-specific ATTs. Define,

$$\mathrm{ATT}_{g,e} \equiv \mathbb{E}[Y_{i,g+e}(g) - Y_{i,g+e}(\infty) | G_i = g]$$
$$\omega_{g,e} \equiv \mathbb{E}[G_i = g | E_{i,t} = e]$$

where the cohort shares that have been treated at each event time ($\omega_{g,e}$) are observed. Rearranging terms,

$$\mathrm{ATT}_e = \sum_g \omega_{g,e} \mathrm{ATT}_{g,e}$$

Thus, given e, it is sufficient to identify $\mathrm{ATT}_{g,e}$, $\forall g$ s.t. $\omega_{g,e} > 0$.

Notation and Identification (3/4)

Control Group: Define a control group membership indicator $\mathcal{C}_{g,e}(G_i)$. At a minimum, $\mathcal{C}_{g,e}(G_i){=}1 \implies G_i > (g+e)$. We may further restrict $\mathcal{C}$ based on context, e.g., some consider the never-treated control group, $\mathcal{C}_{g,e}(G_i){=}1\{G_i{=}\infty\}$.

Assumption 1: Parallel trends.

$$\begin{aligned}\exists b < 0 \text{ s.t.} \quad & \mathbb{E}[Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty) | \mathcal{C}_{g,e}(G_i){=}1] \\ & = \mathbb{E}[Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty) | G_i = g], \ \forall e \geq 0\end{aligned}$$

This restricts the relationship between the treated group $G_i = g$ and the control group $\mathcal{C}_{g,e}(G_i){=}1$: the change in average outcome for the treated group *would have been the same in the absence of treatment* as that of the control group.

Assumption 2: No anticipation.

$$\exists b < 0 \ \text{ s.t. } \mathbb{E}[Y_{i,g+b}(g) | G_i = g] = \mathbb{E}[Y_{i,g+b}(\infty) | G_i = g], \ \ \forall g$$

This restricts *when* the treated cohorts respond to treatment.

Note: Both assumptions need only hold for the event time e and pre-period b chosen by the researcher.

Notation and Identification (4/4)

Difference-in-differences: Define the population estimator,

$$\text{DiD}_{g,e} \equiv \mathbb{E}[Y_{i,g+e} - Y_{i,g+b} | G_i = g] - \mathbb{E}[Y_{i,g+e} - Y_{i,g+b} | \mathcal{C}_{g,e}(G_i) = 1]$$

It depends only on observed outcomes, not counterfactuals.

Impose parallel trends: By the parallel-trends assumption, we can replace the second expectation as follows:

$$\text{DiD}_{g,e} \equiv \mathbb{E}[Y_{i,g+e} - Y_{i,g+b} | G_i = g] - \mathbb{E}[Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty) | G_i = g]$$

Impose no anticipation: By the no-anticipation assumption, we can cancel out the two terms involving $Y_{i,g+b}$:

$$\text{DiD}_{g,e} \equiv \mathbb{E}[Y_{i,g+e} | G_i = g] - \mathbb{E}[Y_{i,g+e}(\infty) | G_i = g] = \text{ATT}_{g,e}$$

Thus, we have proven that $\text{DiD}_{g,e} = \text{ATT}_{g,e}$ if the parallel-trends and no-anticipation assumptions hold for the pair (g, e).

Result: If parallel-trends and no-anticipation hold $\forall g$ s.t. $\omega_{g,e} > 0$,

$$\text{ATT}_e = \sum_{g:\ w_{g,e} > 0} \omega_{g,e} \text{DiD}_{g,e}$$

Estimator used by DiD for Big Data (1/4)

Estimator based on averages. Replacing population means with sample means, the package implements the following DiD:

$$\mathrm{DiD}_{g,e} = \underbrace{\mathbb{E}[Y_{i,g+e} - Y_{i,g+b} | G_i = g]}_{\textbf{Difference for treated group}} - \underbrace{(\mathbb{E}[Y_{i,g+e} - Y_{i,g+b} | \mathcal{C}_{g,e}(G_i) = 1])}_{\textbf{Difference for control group}}$$

where, following Callaway and Sant'Anna (2021), we require that parallel-trends and no-anticipation holds for one of these 3 possible control groups:

$$\begin{aligned} \text{"all"} \quad & \mathcal{C}_{g,e}(G_i) = 1\{G_i > (g+e)\} \\ \text{"future-treated"} \quad & \mathcal{C}_{g,e}(G_i) = 1\{G_i > (g+e) \;\&\; G_i < \infty\} \\ \text{"never-treated"} \quad & \mathcal{C}_{g,e}(G_i) = 1\{G_i = \infty\} \end{aligned}$$

Researcher choices. The DiD researcher must make 3 choices:

1. What is the range of event times e for which you would like ATT_e estimates? Default: $e = -5, ..., 5$.
2. Which pre-period should be the base? Default: $b = -1$.
3. Which of the 3 control selections $\mathcal{C}$ to use? Default: "all".

Estimator used by DiD for Big Data (2/4)

Fix some (e, b). Consider testing $\text{ATT}_{g,e} = 0$.

Notation: Consider treatment group $\mathcal{T}_g \equiv 1\{G_i = g\}$ and control group $\mathcal{C}_g$, which could be any of the three options above.

Define within-i differences $A_i \equiv Y_{i,g+e} - Y_{i,g+b}, i \in \mathcal{T}_g$ with mean $\mu_{A,g} \equiv \mathbb{E}[A_i | i \in \mathcal{T}_g]$, and $B_i \equiv Y_{i,g+e} - Y_{i,g+b}, i \in \mathcal{C}_g$ with mean $\mu_{B,g} \equiv \mathbb{E}[B_i | i \in \mathcal{C}_g]$, where subscripts are dropped if unambiguous.

Hypothesis Testing: Since $\text{ATT}_{g,e} \equiv \mu_{A,g} - \mu_{B,g}$, consider,

$$\text{Test statistic: } \text{DiD}_{g,e} = \overline{A}_g - \overline{B}_g, \quad \text{Null } H_0 : \mu_{A,g} - \mu_{B,g} = 0$$

Central Limit Theorem: Denote the population variances by $\sigma^2_{A,g} \equiv \text{Var}[A_i | i \in \mathcal{T}_g]$ and $\sigma^2_{B,g} \equiv \text{Var}[B_i | i \in \mathcal{C}_g]$. By the CLT under the null, with samples drawn independently across i,

$$\overline{A}_g \sim_d \mathcal{N}\left(\mu_{A,g},\ \sigma^2_{A,g}/N_{A,g}\right), \quad \overline{B}_g \sim_d \mathcal{N}\left(\mu_{B,g},\ \sigma^2_{B,g}/N_{B,g}\right)$$

$$\implies \text{DiD}_{g,e} = \left(\overline{A}_g - \overline{B}_g\right) \sim_d \mathcal{N}\left(0,\ \sigma^2_{A,g}/N_{A,g} + \sigma^2_{B,g}/N_{B,g}\right)$$

Thus, $\text{SE}(\text{DiD}_{g,e}) = \sqrt{\sigma^2_{A,g}/N_{A,g} + \sigma^2_{B,g}/N_{B,g}}$. The empirical counterpart is trivial to compute (e.g. no matrix inversion needed).

Estimator used by DiD for Big Data (3/4)

Rather than the ATT for a specific cohort g, we often are interested in the event time e ATT averaged across cohorts.

Average Effects by Event Time. Let $\omega_g \equiv \mathbb{E}[G_i = g | G_i < \infty]$ denote the share of treated units in cohort g. We can define,

$$\text{DiD}_e \equiv \sum_{g \in \mathcal{G}} \omega_g \text{DiD}_{g,e} = \sum_{g \in \mathcal{G}} \omega_g \left(\overline{A}_g - \overline{B}_g \right), \ \text{ATT}_e \equiv \sum_{g \in \mathcal{G}} \omega_g (\mu_{A,g} - \mu_{B,g})$$

Recall: For a given (g, e), the treated and control group are mutually exclusive. Thus, independence across i ensures that $\text{Cov}(\overline{A}_g, \overline{B}_g) = 0$. We used this result on the previous slide to obtain simple SEs with no covariance terms for $\text{DiD}_{g,e} = \overline{A}_g - \overline{B}_g$.

Repeated i in the event time average. Unlike $\text{DiD}_{g,e}$, DiD_e depends on both $\overline{B}_g$ and $\overline{B}_{g'}$ for different cohorts g, g'. The same individual i often appears in multiple control groups (e.g. never-treated units can appear in all control groups). Thus, it is typically true that $\text{Cov}(\overline{B}_g, \overline{B}_{g'}) \neq 0$, so we cannot ignore covariance terms when calculating the SE for DiD_e. Similarly, if $g < g'$, we often have $\text{Cov}(\overline{B}_g, \overline{A}_{g'}) \neq 0$, since some members i of the control group at g later enter the treated group g'.

Estimator used by DiD for Big Data (4/4)

Event study parameters: For $\mathcal{H} \in \{\mathcal{T}, \mathcal{C}\}$, one may wish to plot averages across event times:

$$\bar{Y}^{\mathcal{H}}_{g,e} = \sum_{i \in \mathcal{H}_g} Y_{i,g+e}, \; \text{SE}(\bar{Y}^{\mathcal{H}}_{g,e}) = \sqrt{\frac{\sigma^2_{\mathcal{H},g,e}}{|\mathcal{H}_g|}}, \; \sigma^2_{\mathcal{H},g,e} = \text{Var}[Y_{i,g+e} | i \in \mathcal{H}_g]$$

$$\bar{Y}^{\mathcal{H}}_{e} = \sum_{g \in \mathcal{G}} \omega_g \bar{Y}^{\mathcal{H}}_{g,e}, \; \text{SE}(\bar{Y}^{\mathcal{H}}_{g,e}) = \sqrt{\sum_{g} \omega_g^2 \text{Var}(\bar{Y}^{\mathcal{H}}_{g,e})},$$

The package provides these means and SEs by default.

Plots: The package also provides automated plots, both for presenting the event study parameters and for presenting the ATT estimates. These can be plotted by (g, e) or by e (average over g).

Accounting for Covariates (1/4)

Recall: Definition of parallel trends.

$$\exists b < 0 \text{ s.t. } \quad \mathbb{E}[Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty) | \mathcal{C}_{g,e}(G_i){=}1] = \mathbb{E}[Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty) | G_i = g], \ \forall e \geq 0$$

Time-invariant Covariate: Suppose potential outcomes in the case with no-treatment are given by the model,

$$Y_{i,t}(\infty) = \alpha_i + \mu_t + X_i \beta_t + \epsilon_{i,t}$$

Is the parallel-trends condition violated? Note that,

$$Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty) = (\mu_{g+e} - \mu_{g+b}) + X_i(\beta_{g+e} - \beta_{g+b})$$

Plugging this into the expectations above, we see that:

1. If $\beta_{g+e} = \beta_{g+b}$, then parallel trends holds, as X_i cancels out in $Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty)$.
2. If $\beta_{g+e} \neq \beta_{g+b}$, then parallel trends holds only if,

$$\mathbb{E}[X_i | \mathcal{C}_{g,e}(G_i){=}1] = \mathbb{E}[X_i | G_i = g]$$

Accounting for Covariates (2/4)

Recap: If $Y_{i,t}(\infty) = \alpha_i + \mu_t + X_i\beta_t + \epsilon_{i,t}$ and $\beta_{g+e} \neq \beta_{g+b}$, then parallel trends holds only if,

$$\mathbb{E}[X_i|\mathcal{C}_{g,e}(G_i)=1] = \mathbb{E}[X_i|G_i = g]$$

"Bin" correction: If $X_i \in \mathcal{X}$ is discrete, parallel trends holds if we condition on treatment and control groups with the same X_i bin:

$$\mathbb{E}[X_i|\mathcal{C}_{g,e}(G_i)=1 \;\&\; X_i = x] - \mathbb{E}[X_i|G_i = g \;\&\; X_i = x] = x - x = 0$$

Parallel trends must hold in this model when conditioning on treatment and control groups within the same $X_i = x$ bin.

Testing: Define $\text{DiD}_{g,e}(x)$ as follows:

$$\mathbb{E}[Y_{i,g+e} - Y_{i,g+b}|G_i=g \;\&\; X_i=x] - \mathbb{E}[Y_{i,g+e} - Y_{i,g+b}|\mathcal{C}_{g,e}(G_i)=1 \;\&\; X_i=x]$$

Then, we can test that $\text{ATT}_{g,e}$ is zero using,

$$\text{DiD}_{g,e} = \sum_{\mathcal{X}} \omega_g(x)\text{DiD}_{g,e}(x), \quad \omega_g(x) = \mathbb{E}[X_i = x|G_i = g]$$

$$\text{SE}\left(\text{DiD}_{g,e}\right) = \sqrt{\sum_{x\in\mathcal{X}} (\omega_g(x))^2 \text{SE}(\text{DiD}_{g,e}(x))^2}$$

There are no covariances because each i has only one $X_i = x$ bin.

Accounting for Covariates (3/4)

Time-varying Covariates: Suppose that it is the covariates X rather than the coefficient β that varies over time:

$$Y_{i,t}(\infty) = \alpha_i + \mu_t + X_{i,t}\beta + \epsilon_{i,t}$$

Is parallel trends violated? Note that,

$$Y_{i,g+e}(\infty) - Y_{i,g+b}(\infty) = (\mu_{g+e} - \mu_{g+b}) + (X_{i,g+e} - X_{i,g+b})\,\beta$$

Plugging this into the expectations above, parallel trends requires

$$\mathbb{E}[X_{i,g+e} - X_{i,g+b} | \mathcal{C}_{g,e}(G_i)=1] = \mathbb{E}[X_{i,g+e} - X_{i,g+b} | G_i = g]$$

Though this will not hold in general, it holds if X is age or time, as $X_{i,g+e} - X_{i,g+b} = (e-b)$ is the same for $G_i = g$ and $\mathcal{C}$.

Discrete correction for time-varying covariates: Suppose $X \in \mathcal{X}$ is discrete. Then, the difference $\tilde{X}_i \equiv X_{i,g+e} - X_{i,g+b}$ is also discrete. We can condition on $\tilde{X}_i = x$ and use the same approach we used for time-invariant covariates above.

Accounting for Covariates (4/4)

Recall: We consider the case in which X varies over time:

$$Y_{i,t}(\infty) = \alpha_i + \mu_t + X_{i,t}\beta + \epsilon_{i,t}$$

Regression representation: Let $\mathcal{H}_{g,e}$ denote the union of the treated and control group for a particular (g, e) pair. Then,

$$\begin{aligned}(Y_{i,g+e} - Y_{i,g+b}) = \tilde{\mu} + 1\{G_i = g\}(Y_{i,g+e}(g) - Y_{i,g+e}(\infty)) \\ + (X_{i,g+e} - X_{i,g+b})\beta + \tilde{\epsilon}, \quad \forall i \in \mathcal{H}_{g,e}\end{aligned}$$

which is a regression equation *with no fixed effects* that can be estimated separately for each g, e pair. In particular, the coefficient on $1\{G_i = g\}$ recovers $\mathbb{E}[Y_{i,g+e}(g) - Y_{i,g+e}(\infty)|G_i = g]$.

OLS: Thus, we can apply OLS to regress $Y_{i,g+e} - Y_{i,g+b}$ on $1\{G_i = g\}$ and $X_{i,g+e} - X_{i,g+b}$, using the standard OLS point estimate and SE for the coefficient on $1\{G_i = g\}$. Note that this OLS formulation accommodates both discrete and continuous $X_{i,t}$. Importantly, no fixed effects have to be estimated, even in the case with continuous time-varying covariates – the regression just has a few regressors, remaining computationally fast and efficient.