Notes on Linear Panel Model

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1 Fixed Effect Model

$$y_{it} = \boldsymbol{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it} \qquad \text{Level 1}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \alpha_i + \begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$

$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i} \qquad \text{Level 2}$$

$$\begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} = \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{pmatrix} + \begin{pmatrix} \boldsymbol{\varepsilon}_1 \\ \vdots \\ \boldsymbol{\varepsilon}_N \end{pmatrix}$$

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon} \qquad \text{Level 3}$$

where α_i is unobserved heterogeneity, $\boldsymbol{\varepsilon}_i$ is idiosyncratic error, $\boldsymbol{u}_i$ is composite error.

1.1 Assumption

1.1.1 Strong/Strict Exogeneity of Regressors

For all t,

$$\mathbb{E}(\varepsilon_{it}|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT}) = 0$$

equivalently,

$$\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{0}$$

1.2 OLS estimator is inconsistent and biased

The necessary condition for OLS estimator to be consistent is $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \boldsymbol{0}$. However,

$$\begin{aligned} \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) &= \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i|\boldsymbol{X}_i)) \\ &= \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i)) \\ &= \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)) \\ &= \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{e}\alpha_i|\boldsymbol{X}_i) + \boldsymbol{X}_i'\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\boldsymbol{0}}) && \text{because of strict exogeneity} \\ &= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\mathbb{E}(\alpha_i|\boldsymbol{X}_i)) \\ &= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \end{aligned}$$

$\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq 0 \iff \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) \neq \boldsymbol{0}$. Thus, OLS estimator is inconsistent if $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq \boldsymbol{0}$.

The necessary condition for OLS estimator to be unbiased is $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0}$. However, $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{0}) = \boldsymbol{0}$. Thus, $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) \neq \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) \neq \boldsymbol{0}$ As a result, OLS estimator is biased if $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq \boldsymbol{0}$.

$\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) = \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\mathbb{E}(\alpha_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\boldsymbol{0}) = \boldsymbol{0}$. Thus, $\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{e}\alpha_i) \neq 0 \implies \mathbb{E}(\alpha_i|\boldsymbol{X}_i) \neq 0$

OLS estimator of $\boldsymbol{\beta}$ is inconsistent and biased if α_i is correlated with $\boldsymbol{X}_i$ ($\boldsymbol{u}_i$ is also correlated with $\boldsymbol{X}_i$). This is called Omitted Variable Bias. To tackle this, we simply eliminate α_i by using different transformer.

1.3 Fixed Effect Estimator / Within Estimator

1.3.1 Demean transformer

$$\boldsymbol{Q} = \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}'$$

Properties:

$$
\begin{aligned}
\boldsymbol{Q}' &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')' \\
&= \boldsymbol{I}_T' - T^{-1}\boldsymbol{e}''\boldsymbol{e}' \\
&= \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' = \boldsymbol{Q}
\end{aligned}
$$

so $\boldsymbol{Q}$ is symmetric

$$
\begin{aligned}
\boldsymbol{Q}\boldsymbol{Q}' &= \boldsymbol{Q}\boldsymbol{Q} \\
&= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')(\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \boldsymbol{I}_T\boldsymbol{I}_T - \boldsymbol{I}_T T^{-1}\boldsymbol{e}\boldsymbol{e}' - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{I}_T + T^{-1}\boldsymbol{e}\boldsymbol{e}'T^{-1}\boldsymbol{e}\boldsymbol{e}' \\
&= \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' - T^{-1}\boldsymbol{e}\boldsymbol{e}' + T^{-2}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{e}\boldsymbol{e}' \\
&= \boldsymbol{I}_T - 2T^{-1}\boldsymbol{e}\boldsymbol{e}' + T^{-2}\boldsymbol{e}T\boldsymbol{e}' \\
&= \boldsymbol{I}_T - 2T^{-1}\boldsymbol{e}\boldsymbol{e}' + T^{-1}\boldsymbol{e}\boldsymbol{e}' \\
&= \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' = \boldsymbol{Q}
\end{aligned}
$$

so $\boldsymbol{Q}$ is idempotent

$$
\begin{aligned}
\boldsymbol{Q}\boldsymbol{e} &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')\boldsymbol{e} \\
&= \boldsymbol{I}_T\boldsymbol{e} - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{e} \\
&= \boldsymbol{e} - T^{-1}\boldsymbol{e}T \\
&= \boldsymbol{e} - \boldsymbol{e} = \boldsymbol{0}
\end{aligned}
$$

1.3.2 Demean transformed model

$$
\begin{aligned}
\boldsymbol{Q}\boldsymbol{X}_i &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')\boldsymbol{X}_i \\
&= \boldsymbol{I}_T\boldsymbol{X}_i - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{X}_i \\
&= \boldsymbol{X}_i - T^{-1}\boldsymbol{e}\begin{pmatrix} 1 & \cdots & 1 \end{pmatrix}\begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} \\
&= \boldsymbol{X}_i - \boldsymbol{e}T^{-1}\sum_{t=1}^{T}\boldsymbol{x}_{it}' \\
&= \boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i'
\end{aligned}
$$

$$\begin{aligned}
\boldsymbol{Q}\boldsymbol{y}_i &= (\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}')\boldsymbol{y}_i \\
&= \boldsymbol{I}_T\boldsymbol{y}_i - T^{-1}\boldsymbol{e}\boldsymbol{e}'\boldsymbol{y}_i \\
&= \boldsymbol{y}_i - T^{-1}\boldsymbol{e}\begin{pmatrix} 1 & \cdots & 1 \end{pmatrix}\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} \\
&= \boldsymbol{y}_i - \boldsymbol{e}T^{-1}\sum_{t=1}^{T} y_{it} \\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{Q}\boldsymbol{y}_i &= \boldsymbol{Q}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i) \\
&= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}\boldsymbol{e}\alpha_i + \boldsymbol{Q}\boldsymbol{\varepsilon}_i \\
&= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{0}\alpha_i + \boldsymbol{Q}\boldsymbol{\varepsilon}_i \\
&= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}\boldsymbol{\varepsilon}_i && \text{Level 2} \\
\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i) && \text{Level 2}
\end{aligned}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}\bar{y}_i = (\begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}\bar{\varepsilon}_i)$$

$$\begin{pmatrix} y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i' \end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} \varepsilon_{i1} - \bar{\varepsilon}_i \\ \vdots \\ \varepsilon_{iT} - \bar{\varepsilon}_i \end{pmatrix}$$

$$\begin{pmatrix} y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i \end{pmatrix} = \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)' \end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} \varepsilon_{i1} - \bar{\varepsilon}_i \\ \vdots \\ \varepsilon_{iT} - \bar{\varepsilon}_i \end{pmatrix}$$

$$y_{it} - \bar{y}_i = (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + (\varepsilon_{it} - \bar{\varepsilon}_i) \qquad \text{Level 1}$$

1.3.3 OLS estimator of the demean transformed model / Fixed Effect (FE) estimator

$$\begin{aligned}
(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i') \\
&= (\begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}\bar{\boldsymbol{x}}_i')'(\begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}\bar{\boldsymbol{x}}_i') \\
&= \begin{pmatrix} \boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i' \end{pmatrix}'\begin{pmatrix} \boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i' \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)' \end{pmatrix}'\begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)' \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i) & \cdots & (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i) \end{pmatrix}\begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i)' \end{pmatrix} \\
&= \sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'
\end{aligned}$$

$$
\begin{aligned}
(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{y}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i) \\
&= (\begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \bar{\boldsymbol{x}}_i')'(\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} - \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \bar{y}_i) \\
&= \begin{pmatrix} \boldsymbol{x}_{i1}' - \bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \bar{\boldsymbol{x}}_i' \end{pmatrix}' \begin{pmatrix} y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{x}_{i1} - \bar{\boldsymbol{x}}_i) & \cdots & (\boldsymbol{x}_{iT} - \bar{\boldsymbol{x}}_i) \end{pmatrix} \begin{pmatrix} y_{i1} - \bar{y}_i \\ \vdots \\ y_{iT} - \bar{y}_i \end{pmatrix} \\
&= \sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i)
\end{aligned}
$$

$$
\begin{aligned}
\hat{\boldsymbol{\beta}}_{within}^{ols} &= [\sum_{i=1}^{N}(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{y}_i && \text{Level 2} \\
&= [\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) && \text{Level 1}
\end{aligned}
$$

$$
\begin{aligned}
(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i') \\
&= (\boldsymbol{X}_i' - \bar{\boldsymbol{x}}_i''\boldsymbol{e}')(\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i') \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \boldsymbol{X}_i'\boldsymbol{e}\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{X}_i + \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{e}\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \boldsymbol{X}_i'\boldsymbol{e}\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{X}_i + \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - (\boldsymbol{e}'\boldsymbol{X}_i)'\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{X}_i + \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - (\sum_{t=1}^{T}\boldsymbol{x}_{it}')'\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_i\sum_{t=1}^{T}\boldsymbol{x}_{it}' + \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - (\sum_{t=1}^{T}\boldsymbol{x}_{it}/T)T\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_iT\sum_{t=1}^{T}\boldsymbol{x}_{it}'/T + \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i' - \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i' + \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i' \\
&= \boldsymbol{X}_i'\boldsymbol{X}_i - \bar{\boldsymbol{x}}_iT\bar{\boldsymbol{x}}_i'
\end{aligned}
$$

$$
\begin{aligned}
(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{y}_i &= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i) \\
&= (\boldsymbol{X}_i' - \bar{\boldsymbol{x}}_i''\boldsymbol{e}')(\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i) \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - \boldsymbol{X}_i'\boldsymbol{e}\bar{y}_i - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{y}_i + \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{e}\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - (\boldsymbol{e}'\boldsymbol{X}_i)'\bar{y}_i - \bar{\boldsymbol{x}}_i\boldsymbol{e}'\boldsymbol{y}_i + \bar{\boldsymbol{x}}_iT\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - (\sum_{t=1}^{T}\boldsymbol{x}_{it}')'\bar{y}_i - \bar{\boldsymbol{x}}_i\sum_{t=1}^{T}y_{it} + \bar{\boldsymbol{x}}_iT\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - (\sum_{t=1}^{T}\boldsymbol{x}_{it}/T)T\bar{y}_i - \bar{\boldsymbol{x}}_iT\sum_{t=1}^{T}y_{it}/T + \bar{\boldsymbol{x}}_iT\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - \bar{\boldsymbol{x}}_iT\bar{y}_i - \bar{\boldsymbol{x}}_iT\bar{y}_i + \bar{\boldsymbol{x}}_iT\bar{y}_i \\
&= \boldsymbol{X}_i'\boldsymbol{y}_i - \bar{\boldsymbol{x}}_iT\bar{y}_i
\end{aligned}
$$

$$\hat{\boldsymbol{\beta}}_{within}^{ols} = [\sum_{i=1}^{N}(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{y}_i$$

$$= [\sum_{i=1}^{N}(\boldsymbol{X}_i'\boldsymbol{X}_i - \bar{\boldsymbol{x}}_i T \bar{\boldsymbol{x}}_i')]^{-1}\sum_{i=1}^{N}(\boldsymbol{X}_i'\boldsymbol{y}_i - \bar{\boldsymbol{x}}_i T \bar{y}_i)$$

$$= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{X}_i - T\sum_{i=1}^{N}\bar{\boldsymbol{x}}_i\bar{\boldsymbol{x}}_i']^{-1}(\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{y}_i - T\sum_{i=1}^{N}\bar{\boldsymbol{x}}_i\bar{y}_i)$$

$$= [\begin{pmatrix}\boldsymbol{X}_1' & \cdots & \boldsymbol{X}_N'\end{pmatrix}\begin{pmatrix}\boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N\end{pmatrix} - T\begin{pmatrix}\bar{\boldsymbol{x}}_1 & \cdots & \bar{\boldsymbol{x}}_N\end{pmatrix}\begin{pmatrix}\bar{\boldsymbol{x}}_1' \\ \vdots \\ \bar{\boldsymbol{x}}_N'\end{pmatrix}]^{-1}(\begin{pmatrix}\boldsymbol{X}_1' & \cdots & \boldsymbol{X}_N'\end{pmatrix}\begin{pmatrix}\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N\end{pmatrix} - T\begin{pmatrix}\bar{\boldsymbol{x}}_1 & \cdots & \bar{\boldsymbol{x}}_N\end{pmatrix}\begin{pmatrix}\bar{y}_1 \\ \vdots \\ \bar{y}_N\end{pmatrix})$$

$$= [\boldsymbol{X}'\boldsymbol{X} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{X}}]^{-1}(\boldsymbol{X}'\boldsymbol{y} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{y}}) \qquad \text{Level 3}$$

1.3.4 FE estimator satisfies the necessary condition of consistency and unbiasedness

The necessary condition for FE estimator (OLS estimator of the demean transformed model) to be consistent is $\mathbb{E}((\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) = \boldsymbol{0}$

$$
\begin{aligned}
\mathbb{E}((\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) &= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) \\
&= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}\boldsymbol{\varepsilon}_i) && \text{as } \boldsymbol{Q} \text{ is idempotent and symmetric} \\
&= \mathbb{E}(\mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)) \\
&= \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{Q}\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{0}) && \text{because of strict exogeneity} \\
&= \boldsymbol{0}
\end{aligned}
$$

Thus, FE estimator satisfies the necessary condition of consistency given strict exogeneity assumption. Indeed, strict exogeneity is stronger than what is required. To see this, first note that for any t

$$\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \mathbb{E}(\varepsilon_{it}|\boldsymbol{x}_{i1},\cdots,\boldsymbol{x}_{iT}) = 0 \implies \mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = 0 \qquad \text{for all s}$$

It is because for any t and s

$$
\begin{aligned}
\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) &= \mathbb{E}(\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}|\boldsymbol{x}_{i1},\cdots,\boldsymbol{x}_{iT})) \\
&= \mathbb{E}(\boldsymbol{x}_{is}\underbrace{\mathbb{E}(\varepsilon_{it}|\boldsymbol{x}_{i1},\cdots,\boldsymbol{x}_{iT})}_{0}) \\
&= \boldsymbol{0}
\end{aligned}
$$

The necessary condition for FE estimator (OLS estimator of the demean transformed model) to be consistent can also be written as $\mathbb{E}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\varepsilon_{it} - \bar{\varepsilon}_i)) = \boldsymbol{0}$

$$\mathbb{E}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\varepsilon_{it} - \bar{\varepsilon}_i)) = \mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{it}) - \mathbb{E}(\boldsymbol{x}_{it}\bar{\varepsilon}_i) - \mathbb{E}(\bar{\boldsymbol{x}}_i\varepsilon_{it}) + \mathbb{E}(\bar{\boldsymbol{x}}_i\bar{\varepsilon}_i) = \boldsymbol{0}$$

It is because $\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \boldsymbol{0}$ for any t and s implies

$$\mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{it}) = \boldsymbol{0}$$

$$\mathbb{E}(\boldsymbol{x}_{it}\bar{\varepsilon}_i) = \mathbb{E}(\boldsymbol{x}_{it}T^{-1}\sum_{s=1}^{T}\varepsilon_{is}) = T^{-1}\sum_{s=1}^{T}\underbrace{\mathbb{E}(\boldsymbol{x}_{it}\varepsilon_{is})}_{0} = \boldsymbol{0}$$

$$\mathbb{E}(\bar{\boldsymbol{x}}_i\varepsilon_{it}) = \mathbb{E}(T^{-1}\sum_{s=1}^{T}\boldsymbol{x}_{is}\varepsilon_{it}) = T^{-1}\sum_{s=1}^{T}\underbrace{\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it})}_{0} = \boldsymbol{0}$$

$$\mathbb{E}(\bar{\boldsymbol{x}}_i\bar{\varepsilon}_i) = \mathbb{E}(T^{-1}\sum_{s=1}^{T}\boldsymbol{x}_{is}T^{-1}\sum_{t=1}^{T}\varepsilon_{it}) = T^{-2}\sum_{s=1}^{T}\sum_{t=1}^{T}\underbrace{\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it})}_{0} = \boldsymbol{0}$$

Thus, weaker assumption $\mathbb{E}(\boldsymbol{x}_{is}\varepsilon_{it}) = \boldsymbol{0}$ for any t and s is sufficient for $\mathbb{E}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\varepsilon_{it} - \bar{\varepsilon}_i)) = \boldsymbol{0}$

The necessary condition of FE estimator to be unbiased is $\mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{Q}\boldsymbol{X}_i) = \boldsymbol{0}$

$$\mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{Q}\boldsymbol{X}_i) = \boldsymbol{Q}\underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{\boldsymbol{0}} \qquad \text{as } \boldsymbol{Q} \text{ is constant and strict exogeneity}$$

$$= \boldsymbol{0}$$

Thus, FE estimator satisfies the necessary condition of unbiasedness given strict exogeneity assumption.

1.3.5 Variance of $\hat{\boldsymbol{\beta}}_{within}^{ols}$

because of independence of i,

$$Var(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i) = \sum_{i=1}^N Var(\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i)$$

$$= \sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i)(\boldsymbol{X}_i'\boldsymbol{Q}')'$$

$$= \sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}''\boldsymbol{X}_i''$$

$$= \sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}\boldsymbol{X}_i$$

$$[\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1'} = [\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{'-1}$$

$$= [\sum_{i=1}^N (\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i)']^{-1}$$

$$= [\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}''\boldsymbol{X}_i'']^{-1}$$

$$= [\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$Var(\hat{\boldsymbol{\beta}}_{within}^{ols}|\boldsymbol{X}_i) = Var([\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i)$$

$$= [\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}Var(\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i|\boldsymbol{X}_i)[\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1'}$$

$$= [\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^N \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

If ε_{it} is homoskedasticity and serially uncorrelated across t i.e., $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2 \boldsymbol{I}_T$ and independence across i and with strict exogeneity, we have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma_\varepsilon^2 \boldsymbol{I}_T]$, $Var(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{Q}Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}' = \boldsymbol{Q}\sigma_\varepsilon^2 \boldsymbol{I}_T \boldsymbol{Q}' = \sigma_\varepsilon^2 \boldsymbol{Q}\boldsymbol{Q}' = \sigma_\varepsilon^2 \boldsymbol{Q} = \sigma_\varepsilon^2(\boldsymbol{I}_T - $

$T^{-1}\boldsymbol{e}\boldsymbol{e}') = \sigma_\varepsilon^2 \begin{pmatrix} 1-\frac{1}{T} & -\frac{1}{T} & \cdots & -\frac{1}{T} \\ -\frac{1}{T} & 1-\frac{1}{T} & \cdots & -\frac{1}{T} \\ \vdots & \vdots & \vdots & \vdots \\ -\frac{1}{T} & -\frac{1}{T} & \cdots & 1-\frac{1}{T} \end{pmatrix}$. Thus, $\boldsymbol{Q}\boldsymbol{\varepsilon}_i$ is homoskedasticity but negatively serially correlated.

$$= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\sigma_\varepsilon^2 \underbrace{\boldsymbol{Q}\boldsymbol{Q}}_{\boldsymbol{Q}}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= \sigma_\varepsilon^2[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= \sigma_\varepsilon^2 \boldsymbol{I}_T[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= \sigma_\varepsilon^2[\sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= \sigma_\varepsilon^2[\sum_{i=1}^{N} \sum_{t=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1} \qquad \text{Level 1}$$

$$Var(\varepsilon_{it} - \bar{\varepsilon}_i) = \sigma_\varepsilon^2(1 - \frac{1}{T})$$

$$\sigma_\varepsilon^2 = \frac{T}{T-1} Var(\varepsilon_{it} - \bar{\varepsilon}_i)$$

$$\hat{\sigma}_\varepsilon^2 = \frac{T}{T-1} \widehat{Var(\varepsilon_{it} - \bar{\varepsilon}_i)}$$

$$= \frac{T}{T-1} \frac{\sum_{i=1}^{N} \sum_{t=1}^{T} (y_{it} - \bar{y}_i - (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\hat{\boldsymbol{\beta}}_{within}^{ols})^2}{NT - (K+N)}$$

$$= \frac{T}{T-1} \frac{\sum_{i=1}^{N} \sum_{t=1}^{T} (y_{it} - \boldsymbol{x}_{it}'\hat{\boldsymbol{\beta}}_{within}^{ols} - \overbrace{(\bar{y}_i - \bar{\boldsymbol{x}}_i'\hat{\beta}_{within}^{ols})}^{\hat{\alpha}_i})^2}{\underbrace{NT - (K+N)}_{N(T-1)-K}} \qquad \text{Usually, } \frac{T}{T-1} \text{ is ignored.}$$

If $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim inid\ [\boldsymbol{0}, \boldsymbol{\Omega}_i]$

$$= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \mathbb{E}(\boldsymbol{Q}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i))'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\boldsymbol{0})(\boldsymbol{Q}\boldsymbol{\varepsilon}_i - \boldsymbol{Q}\boldsymbol{0})'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\mathbb{E}[\boldsymbol{Q}\boldsymbol{\varepsilon}_i(\boldsymbol{Q}\boldsymbol{\varepsilon}_i)'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= [\sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1} \sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\mathbb{E}[\boldsymbol{Q}\boldsymbol{\varepsilon}_i(\boldsymbol{Q}\boldsymbol{\varepsilon}_i)'|\boldsymbol{X}_i]\boldsymbol{Q}\boldsymbol{X}_i[\sum_{i=1}^{N} (\boldsymbol{Q}\boldsymbol{X}_i)'\boldsymbol{Q}\boldsymbol{X}_i]^{-1}$$

$$= [\sum_{i=1}^{N} \sum_{t=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1} \sum_{i=1}^{N} \sum_{t=1}^{T} \sum_{s=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)\mathbb{E}[\dot{\varepsilon}_{it}\dot{\varepsilon}_{is}|\boldsymbol{X}_i](\boldsymbol{x}_{is} - \bar{\boldsymbol{x}}_i)'[\sum_{i=1}^{N} \sum_{t=1}^{T} (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)']^{-1}$$

$$\sum_{i=1}^{N}(\boldsymbol{QX}_i)'\mathbb{E}[\boldsymbol{Q\varepsilon}_i(\boldsymbol{Q\varepsilon}_i)'|\boldsymbol{X}_i]\boldsymbol{QX}_i = \sum_{i=1}^{N}(\boldsymbol{QX}_i)'\mathbb{E}[\dot{\boldsymbol{\varepsilon}}_i\dot{\boldsymbol{\varepsilon}}_i'|\boldsymbol{X}_i]\boldsymbol{QX}_i$$

$$= \sum_{i=1}^{N}\begin{pmatrix}(\boldsymbol{x}_{i1}-\bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT}-\bar{\boldsymbol{x}}_i)'\end{pmatrix}'\begin{pmatrix}\mathbb{E}[\dot{\varepsilon}_{i1}^2|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{i1}\dot{\varepsilon}_{iT}|\boldsymbol{X}_i] \\ \vdots & \ddots & \vdots \\ \mathbb{E}[\dot{\varepsilon}_{iT}\dot{\varepsilon}_{i1}|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{iT}^2|\boldsymbol{X}_i]\end{pmatrix}\begin{pmatrix}(\boldsymbol{x}_{i1}-\bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT}-\bar{\boldsymbol{x}}_i)'\end{pmatrix}$$

$$= \sum_{i=1}^{N}\begin{pmatrix}(\boldsymbol{x}_{i1}-\bar{\boldsymbol{x}}_i) & (\boldsymbol{x}_{iT}-\bar{\boldsymbol{x}}_i)\end{pmatrix}\begin{pmatrix}\mathbb{E}[\dot{\varepsilon}_{i1}^2|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{i1}\dot{\varepsilon}_{iT}|\boldsymbol{X}_i] \\ \vdots & \ddots & \vdots \\ \mathbb{E}[\dot{\varepsilon}_{iT}\dot{\varepsilon}_{i1}|\boldsymbol{X}_i] & \cdots & \mathbb{E}[\dot{\varepsilon}_{iT}^2|\boldsymbol{X}_i]\end{pmatrix}\begin{pmatrix}(\boldsymbol{x}_{i1}-\bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT}-\bar{\boldsymbol{x}}_i)'\end{pmatrix}$$

$$= \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T}(\boldsymbol{x}_{it}-\bar{\boldsymbol{x}}_i)\mathbb{E}[\dot{\varepsilon}_{it}\dot{\varepsilon}_{is}|\boldsymbol{X}_i](\boldsymbol{x}_{is}-\bar{\boldsymbol{x}}_i)'$$

1.3.6 GLS estimator of the demean transformed model

If $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0},\sigma_\varepsilon^2\boldsymbol{I}_T]$ then $\boldsymbol{Q\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0},\sigma_\varepsilon^2\boldsymbol{Q}]$

We want to find a GLS transformer $\boldsymbol{T}_{GLS}$ such that

$$Var(\boldsymbol{T}_{GLS}\boldsymbol{Q\varepsilon}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2\boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}Var(\boldsymbol{Q\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{T}_{GLS}' = \sigma_\varepsilon^2\boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\sigma_\varepsilon^2\boldsymbol{Q}\boldsymbol{T}_{GLS}' = \sigma_\varepsilon^2\boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2}\boldsymbol{Q}^{1/2}\boldsymbol{T}_{GLS}' = \boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2}\boldsymbol{Q}'^{1/2}\boldsymbol{T}_{GLS}' = \boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2}(\boldsymbol{T}_{GLS}\boldsymbol{Q}^{1/2})' = \boldsymbol{I}_T$$

So, $\boldsymbol{T}_{GLS} = \boldsymbol{Q}^{-1/2}$

$$\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i = \boldsymbol{Q}^{-1/2}(\boldsymbol{QX}_i\boldsymbol{\beta}+\boldsymbol{Q\varepsilon}_i) = \boldsymbol{Q}^{-1/2}\boldsymbol{QX}_i\boldsymbol{\beta}+\boldsymbol{Q}^{-1/2}\boldsymbol{Q\varepsilon}_i$$

so that $Var(\boldsymbol{Q}^{-1/2}\boldsymbol{Q\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{Q}^{-1/2}Var(\boldsymbol{Q\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{Q}'^{-1/2} = \boldsymbol{Q}^{-1/2}\sigma_\varepsilon^2\boldsymbol{Q}\boldsymbol{Q}^{-1/2} = \sigma_\varepsilon^2\boldsymbol{Q}^{-1/2}\boldsymbol{Q}^{1/2}\boldsymbol{Q}^{1/2}\boldsymbol{Q}^{-1/2} = \sigma_\varepsilon^2\boldsymbol{I}_T$

By Gauss Markov Theorem, GLS estimator is efficient.

$$\hat{\boldsymbol{\beta}}_{within}^{gls} = [\sum_{i=1}^{N}(\boldsymbol{Q}^{-1/2}\boldsymbol{QX}_i)'\boldsymbol{Q}^{-1/2}\boldsymbol{QX}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{Q}^{-1/2}\boldsymbol{QX}_i)'\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i$$

$$= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}'^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{QX}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}'^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i$$

$$= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{QX}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-1/2}\boldsymbol{Q}^{-1/2}\boldsymbol{Q}\boldsymbol{y}_i$$

$$= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{QX}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{Q}\boldsymbol{y}_i$$

$$= [\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{QX}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{Q}'\boldsymbol{Q}\boldsymbol{y}_i = \hat{\boldsymbol{\beta}}_{within}^{ols} \qquad\text{So, FE estimator is also efficient}$$

for generalized inverse, $\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{Q} = \boldsymbol{Q}$

as $\boldsymbol{Q}$ is idempotent and symmetry, $\boldsymbol{Q} = \boldsymbol{QQ}' = \boldsymbol{Q}'\boldsymbol{Q}$

so, $\boldsymbol{Q}'\boldsymbol{Q}^{-}\boldsymbol{Q} = \boldsymbol{Q}'\boldsymbol{Q}$

1.4 First-Difference Estimator

1.4.1 First-difference transformer

$$\boldsymbol{\Delta} = \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix}$$

$$\boldsymbol{\Delta}\boldsymbol{\Delta}' = \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix}'$$

$$= \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} -1 & 0 & 0 & \cdots & 0 & 0 \\ 1 & -1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & -1 \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 2 & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2 & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2 & -1 \\ 0 & 0 & 0 & \cdots & -1 & 2 \end{pmatrix}$$

$$\boldsymbol{\Delta}\boldsymbol{e} = \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \\ \vdots \\ \vdots \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ \vdots \\ 0 \end{pmatrix} = \boldsymbol{0}$$

1.4.2 First difference transformed model

$$\begin{aligned} \boldsymbol{\Delta}\boldsymbol{y}_i &= \boldsymbol{\Delta}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i) \\ &= \boldsymbol{\Delta}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{\Delta}\boldsymbol{e}\alpha_i + \boldsymbol{\Delta}\boldsymbol{\varepsilon}_i \\ &= \boldsymbol{\Delta}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{0}\alpha_i + \boldsymbol{\Delta}\boldsymbol{\varepsilon}_i \\ &= \boldsymbol{\Delta}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{\Delta}\boldsymbol{\varepsilon}_i \qquad\qquad \text{Level 2} \end{aligned}$$

$$\begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} y_{i1} \\ y_{i2} \\ y_{i3} \\ \vdots \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} \boldsymbol{x}'_{i1} \\ \boldsymbol{x}'_{i2} \\ \boldsymbol{x}'_{i3} \\ \vdots \\ \vdots \\ \boldsymbol{x}'_{iT} \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 \\ 0 & 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_{i1} \\ \varepsilon_{i2} \\ \varepsilon_{i3} \\ \vdots \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$

$$
\begin{pmatrix} y_{i2} - y_{i1} \\ y_{i3} - y_{i2} \\ y_{i4} - y_{i3} \\ \vdots \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}'_{i2} - \boldsymbol{x}'_{i1} \\ \boldsymbol{x}'_{i3} - \boldsymbol{x}'_{i2} \\ \boldsymbol{x}'_{i4} - \boldsymbol{x}'_{i3} \\ \vdots \\ \vdots \\ \boldsymbol{x}'_{iT} - \boldsymbol{x}'_{i,T-1} \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \varepsilon_{i2} - \varepsilon_{i1} \\ \varepsilon_{i3} - \varepsilon_{i2} \\ \varepsilon_{i4} - \varepsilon_{i3} \\ \vdots \\ \vdots \\ \varepsilon_{iT} - \varepsilon_{i,T-1} \end{pmatrix}
$$

$$
\begin{pmatrix} y_{i2} - y_{i1} \\ y_{i3} - y_{i2} \\ y_{i4} - y_{i3} \\ \vdots \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix} = \begin{pmatrix} (\boldsymbol{x}_{i2} - \boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4} - \boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1})' \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \varepsilon_{i2} - \varepsilon_{i1} \\ \varepsilon_{i3} - \varepsilon_{i2} \\ \varepsilon_{i4} - \varepsilon_{i3} \\ \vdots \\ \vdots \\ \varepsilon_{iT} - \varepsilon_{i,T-1} \end{pmatrix}
$$

$$
y_{it} - y_{i,t-1} = (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})'\boldsymbol{\beta} + (\varepsilon_{it} - \varepsilon_{i,t-1}) \qquad\qquad \text{Level 1}
$$

1.4.3   OLS estimator of the first difference transformed model

$$
(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i = \begin{pmatrix} (\boldsymbol{x}_{i2} - \boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4} - \boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1})' \end{pmatrix}' \begin{pmatrix} (\boldsymbol{x}_{i2} - \boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4} - \boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1})' \end{pmatrix}
$$

$$
= \begin{pmatrix} (\boldsymbol{x}_{i2} - \boldsymbol{x}_{i1}) & (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2}) & (\boldsymbol{x}_{i4} - \boldsymbol{x}_{i3}) & \cdots & \cdots & (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1}) \end{pmatrix} \begin{pmatrix} (\boldsymbol{x}_{i2} - \boldsymbol{x}_{i1})' \\ (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2})' \\ (\boldsymbol{x}_{i4} - \boldsymbol{x}_{i3})' \\ \vdots \\ \vdots \\ (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1})' \end{pmatrix}
$$

$$
= \sum_{t=2}^{T} (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})(\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})'
$$

$$
(\mathbf{\Delta X}_i)' \mathbf{\Delta y}_i = \begin{pmatrix} (\mathbf{x}_{i2} - \mathbf{x}_{i1})' \\ (\mathbf{x}_{i3} - \mathbf{x}_{i2})' \\ (\mathbf{x}_{i4} - \mathbf{x}_{i3})' \\ \vdots \\ \vdots \\ (\mathbf{x}_{iT} - \mathbf{x}_{i,T-1})' \end{pmatrix}' \begin{pmatrix} y_{i2} - y_{i1} \\ y_{i3} - y_{i2} \\ y_{i4} - y_{i3} \\ \vdots \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix}
$$

$$
= \left((\mathbf{x}_{i2} - \mathbf{x}_{i1}) \quad (\mathbf{x}_{i3} - \mathbf{x}_{i2}) \quad (\mathbf{x}_{i4} - \mathbf{x}_{i3}) \quad \cdots \quad \cdots \quad (\mathbf{x}_{iT} - \mathbf{x}_{i,T-1}) \right) \begin{pmatrix} y_{i2} - y_{i1} \\ y_{i3} - y_{i2} \\ y_{i4} - y_{i3} \\ \vdots \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix}
$$

$$
= \sum_{t=2}^{T} (\mathbf{x}_{it} - \mathbf{x}_{i,t-1})(y_{it} - y_{i,t-1})
$$

$$
\hat{\boldsymbol{\beta}}_{fd}^{ols} = [\sum_{i=1}^{N} (\mathbf{\Delta X}_i)' \mathbf{\Delta X}_i]^{-1} \sum_{i=1}^{N} (\mathbf{\Delta X}_i)' \mathbf{\Delta y}_i \qquad\qquad\text{Level 2}
$$

$$
= [\sum_{i=1}^{N} \sum_{t=2}^{T} (\mathbf{x}_{it} - \mathbf{x}_{i,t-1})(\mathbf{x}_{it} - \mathbf{x}_{i,t-1})']^{-1} \sum_{i=1}^{N} \sum_{t=2}^{T} (\mathbf{x}_{it} - \mathbf{x}_{i,t-1})(y_{it} - y_{i,t-1}) \qquad\text{Level 1}
$$

1.4.4 FD estimator satisfies the necessary condition of consistency and unbiasedness

The necessary condition for FD estimator (OLS estimator of the FD transformed model) to be consistent is $\mathbb{E}(\mathbf{\Delta X}_i)' \mathbf{\Delta \varepsilon}_i) = \mathbf{0}$

$$
\begin{aligned}
\mathbb{E}((\mathbf{\Delta X}_i)' \mathbf{\Delta \varepsilon}_i) &= \mathbb{E}(\mathbf{X}_i' \mathbf{\Delta}' \mathbf{\Delta \varepsilon}_i) \\
&= \mathbb{E}(\mathbb{E}(\mathbf{X}_i' \mathbf{\Delta \Delta}' \mathbf{\varepsilon}_i | \mathbf{X}_i)) \\
&= \mathbb{E}(\mathbf{X}_i' \mathbf{\Delta \Delta}' \underbrace{\mathbb{E}(\mathbf{\varepsilon}_i | \mathbf{X}_i)}_{\mathbf{0}}) \qquad\qquad \text{because of strict exogeneity} \\
&= \mathbf{0}
\end{aligned}
$$

Thus, FD estimator satisfies the necessary condition of consistency given strict exogeneity assumption. Indeed, strict exogeneity is stronger than what is required. To see this, first note that for any t

$$
\mathbb{E}(\mathbf{\varepsilon}_i | \mathbf{X}_i) = \mathbb{E}(\varepsilon_{it} | \mathbf{x}_{i1}, \cdots, \mathbf{x}_{iT}) = 0 \implies \mathbb{E}(\mathbf{x}_{is} \varepsilon_{it}) = 0 \qquad\qquad \text{for all s}
$$

The necessary condition for FD estimator (OLS estimator of the demean transformed model) to be consistent can also be written as $\mathbb{E}((\mathbf{x}_{it} - \mathbf{x}_{i,t-1})(\varepsilon_{it} - \varepsilon_{i,t-1})) = \mathbf{0}$

$$
\mathbb{E}((\mathbf{x}_{it} - \mathbf{x}_{i,t-1})(\varepsilon_{it} - \varepsilon_{i,t-1})) = \mathbb{E}(\mathbf{x}_{it} \varepsilon_{it}) - \mathbb{E}(\mathbf{x}_{it} \varepsilon_{i,t-1}) - \mathbb{E}(\mathbf{x}_{i,t-1} \varepsilon_{it}) + \mathbb{E}(\mathbf{x}_{i,t-1} \varepsilon_{i,t-1}) = \mathbf{0}
$$

It is because $\mathbb{E}(\mathbf{x}_{is} \varepsilon_{it}) = \mathbf{0}$ for any t and s implies

$$
\mathbb{E}(\mathbf{x}_{it} \varepsilon_{it}) = \mathbb{E}(\mathbf{x}_{it} \varepsilon_{i,t-1}) = \mathbb{E}(\mathbf{x}_{i,t-1} \varepsilon_{it}) = \mathbb{E}(\mathbf{x}_{i,t-1} \varepsilon_{i,t-1}) = \mathbf{0}
$$

Thus, weaker assumption $\mathbb{E}(\mathbf{x}_{is} \varepsilon_{it}) = \mathbf{0}$ for any t and s is sufficient for $\mathbb{E}((\mathbf{x}_{it} - \mathbf{x}_{i,t-1})(\varepsilon_{it} - \varepsilon_{i,t-1})) = \mathbf{0}$

The necessary condition of FD estimator to be unbiased is $\mathbb{E}(\mathbf{\Delta \varepsilon}_i | \mathbf{\Delta X}_i) = \mathbf{0}$

$$
\begin{aligned}
\mathbb{E}(\mathbf{\Delta \varepsilon}_i | \mathbf{\Delta X}_i) &= \mathbf{\Delta} \underbrace{\mathbb{E}(\mathbf{\varepsilon}_i | \mathbf{X}_i)}_{\mathbf{0}} \qquad\qquad \text{as } \mathbf{\Delta} \text{ is constant and strict exogeneity} \\
&= \mathbf{0}
\end{aligned}
$$

Thus, FD estimator satisfies the necessary condition of unbiasedness given strict exogeneity assumption.

1.4.5 Variance of $\hat{\boldsymbol{\beta}}_{fd}^{ols}$

$$Var(\hat{\boldsymbol{\beta}}_{fd}^{ols}|\boldsymbol{X}_i) = Var([\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta y}_i|\boldsymbol{X}_i)$$

$$= [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}Var(\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta y}_i|\boldsymbol{X}_i)[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1'}$$

$$= [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'Var(\boldsymbol{\Delta \varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}$$

If ε_{it} is homoskedasticity and serially uncorrelated across t and independence across i and with strict exogeneity, we have

$$\varepsilon_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma_\varepsilon^2\boldsymbol{I}_T],\ Var(\boldsymbol{\Delta\varepsilon_i}|\boldsymbol{X}_i) = \boldsymbol{\Delta}Var(\boldsymbol{\varepsilon}|\boldsymbol{X}_i)\boldsymbol{\Delta}' = \boldsymbol{\Delta}\sigma_\varepsilon^2\boldsymbol{I}_T\boldsymbol{\Delta}' = \sigma_\varepsilon^2\boldsymbol{\Delta\Delta}' = \sigma_\varepsilon^2 \begin{pmatrix} 2 & -1 & 0 & \cdots & 0 & 0 \\ -1 & 2 & -1 & \cdots & 0 & 0 \\ 0 & -1 & 2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 2 & -1 \\ 0 & 0 & 0 & \cdots & -1 & 2 \end{pmatrix}$$ Thus,

$\boldsymbol{\Delta\varepsilon}_i$ is homoskedasticity but not serially uncorrelated e.g. $Cov(\varepsilon_{it} - \varepsilon_{i,t-1}, \varepsilon_{i,t-1} - \varepsilon_{i,t-2}|\boldsymbol{X}_i) = -\sigma_\varepsilon^2 < 0$. As a result, the necessary condition for FD estimator to be efficient is not satisfied.

$$= [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\sigma_\varepsilon^2\boldsymbol{\Delta\Delta}'\boldsymbol{\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}$$

$$= \sigma_\varepsilon^2[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}_i'\boldsymbol{\Delta}'\boldsymbol{\Delta\Delta}'\boldsymbol{\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}$$

If $\varepsilon_i|\boldsymbol{X}_i \sim inid\ [\boldsymbol{0}, \boldsymbol{\Omega}_i],\ Var(\boldsymbol{\Delta\varepsilon_i}|\boldsymbol{X}_i) = \boldsymbol{\Delta}Var(\boldsymbol{\varepsilon}|\boldsymbol{X}_i)\boldsymbol{\Delta}' = \boldsymbol{\Delta}\mathbb{E}[(\varepsilon_i - \mathbb{E}[\varepsilon_i|\boldsymbol{X}_i])(\varepsilon_i - \mathbb{E}[\varepsilon_i|\boldsymbol{X}_i])'|\boldsymbol{X}_i]\boldsymbol{\Delta}' = \boldsymbol{\Delta}\mathbb{E}[(\varepsilon_i - \boldsymbol{0})(\varepsilon_i - \boldsymbol{0})'|\boldsymbol{X}_i]\boldsymbol{\Delta}' = \boldsymbol{\Delta}\mathbb{E}[\varepsilon_i\varepsilon_i'|\boldsymbol{X}_i]\boldsymbol{\Delta}' = \mathbb{E}[\boldsymbol{\Delta}\varepsilon_i\varepsilon_i'\boldsymbol{\Delta}'|\boldsymbol{X}_i] = \mathbb{E}[\boldsymbol{\Delta}\varepsilon_i(\boldsymbol{\Delta}\varepsilon_i)'|\boldsymbol{X}_i]$

$$= [\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'E[\boldsymbol{\Delta}\varepsilon_i(\boldsymbol{\Delta}\varepsilon_i)'|\boldsymbol{X}_i]\boldsymbol{\Delta X}_i[\sum_{i=1}^{N}(\boldsymbol{\Delta X}_i)'\boldsymbol{\Delta X}_i]^{-1}$$

If ε_{it} follows random walk process i.e., $\varepsilon_{it} = \varepsilon_{i,t-1} + v_{it}$ where v_{it} follows white noise process, $\varepsilon_{it} - \varepsilon_{i,t-1} = v_{it}$ follows white noise process as well. Thus, $\varepsilon_{it} - \varepsilon_{i,t-1}$ is homoskedasticity and serially uncorrelated as white noise process is homoskedasticity and serially uncorrelated. As a result, FD is efficient in this case.

1.5 Least-Squares Dummy Variable Estimator

$$\boldsymbol{y} = (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} = ((\boldsymbol{I}_N \otimes \boldsymbol{e}) \quad \boldsymbol{X})\begin{pmatrix} \boldsymbol{\alpha} \\ \boldsymbol{\beta} \end{pmatrix} + \boldsymbol{\varepsilon}$$

$$((\boldsymbol{I}_N \otimes \boldsymbol{e}) \quad \boldsymbol{X})'((\boldsymbol{I}_N \otimes \boldsymbol{e}) \quad \boldsymbol{X}) = \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})' \\ \boldsymbol{X}' \end{pmatrix}((\boldsymbol{I}_N \otimes \boldsymbol{e}) \quad \boldsymbol{X})$$

$$= \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & (\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{X} \\ \boldsymbol{X}'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}'\boldsymbol{X} \end{pmatrix}$$

$$(\boldsymbol{I}_N \otimes \boldsymbol{e})'(\boldsymbol{I}_N \otimes \boldsymbol{e} = \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}' \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}$$

$$= \begin{pmatrix} \boldsymbol{e}' & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}' \end{pmatrix} \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}$$

$$= \begin{pmatrix} \boldsymbol{e}'\boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}'\boldsymbol{e} \end{pmatrix}$$

$$= \begin{pmatrix} T & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & T \end{pmatrix}$$

$$= T\boldsymbol{I}_N$$

$$(\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{X} = \begin{pmatrix} \boldsymbol{e}' & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}' \end{pmatrix} \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix}$$

$$= \begin{pmatrix} \boldsymbol{e}'\boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{e}'\boldsymbol{X}_N \end{pmatrix}$$

$$= \begin{pmatrix} \sum_{t=1}^{T} \boldsymbol{x}'_{1t} \\ \vdots \\ \sum_{t=1}^{T} \boldsymbol{x}'_{Nt} \end{pmatrix}$$

$$= \begin{pmatrix} T \sum_{t=1}^{T} \boldsymbol{x}'_{1t}/T \\ \vdots \\ T \sum_{t=1}^{T} \boldsymbol{x}'_{Nt}/T \end{pmatrix}$$

$$= \begin{pmatrix} T\bar{\boldsymbol{x}}'_1 \\ \vdots \\ T\bar{\boldsymbol{x}}'_N \end{pmatrix}$$

$$= T\bar{\boldsymbol{X}}$$

$$\begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X} \end{pmatrix}' \boldsymbol{y} = \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})' \\ \boldsymbol{X}' \end{pmatrix} \boldsymbol{y}$$

$$= \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{y} \\ \boldsymbol{X}'\boldsymbol{y} \end{pmatrix}$$

$$\begin{pmatrix} \hat{\boldsymbol{\alpha}}_{dv}^{ols} \\ \hat{\boldsymbol{\beta}}_{dv}^{ols} \end{pmatrix} = [(\begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X} \end{pmatrix}' \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X} \end{pmatrix}]^{-1} \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X} \end{pmatrix}' \boldsymbol{y}$$

$$= \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & (\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{X} \\ \boldsymbol{X}'(\boldsymbol{I}_N \otimes \boldsymbol{e}) & \boldsymbol{X}'\boldsymbol{X} \end{pmatrix}^{-1} \begin{pmatrix} (\boldsymbol{I}_N \otimes \boldsymbol{e})'\boldsymbol{y} \\ \boldsymbol{X}'\boldsymbol{y} \end{pmatrix}$$

$$= \begin{pmatrix} T\boldsymbol{I}_N & T\bar{\boldsymbol{X}} \\ T\bar{\boldsymbol{X}}' & \boldsymbol{X}'\boldsymbol{X} \end{pmatrix}^{-1} \begin{pmatrix} T\bar{\boldsymbol{y}} \\ \boldsymbol{X}'\boldsymbol{y} \end{pmatrix}$$

$$\hat{\boldsymbol{\beta}}_{dv}^{ols} = [\boldsymbol{X}'\boldsymbol{X} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{X}}]^{-1}(\boldsymbol{X}'\boldsymbol{y} - T\bar{\boldsymbol{X}}'\bar{\boldsymbol{y}}) = \hat{\boldsymbol{\beta}}_{within}^{ols}$$

There is an easier way to show the equivalence of within estimator and dummy variable estimator

Let $\boldsymbol{E} := (\boldsymbol{I}_N \otimes \boldsymbol{e}) = \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}$

$$\boldsymbol{y} = \boldsymbol{E}\boldsymbol{\alpha} + \boldsymbol{\varepsilon}_{yE}$$

$$
\begin{aligned}
\hat{\boldsymbol{\alpha}} &= (\boldsymbol{E}'\boldsymbol{E})^{-1}\boldsymbol{E}'\boldsymbol{y} \\
&= \begin{pmatrix} \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}' \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \end{pmatrix}^{-1} \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}' \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \begin{pmatrix} \boldsymbol{e}' & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}' \end{pmatrix} \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \end{pmatrix}^{-1} \begin{pmatrix} \boldsymbol{e}' & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}' \end{pmatrix} \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \boldsymbol{e}'\boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e}'\boldsymbol{e} \end{pmatrix}^{-1} \begin{pmatrix} \boldsymbol{e}'\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{e}'\boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{e}'\boldsymbol{e})^{-1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & (\boldsymbol{e}'\boldsymbol{e})^{-1} \end{pmatrix} \begin{pmatrix} \boldsymbol{e}'\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{e}'\boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} (\boldsymbol{e}'\boldsymbol{e})^{-1}\boldsymbol{e}'\boldsymbol{y}_1 \\ \vdots \\ (\boldsymbol{e}'\boldsymbol{e})^{-1}\boldsymbol{e}'\boldsymbol{y}_N \end{pmatrix} \\
&= \begin{pmatrix} T^{-1}\sum_{t=1}^{T} y_{1t} \\ \vdots \\ T^{-1}\sum_{t=1}^{T} y_{Nt} \end{pmatrix} \\
&= \begin{pmatrix} \bar{y}_1 \\ \vdots \\ \bar{y}_N \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
\hat{\boldsymbol{\varepsilon}}_{yE} = \boldsymbol{y} - \boldsymbol{E}\hat{\boldsymbol{\alpha}} &= \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} - \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \begin{pmatrix} \bar{y}_1 \\ \vdots \\ \bar{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} - \begin{pmatrix} \boldsymbol{e}\bar{y}_1 \\ \vdots \\ \boldsymbol{e}\bar{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \boldsymbol{y}_1 - \boldsymbol{e}\bar{y}_1 \\ \vdots \\ \boldsymbol{y}_N - \boldsymbol{e}\bar{y}_N \end{pmatrix} \\
&= \begin{pmatrix} \boldsymbol{Q}\boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{Q}\boldsymbol{y}_N \end{pmatrix} \\
&= \boldsymbol{Q}\boldsymbol{y}
\end{aligned}
$$

Similarly,

$$\boldsymbol{X} = \boldsymbol{E}\boldsymbol{\alpha} + \boldsymbol{\varepsilon}_{XE}$$
$$\hat{\boldsymbol{\varepsilon}}_{XE} = \boldsymbol{Q}\boldsymbol{X}$$

$$y = X\beta + (I_N \otimes e)\alpha + \varepsilon$$
$$y = X\beta + E\alpha + \varepsilon$$

By Frisch-Waugh-Lovell Theorem,

$$\hat{\beta}_{dv}^{ols} = (\hat{\varepsilon}'_{XE}\hat{\varepsilon}_{XE})^{-1}\hat{\varepsilon}'_{XE}\hat{\varepsilon}_{yE}$$
$$= [(QX)'QX]^{-1}(QX)'Qy = \hat{\beta}_{within}^{ols}$$

If $N \to \infty$, the number of α_i estimated goes to infinity. If T is fixed, the LSDV estimates of β is consistent (as LSDV = FE estimates for β which is consistent for fixed T) but inconsistent for α. (There is no incidental parameters problem as the estimates of β are not contaminated). If T also $\to \infty$, then the LSDV estimates of α is also consistent.

2 Random Effect Model

$$y_{it} = \boldsymbol{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \alpha_i + \begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$

$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i}$$

$$\begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} = \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{pmatrix} + \begin{pmatrix} \boldsymbol{\varepsilon}_1 \\ \vdots \\ \boldsymbol{\varepsilon}_N \end{pmatrix}$$

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon}$$

2.1 Assumptions

2.1.1 1. Strong/Strict Exogeneity of Regressors

for all t,

$$E(\varepsilon_{it}|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT}) = 0$$

equivalently,

$$E(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{0}$$

2.1.2 2. Covariance Structure

$$\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma_\varepsilon^2 \boldsymbol{I}_T]$$
$$\alpha_i|\boldsymbol{X}_i \sim iid\ [0, \sigma_\alpha^2]$$
$$\boldsymbol{\varepsilon}_i \perp \alpha_i|\boldsymbol{X}_i$$

2.2 Moments of $\boldsymbol{u}_i|\boldsymbol{X}_i$

$$\begin{aligned} \boldsymbol{\Omega} := Var(\boldsymbol{u}_i|\boldsymbol{X}_i) &= Var(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) && \text{because of } \boldsymbol{\varepsilon}_i \perp \alpha_i|\boldsymbol{X}_i \\ &= Var(\boldsymbol{e}\alpha_i|\boldsymbol{X}_i) + Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) \\ &= \boldsymbol{e}Var(\alpha_i|\boldsymbol{X}_i)\boldsymbol{e}' + Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) \\ &= \sigma_\alpha^2 \boldsymbol{e}\boldsymbol{e}' + \sigma_\varepsilon^2 \boldsymbol{I}_T \\ &= \begin{pmatrix} \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 \\ \vdots & \ddots & \vdots \\ \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 \end{pmatrix} + \begin{pmatrix} \sigma_\varepsilon^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_\varepsilon^2 \end{pmatrix} \\ &= \begin{pmatrix} \sigma_\alpha^2 + \sigma_\varepsilon^2 & \cdots & \sigma_\alpha^2 \\ \vdots & \ddots & \vdots \\ \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 + \sigma_\varepsilon^2 \end{pmatrix} \end{aligned}$$

$$\begin{aligned} \mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) &= \mathbb{E}(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) \\ &= \boldsymbol{e}\underbrace{\mathbb{E}(\alpha_i|\boldsymbol{X}_i)}_{0} + \underbrace{\mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)}_{0} \\ &= \boldsymbol{0} \end{aligned}$$

Note that $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = \mathbb{E}(\alpha_i|\boldsymbol{x}_{i1}, \cdots, \boldsymbol{x}_{iT}) = 0$ called orthogonality assumption. $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies Cov(\alpha_i, \boldsymbol{X}_i) = \boldsymbol{0}$ It is because $Cov(\alpha_i, \boldsymbol{X}_i) = \mathbb{E}(\alpha_i\boldsymbol{X}_i) - \mathbb{E}(\alpha_i)\mathbb{E}(\boldsymbol{X}_i) = \mathbb{E}(\mathbb{E}(\alpha_i\boldsymbol{X}_i|\boldsymbol{X}_i)) - \mathbb{E}(\mathbb{E}(\alpha_i|\boldsymbol{X}_i))\mathbb{E}(\boldsymbol{X}_i) = \mathbb{E}(\mathbb{E}(\alpha_i|\boldsymbol{X}_i)\boldsymbol{X}_i) = \boldsymbol{0}$ There is no OVB i.e., $\boldsymbol{u}_i$ is not correlated with $\boldsymbol{X}_i$

$\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0}$ means that the necessary condition for OLS estimator to be unbiased is satisfied. Moreover, $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{X}_i'\boldsymbol{u}_i) = \boldsymbol{0}$ which means that the necessary condition for OLS estimator to be consistent is also satisfied. However, $\boldsymbol{u}_i|\boldsymbol{X}_i$ is homoskedasticity but serially correlated. Thus, the necessary condition for OLS estimator to be efficient is not satisfied. As a result, it is not efficient.

As we know the covariance structure of $\boldsymbol{u}_i|\boldsymbol{X}_i$ due to the strong assumptions in random effect model, we can use GLS estimation, which yields efficient estimates.

2.3 Random Effect Estimator (GLS Estimator)

We want to find a GLS transformer $\boldsymbol{T}_{GLS}$ such that

$$Var(\boldsymbol{T}_{GLS}\boldsymbol{u}_i|\boldsymbol{X}_i) = \sigma_\varepsilon^2 \boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}Var(\boldsymbol{u}_i|\boldsymbol{X}_i)\boldsymbol{T}_{GLS}' = \sigma_\varepsilon^2 \boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\boldsymbol{\Omega}\boldsymbol{T}_{GLS}' = \sigma_\varepsilon^2 \boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}^{1/2}\boldsymbol{T}_{GLS}' = \sigma_\varepsilon^2 \boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}'^{1/2}\boldsymbol{T}_{GLS}' = \sigma_\varepsilon^2 \boldsymbol{I}_T$$
$$\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2}(\boldsymbol{T}_{GLS}\boldsymbol{\Omega}^{1/2})' = \sigma_\varepsilon^2 \boldsymbol{I}_T$$

So, $\boldsymbol{T}_{GLS} = \sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}$

Define $\psi^2 := \frac{\sigma_\varepsilon^2}{T\sigma_\alpha^2 + \sigma_\varepsilon^2}$

$$\begin{aligned}
\boldsymbol{\Omega} &= \sigma_\varepsilon^2 \boldsymbol{I}_T + \sigma_\alpha^2 \boldsymbol{e}\boldsymbol{e}' \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{\sigma_\alpha^2}{\sigma_\varepsilon^2}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{T\sigma_\alpha^2}{\sigma_\varepsilon^2}T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{T\sigma_\alpha^2 + \sigma_\varepsilon^2 - \sigma_\varepsilon^2}{\sigma_\varepsilon^2}T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + (\frac{T\sigma_\alpha^2 + \sigma_\varepsilon^2}{\sigma_\varepsilon^2} - 1)T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + (\frac{1}{\psi^2} - 1)T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T + \frac{1}{\psi^2}T^{-1}\boldsymbol{e}\boldsymbol{e}' - T^{-1}\boldsymbol{e}\boldsymbol{e}') \\
&= \sigma_\varepsilon^2(\boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}' + \frac{1}{\psi^2}(T^{-1}\boldsymbol{e}\boldsymbol{e}' - \boldsymbol{I}_T + \boldsymbol{I}_T)) \\
&= \sigma_\varepsilon^2(\boldsymbol{Q} + \frac{1}{\psi^2}(\boldsymbol{I}_T - \boldsymbol{Q}))
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\Omega}^{-1} &= [\sigma_\varepsilon^2(\boldsymbol{Q} + \frac{1}{\psi^2}(\boldsymbol{I}_T - \boldsymbol{Q}))]^{-1} \\
&= \sigma_\varepsilon^{-2}(\boldsymbol{Q}^- + \psi^2(\boldsymbol{I}_T^{-1} - \boldsymbol{Q}^-)) \\
&= \sigma_\varepsilon^{-2}(\boldsymbol{Q} + \psi^2(\boldsymbol{I}_T - \boldsymbol{Q}))
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\Omega}^{-1/2} &= \sigma_\varepsilon^{-1}(\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q})) \\
\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2} &= (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))
\end{aligned}$$

$$\sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{y}_i = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + (\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)) = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{u}_i) = \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{X}_i\boldsymbol{\beta} + \sigma_\varepsilon\boldsymbol{\Omega}^{-1/2}\boldsymbol{u}_i$$

so that $Var(\sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}\boldsymbol{u}_i|\boldsymbol{X}_i) = \sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}Var(\boldsymbol{u}_i|\boldsymbol{X}_i)\sigma_\varepsilon \boldsymbol{\Omega}'^{-1/2} = \sigma_\varepsilon^2 \boldsymbol{\Omega}^{-1/2}\boldsymbol{\Omega}\boldsymbol{\Omega}^{-1/2} = \sigma_\varepsilon^2 \boldsymbol{\Omega}^{-1/2}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}^{1/2}\boldsymbol{\Omega}^{-1/2} = \sigma_\varepsilon^2 \boldsymbol{I}_T$

$$
\begin{aligned}
\sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}\boldsymbol{y}_i = (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{y}_i &= \boldsymbol{Q}\boldsymbol{y}_i + \psi(\boldsymbol{I}_T\boldsymbol{y}_i - \boldsymbol{Q}\boldsymbol{y}_i) \\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i + \psi(\boldsymbol{y}_i - \boldsymbol{y}_i + \boldsymbol{e}\bar{y}_i) \\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i + \psi\boldsymbol{e}\bar{y}_i \\
&= \boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i(1 - \psi) \\
&= \boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i
\end{aligned}
$$

$$
\begin{aligned}
\sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}\boldsymbol{X}_i\boldsymbol{\beta} = (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{X}_i\boldsymbol{\beta} &= \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta} + \psi(\boldsymbol{I}_T\boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{Q}\boldsymbol{X}_i\boldsymbol{\beta}) \\
&= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + \psi(\boldsymbol{X}_i\boldsymbol{\beta} - (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta}) \\
&= (\boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta}) + \psi(\boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta}) \\
&= \boldsymbol{X}_i\boldsymbol{\beta} - \boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta} + \psi\boldsymbol{e}\bar{\boldsymbol{x}}_i'\boldsymbol{\beta} \\
&= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i' + \psi\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} \\
&= (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i'(1 - \psi))\boldsymbol{\beta} \\
&= (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta}
\end{aligned}
$$

$$
\begin{aligned}
\sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}\boldsymbol{e}\alpha_i = (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{e}\alpha_i &= \boldsymbol{Q}\boldsymbol{e}\alpha_i + \psi(\boldsymbol{I}_T\boldsymbol{e}\alpha_i - \boldsymbol{Q}\boldsymbol{e}\alpha_i) \\
&= \boldsymbol{0}\alpha_i + \psi(\boldsymbol{e}\alpha_i - \boldsymbol{0}\alpha_i) \\
&= \psi\boldsymbol{e}\alpha_i \\
&= (1 - \lambda)\boldsymbol{e}\alpha_i
\end{aligned}
$$

$$
\begin{aligned}
(\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{y}_i &= (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{X}_i\boldsymbol{\beta} + (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{e}\alpha_i + (\boldsymbol{Q} + \psi(\boldsymbol{I}_T - \boldsymbol{Q}))\boldsymbol{\varepsilon}_i \quad &\text{Level 2} \\
\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i &= (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1 - \lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i) \quad &\text{where } \lambda = 1 - \psi = 1 - \frac{\sigma_\varepsilon}{\sqrt{T\sigma_\alpha^2 + \sigma_\varepsilon^2}}
\end{aligned}
$$

Random effect estimator is the OLS estimator of the beta in the transformed model $\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1 - \lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)$

Fixed effect / within estimator is the OLS estimator of the beta in the transformed model $\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)$

Pooled OLS estimator is the OLS estimator of the beta in the original model $\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i$

As $T \to \infty$, $\lambda \to 1$, $\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1 - \lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)$ converges to $\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)$ Thus, random effect estimator converges to fixed effect / within estimator as $T \to \infty$, $\lambda \to 1$

As $\sigma_\alpha^2 \to 0$, $\lambda \to 0$, $\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1 - \lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)$ converges to $\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i$ Thus, random effect estimator converges to pooled OLS estimator as $\sigma_\alpha^2 \to 0$, $\lambda \to 0$

$$
\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + (1 - \lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i) \qquad \text{Level 2}
$$

$$
\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} - \lambda \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \bar{y}_i = \left(\begin{pmatrix} \boldsymbol{x}_{i1}' \\ \vdots \\ \boldsymbol{x}_{iT}' \end{pmatrix} - \lambda \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \bar{\boldsymbol{x}}_i' \right)\boldsymbol{\beta} + (1 - \lambda)\begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \alpha_i + \left(\begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix} - \lambda \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \bar{\varepsilon}_i \right)
$$

$$
\begin{pmatrix} y_{i1} - \lambda\bar{y}_i \\ \vdots \\ y_{iT} - \lambda\bar{y}_i \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}_{i1}' - \lambda\bar{\boldsymbol{x}}_i' \\ \vdots \\ \boldsymbol{x}_{iT}' - \lambda\bar{\boldsymbol{x}}_i' \end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} (1 - \lambda)\alpha_i \\ \vdots \\ (1 - \lambda)\alpha_i \end{pmatrix} + \begin{pmatrix} \varepsilon_{i1} - \lambda\bar{\varepsilon}_i \\ \vdots \\ \varepsilon_{iT} - \lambda\bar{\varepsilon}_i \end{pmatrix}
$$

$$
\begin{pmatrix} y_{i1} - \lambda\bar{y}_i \\ \vdots \\ y_{iT} - \lambda\bar{y}_i \end{pmatrix} = \begin{pmatrix} (\boldsymbol{x}_{i1} - \lambda\bar{\boldsymbol{x}}_i)' \\ \vdots \\ (\boldsymbol{x}_{iT} - \lambda\bar{\boldsymbol{x}}_i)' \end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} (1 - \lambda)\alpha_i \\ \vdots \\ (1 - \lambda)\alpha_i \end{pmatrix} + \begin{pmatrix} \varepsilon_{i1} - \lambda\bar{\varepsilon}_i \\ \vdots \\ \varepsilon_{iT} - \lambda\bar{\varepsilon}_i \end{pmatrix}
$$

$$
y_{it} - \lambda\bar{y}_i = (\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + \underbrace{(1 - \lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)}_{v_{it}} \qquad \text{Level 1}
$$

$$\hat{\boldsymbol{\beta}}_{re}^{ols} = [\sum_{i=1}^{N}(\boldsymbol{X}_i - \lambda \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{X}_i - \lambda \boldsymbol{e}\bar{\boldsymbol{x}}_i')]^{-1}\sum_{i=1}^{N}(\boldsymbol{X}_i - \lambda \boldsymbol{e}\bar{\boldsymbol{x}}_i')'(\boldsymbol{y}_i - \lambda \boldsymbol{e}\bar{y}_i) \qquad \text{Level 2}$$

$$= [\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)']^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)(y_{it} - \lambda\bar{y}_i) \qquad \text{Level 1}$$

If $\boldsymbol{x}_{it}$ is replaced by $\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}$ and $\bar{\boldsymbol{x}}_i$ is replaced by $\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}$

$$
\begin{aligned}
(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}) &= \boldsymbol{x}_{it} - \bar{\boldsymbol{x}} - \lambda\bar{\boldsymbol{x}}_i + \lambda\bar{\boldsymbol{x}} \\
&= \boldsymbol{x}_{it} - \bar{\boldsymbol{x}} - (1-\psi)\bar{\boldsymbol{x}}_i + (1-\psi)\bar{\boldsymbol{x}} \\
&= \boldsymbol{x}_{it} - \bar{\boldsymbol{x}} - \bar{\boldsymbol{x}}_i + \psi\bar{\boldsymbol{x}}_i + \bar{\boldsymbol{x}} - \psi\bar{\boldsymbol{x}} \\
&= (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + \psi(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})
\end{aligned}
$$

$$
\begin{aligned}
\sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))' &= \sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + \psi(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + \psi(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \psi\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' + \\
&\quad \psi\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})'
\end{aligned}
$$

It is because

$$
\begin{aligned}
\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' &= \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' - \sum_{i=1}^{N}\sum_{t=1}^{T}\bar{\boldsymbol{x}}_i(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' - \sum_{i=1}^{N}T\bar{\boldsymbol{x}}_i(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' - \sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \boldsymbol{0}
\end{aligned}
$$

Similarly, if y_{it} is replaced by $y_{it} - \bar{y}$ and $\bar{y}_i$ is replaced by $\bar{y}_i - \bar{y}$

$$\sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}) - \lambda(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))((y_{it} - \bar{y}) - \lambda(\bar{x}_i - \bar{y})) = \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{y}_i - \bar{y})$$

$$\hat{\boldsymbol{\beta}}_{re}^{ols} = (\overbrace{\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'}^{Within} + \psi^2\overbrace{\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})'}^{Between})^{-1}$$
$$(\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) + \psi^2\sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{y}_i - \bar{y}))$$

If $T \to \infty$, $\psi^2 \to 0$, $\hat{\boldsymbol{\beta}}_{re}^{ols} \to \hat{\boldsymbol{\beta}}_{within}^{ols}$

If $\sigma_\alpha^2 \to 0$, $\psi^2 \to 1$, $\hat{\boldsymbol{\beta}}_{re}^{ols} \to \hat{\boldsymbol{\beta}}_{pool}^{ols}$ It is because

$$
\begin{aligned}
\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}})(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}})' &= \sum_{i=1}^{N}\sum_{t=1}^{T}((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + (\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))((\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) + (\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}}))' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' + \\
&\quad \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})' \\
&= \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})'
\end{aligned}
$$

Similarly,

$$
\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}})(y_{it} - \bar{y}) = \sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{y}_i - \bar{y})
$$

Thus,

$$
\begin{aligned}
\hat{\boldsymbol{\beta}}_{pool}^{ols} &= (\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}})(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}})')^{-1}(\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}})(y_{it} - \bar{y})) \\
&= (\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)' + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})')^{-1} \\
&\quad (\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)(y_{it} - \bar{y}_i) + \sum_{i=1}^{N}\sum_{t=1}^{T}(\bar{\boldsymbol{x}}_i - \bar{\boldsymbol{x}})(\bar{y}_i - \bar{y}))
\end{aligned}
$$

So, pooled OLS estimator is an inefficient weighted average of within and between effects. RE estimator is an efficient weighted average of within and between effects.

As RE model assumes $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\ [\boldsymbol{0}, \sigma_\varepsilon^2 \boldsymbol{I}_T]$

$$
Var(\hat{\boldsymbol{\beta}}_{re}^{ols}) = \sigma_\varepsilon^2 [\sum_{i=1}^{N}\sum_{t=1}^{T}(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)(\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)']^{-1}
$$

2.3.1 Between Effect Model and estimation of σ_α^2

$$
\begin{aligned}
\bar{y}_i &= \bar{\boldsymbol{x}}_i'\boldsymbol{\beta} + \overbrace{\alpha_i + \bar{\varepsilon}_i}^{v_i} \\
\sigma_B^2 = Var(v_i) &= Var(\alpha_i + \bar{\varepsilon}_i) \\
&= Var(\alpha_i) + Var(\bar{\varepsilon}_i) \\
&= Var(\alpha_i) + T^{-1}Var(\varepsilon_{it}) \qquad\qquad \text{as } \varepsilon_{it} \text{ is serially uncorrelated}
\end{aligned}
$$

$$
\underbrace{Var(\alpha_i)}_{\sigma_\alpha^2} = \underbrace{Var(v_i)}_{\sigma_B^2} - T^{-1}\underbrace{Var(\varepsilon_{it})}_{\sigma_\varepsilon^2}
$$

3 GMM Estimation of Linear Panel Model

3.1 Linear Panel Model

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}'_{i1} \\ \vdots \\ \boldsymbol{x}'_{iT} \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix}$$

$$\boldsymbol{y}_i = \boldsymbol{X}_i \boldsymbol{\beta} + \boldsymbol{u}_i$$

3.2 Exogeneity Assumption

$$\mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{u}_i) = \boldsymbol{0}$$

$\boldsymbol{Z}_i$ is T x r matrix. r is equal to the number of exogeneous variables in $\boldsymbol{X}_i$ plus the number of instrumental variables for endogenous variables in $\boldsymbol{X}_i$. In GMM context, r is also the number of moment conditions.

K is the number of parameters.

$r \geq K$. If $r = K$, the model is just-identified, GMM is the same as MM; if $r > K$, the model is over-identified.

3.2.1 1. Summation Assumption

The weakest exogeneity assumption

$$\boldsymbol{Z}_i = \begin{pmatrix} \boldsymbol{z}'_{i1} \\ \vdots \\ \boldsymbol{z}'_{iT} \end{pmatrix}$$

$$\mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{u}_i) = \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}'_{i1} \\ \vdots \\ \boldsymbol{z}'_{iT} \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix} \right) = \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}_{i1} & \cdots & \boldsymbol{z}_{iT} \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix} \right) = \mathbb{E}(\sum_{t=1}^{T} \boldsymbol{z}_{it} u_{it}) = \boldsymbol{0}$$

3.2.2 2. Contemporaneous Exogeneity Assumption

Stronger

$$\boldsymbol{Z}_i = \begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix}$$

$$\begin{aligned} \mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{u}_i) &= \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}'_{i1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{z}'_{iT} \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix} \right) \\ &= \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}_{i1} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{z}_{iT} \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix} \right) \\ &= \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}_{i1} u_{i1} \\ \vdots \\ \boldsymbol{z}_{iT} u_{iT} \end{pmatrix} \right) \\ &= \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{i1}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT} u_{iT}) \end{pmatrix} = \boldsymbol{0} \end{aligned}$$

3.2.3   3. Weak/Sequential Exogeneity Assumption

More stronger

$$
\boldsymbol{Z}_i = \begin{pmatrix} \boldsymbol{z}_{i1}' & \boldsymbol{0} & \cdots & & \boldsymbol{0} \\ \vdots & (\boldsymbol{z}_{i1}' \ \ \boldsymbol{z}_{i2}') & \vdots & & \vdots \\ \vdots & \vdots & \ddots & & \vdots \\ \boldsymbol{0} & \cdots & & \boldsymbol{0} & (\boldsymbol{z}_{i1}' \ \cdots \ \boldsymbol{z}_{iT}') \end{pmatrix}
$$

$$
\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}_{i1}' & \boldsymbol{0} & \cdots & & \boldsymbol{0} \\ \vdots & (\boldsymbol{z}_{i1}' \ \ \boldsymbol{z}_{i2}') & \vdots & & \vdots \\ \vdots & \vdots & \ddots & & \vdots \\ \boldsymbol{0} & \cdots & & \boldsymbol{0} & (\boldsymbol{z}_{i1}' \ \cdots \ \boldsymbol{z}_{iT}') \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix} \right)
$$

$$
= \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}_{i1} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \begin{pmatrix}\boldsymbol{z}_{i1}\\\boldsymbol{z}_{i2}\end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ & & & \begin{pmatrix}\boldsymbol{z}_{i1}\\\vdots\\\boldsymbol{z}_{iT}\end{pmatrix} \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix} \right)
$$

$$
= \mathbb{E}\left(\begin{pmatrix} \boldsymbol{z}_{i1}u_{i1} \\ \begin{pmatrix}\boldsymbol{z}_{i1}u_{i2}\\\boldsymbol{z}_{i2}u_{i2}\end{pmatrix} \\ \vdots \\ \begin{pmatrix}\boldsymbol{z}_{i1}u_{iT}\\\vdots\\\boldsymbol{z}_{iT}u_{iT}\end{pmatrix} \end{pmatrix} \right) = \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1}u_{i1}) \\ \begin{pmatrix}\mathbb{E}(\boldsymbol{z}_{i1}u_{i2})\\\mathbb{E}(\boldsymbol{z}_{i2}u_{i2})\end{pmatrix} \\ \vdots \\ \begin{pmatrix}\mathbb{E}(\boldsymbol{z}_{i1}u_{iT})\\\vdots\\\mathbb{E}(\boldsymbol{z}_{iT}u_{iT})\end{pmatrix} \end{pmatrix} = \boldsymbol{0}
$$

which is equivalent as $E(\boldsymbol{z}_{is}u_{it}) = \boldsymbol{0}$ for $s \leq t$

Strong form of sequential exogeneity $E(u_{it}|\boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1}) = 0$ implies weak form of sequential exogeneity implies $E(\boldsymbol{z}_{is}u_{it}) = \boldsymbol{0}$ for $s \leq t$ as $\mathbb{E}(\boldsymbol{z}_{is}u_{it}) = \mathbb{E}(\mathbb{E}(\boldsymbol{z}_{is}u_{it}|\boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1})) = \mathbb{E}(\boldsymbol{z}_{is}\underbrace{\mathbb{E}(u_{it}|\boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1})}_{0}) = \boldsymbol{0}$ for $s \leq t$

It also implies $Cov(\boldsymbol{z}_{is}, u_{it}) = \boldsymbol{0}$ for $s \leq t$ as $Cov(\boldsymbol{z}_{is}, u_{it}) = \underbrace{\mathbb{E}(\boldsymbol{z}_{is}u_{it})}_{\boldsymbol{0}} - \mathbb{E}(\boldsymbol{z}_{is})\mathbb{E}(u_{it}) = -\mathbb{E}(\boldsymbol{z}_{is})\mathbb{E}(\underbrace{\mathbb{E}(u_{it}|\boldsymbol{z}_{it}, \cdots, \boldsymbol{z}_{i1})}_{0}) = \boldsymbol{0}$ for $s \leq t$

3.2.4   4. Strong/Strict Exogeneity Assumption

The strongest exogeneity assumption

$$
\boldsymbol{Z}_i = \begin{pmatrix} (\boldsymbol{z}_{i1}' \ \cdots \ \boldsymbol{z}_{iT}') & \boldsymbol{0} & \cdots & & \boldsymbol{0} \\ \vdots & (\boldsymbol{z}_{i1}' \ \cdots \ \boldsymbol{z}_{iT}') & \vdots & & \vdots \\ \vdots & & \vdots & \ddots & \vdots \\ \boldsymbol{0} & & \cdots & \boldsymbol{0} & (\boldsymbol{z}_{i1}' \ \cdots \ \boldsymbol{z}_{iT}') \end{pmatrix}
$$

$$\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \mathbb{E}(\begin{pmatrix} (\boldsymbol{z}_{i1}' \cdots \boldsymbol{z}_{iT}') & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & (\boldsymbol{z}_{i1}' \cdots \boldsymbol{z}_{iT}') & \vdots & \vdots \\ \vdots & & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & (\boldsymbol{z}_{i1}' \cdots \boldsymbol{z}_{iT}') \end{pmatrix}' \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix})$$

$$= \mathbb{E}(\begin{pmatrix} \begin{pmatrix} \boldsymbol{z}_{i1} \\ \vdots \\ \boldsymbol{z}_{iT} \end{pmatrix} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \begin{pmatrix} \boldsymbol{z}_{i1} \\ \vdots \\ \boldsymbol{z}_{iT} \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \begin{pmatrix} \boldsymbol{z}_{i1} \\ \vdots \\ \boldsymbol{z}_{iT} \end{pmatrix} \end{pmatrix} \begin{pmatrix} u_{i1} \\ \vdots \\ u_{iT} \end{pmatrix})$$

$$= \mathbb{E}(\begin{pmatrix} \begin{pmatrix} \boldsymbol{z}_{i1} u_{i1} \\ \vdots \\ \boldsymbol{z}_{iT} u_{i1} \end{pmatrix} \\ \begin{pmatrix} \boldsymbol{z}_{i1} u_{i2} \\ \vdots \\ \boldsymbol{z}_{iT} u_{i2} \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \boldsymbol{z}_{i1} u_{iT} \\ \vdots \\ \boldsymbol{z}_{iT} u_{iT} \end{pmatrix} \end{pmatrix})$$

$$= \begin{pmatrix} \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{i1}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT} u_{i1}) \end{pmatrix} \\ \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{i2}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT} u_{i2}) \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \mathbb{E}(\boldsymbol{z}_{i1} u_{iT}) \\ \vdots \\ \mathbb{E}(\boldsymbol{z}_{iT} u_{iT}) \end{pmatrix} \end{pmatrix} = \boldsymbol{0}$$

which is equivalent as $\mathbb{E}(\boldsymbol{z}_{is} u_{it}) = \boldsymbol{0}$ for $s = 1, \cdots, T$

Strong form of strict exogeneity $\mathbb{E}(u_{it}|\boldsymbol{z}_{i1}, \cdots, \boldsymbol{z}_{iT}) = 0$ implies weak form of strict exogeneity $\mathbb{E}(\boldsymbol{z}_{is} u_{it}) = \boldsymbol{0}$ for $s = 1, \cdots, T$

since for $s = 1, \cdots, T$

$$\mathbb{E}(\boldsymbol{z}_{is} u_{it}) = \mathbb{E}(\mathbb{E}(\boldsymbol{z}_{is} u_{it}|\boldsymbol{z}_{i1}, \cdots, \boldsymbol{z}_{iT}))$$
$$= \mathbb{E}(\boldsymbol{z}_{is} \underbrace{\mathbb{E}(u_{it}|\boldsymbol{z}_{i1}, \cdots, \boldsymbol{z}_{iT})}_{0})$$
$$= \boldsymbol{0}$$

3.3 GMM Estimator of Linear Panel Model

3.3.1 Population Moment Condition

$$\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0)) = \boldsymbol{0}$$

where $\boldsymbol{\beta}_0$ is the true population parameter

So, $g(\boldsymbol{d}_i; \boldsymbol{\theta}_0) = \boldsymbol{Z}_i'\boldsymbol{u}_i = \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0)$

3.3.2 Objective Function

We want to find $\boldsymbol{\beta}$ from the parameter space such that the distance between $\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N$ and $\mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))$ i.e.,

$$\rho(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N, \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))) \qquad \text{where } \rho(.) \text{ is a metric function}$$

$$= || \sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N - \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0)) ||$$

$$= (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N - \underbrace{\mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))}_{\boldsymbol{0}})' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N - \underbrace{\mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta}_0))}_{\boldsymbol{0}})$$

$$= (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N) \geq 0 \qquad \text{as distance cannot be negative}$$

is as close to the zero as possible. The distance is a function of $\boldsymbol{\beta}$ i.e.,

$$Q_N(\boldsymbol{\beta}) := (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N) \geq 0$$

If $\boldsymbol{W}_N$ is symmetric and positive definite, then $Q_N(\boldsymbol{\beta})$ is strictly convex. So, we can find the target $\boldsymbol{\beta}$ by using first order condition.

3.3.3 Gradient Vector

$$\triangledown Q_N(\boldsymbol{\beta}) = \frac{\partial Q_N(\boldsymbol{\beta})}{\partial \boldsymbol{\beta}} = \frac{\partial(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)}{\partial \boldsymbol{\beta}}$$

$$= 2(\frac{\partial(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)}{\partial \boldsymbol{\beta}'})' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)$$

$$= 2[\sum_{i=1}^{N} (\frac{\partial \boldsymbol{Z}_i'\boldsymbol{y}_i}{\partial \boldsymbol{\beta}'} - \frac{\partial \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta}}{\partial \boldsymbol{\beta}'})/N]' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)$$

$$= 2[\sum_{i=1}^{N} -\frac{\partial \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta}}{\partial \boldsymbol{\beta}'}/N]' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)$$

$$= -2(1/N^2) \sum_{i=1}^{N} (\boldsymbol{Z}_i'\boldsymbol{X}_i)' \boldsymbol{W}_N \sum_{i=1}^{N} (\boldsymbol{Z}_i'\boldsymbol{y}_i - \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta})$$

$$= -2(1/N^2) \sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i'' \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i - \sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i\boldsymbol{\beta})$$

$$= -2(1/N^2)[(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i) \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i) - (\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i) \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)\boldsymbol{\beta}]$$

If $r = K$, both $(\frac{\partial(\sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\boldsymbol{\beta})/N)}{\partial \boldsymbol{\beta}'})'$ and $\boldsymbol{W}_N$ are square matrixes and invertible. In this case, FOC is $\triangledown Q_N(\hat{\boldsymbol{\beta}}_{pmm}) = \sum_{i=1}^{N} \boldsymbol{Z}_i'(\boldsymbol{y}_i - \boldsymbol{X}_i\hat{\boldsymbol{\beta}}_{pmm})/N = \boldsymbol{0}$ which is MM estimation.

3.3.4   First Order Condition

$$-2(1/N^2)[(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i) - (\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)\hat{\boldsymbol{\beta}}_{pgmm}] = \boldsymbol{0}$$

$$(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i) - (\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)\hat{\boldsymbol{\beta}}_{pgmm} = \boldsymbol{0}$$

$$(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i) = (\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)\hat{\boldsymbol{\beta}}_{pgmm}$$

$$[(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)]^{-1}(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i) = \hat{\boldsymbol{\beta}}_{pgmm}$$

Special case: if $\boldsymbol{W}_N = (\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{Z}_i)^{-1}$

$$\hat{\boldsymbol{\beta}}_{pgmm} = [(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\overbrace{(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{Z}_i)^{-1}(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)}^{\hat{\boldsymbol{\Gamma}}_{2SLS}}]^{-1} \overbrace{(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{Z}_i)^{-1}}^{\hat{\boldsymbol{\Gamma}}_{2SLS}'}(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i)$$

$$= [\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i\hat{\boldsymbol{\Gamma}}_{2SLS}]^{-1}\hat{\boldsymbol{\Gamma}}_{2SLS}'\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i$$

$$= [\sum_{i=1}^{N} \boldsymbol{X}_i'\underbrace{\boldsymbol{Z}_i\hat{\boldsymbol{\Gamma}}_{2SLS}}_{\hat{\boldsymbol{X}}_i}]^{-1}\sum_{i=1}^{N} \underbrace{(\boldsymbol{Z}_i\hat{\boldsymbol{\Gamma}}_{2SLS})'}_{\hat{\boldsymbol{X}}_i'}\boldsymbol{y}_i = \hat{\boldsymbol{\beta}}_{p2SLS}$$

Special case: if $r = K$, the model is just-identified, GMM is the same as MM,

$$\hat{\boldsymbol{\beta}}_{pmm} = \hat{\boldsymbol{\beta}}_{pgmm} = [(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)]^{-1}(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i)$$

$$= (\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)^{-1}\boldsymbol{W}_N^{-1}(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)^{-1}(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i)$$

$$= (\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)^{-1}(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i) = \hat{\boldsymbol{\beta}}_{piv}$$

Special case: if all regressors are exogeneous: $\boldsymbol{Z}_i = \boldsymbol{X}_i$ (which implies $r = K$),

$$\hat{\boldsymbol{\beta}}_{pgmm} = \hat{\boldsymbol{\beta}}_{piv}$$

$$= (\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{X}_i)^{-1}(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{y}_i) = \hat{\boldsymbol{\beta}}_{pols}$$

$$\hat{\boldsymbol{\beta}}_{pgmm} = [(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{X}_i)]^{-1}(\sum_{i=1}^{N} \boldsymbol{X}_i'\boldsymbol{Z}_i)\boldsymbol{W}_N(\sum_{i=1}^{N} \boldsymbol{Z}_i'\boldsymbol{y}_i)$$

$$= [(\boldsymbol{X}_1' \quad \cdots \quad \boldsymbol{X}_N')\begin{pmatrix}\boldsymbol{Z}_1\\ \vdots\\ \boldsymbol{Z}_N\end{pmatrix}\boldsymbol{W}_N(\boldsymbol{Z}_1' \quad \cdots \quad \boldsymbol{Z}_N')\begin{pmatrix}\boldsymbol{X}_1\\ \vdots\\ \boldsymbol{X}_N\end{pmatrix}]^{-1}(\boldsymbol{X}_1' \quad \cdots \quad \boldsymbol{X}_N')\begin{pmatrix}\boldsymbol{Z}_1\\ \vdots\\ \boldsymbol{Z}_N\end{pmatrix}\boldsymbol{W}_N(\boldsymbol{Z}_1' \quad \cdots \quad \boldsymbol{Z}_N')\begin{pmatrix}\boldsymbol{y}_1\\ \vdots\\ \boldsymbol{y}_N\end{pmatrix}$$

$$= [\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{X}]^{-1}\boldsymbol{X}'\boldsymbol{Z}\boldsymbol{W}_N\boldsymbol{Z}'\boldsymbol{y}$$

3.4 Variance of $\hat{\boldsymbol{\beta}}_{pgmm}$

$$
\begin{aligned}
Var(\boldsymbol{X'ZW_N Z'y}|\boldsymbol{X},\boldsymbol{Z}) &= \boldsymbol{X'ZW_N Z'}Var(\boldsymbol{y}|\boldsymbol{X},\boldsymbol{Z})(\boldsymbol{X'ZW_N Z'})' \\
&= \boldsymbol{X'ZW_N Z'}Var(\boldsymbol{X\beta}+\boldsymbol{u}|\boldsymbol{X},\boldsymbol{Z})(\boldsymbol{Z''W_N' Z'X''}) \\
&= \boldsymbol{X'ZW_N Z'}Var(\boldsymbol{u}|\boldsymbol{X},\boldsymbol{Z})(\boldsymbol{ZW_N Z'X}) \\
&= \boldsymbol{X'ZW_N}Var(\boldsymbol{Z'u}|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W_N Z'X} \\
&= \boldsymbol{X'ZW_N}\mathbb{E}((\boldsymbol{Z'u}-\mathbb{E}(\boldsymbol{Z'u}|\boldsymbol{X},\boldsymbol{Z}))(\boldsymbol{Z'u}-\mathbb{E}(\boldsymbol{Z'u}|\boldsymbol{X},\boldsymbol{Z}))'|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W_N Z'X} \\
&= \boldsymbol{X'ZW_N}\mathbb{E}((\boldsymbol{Z'u})(\boldsymbol{Z'u})'|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W_N Z'X} \\
&= \boldsymbol{X'ZW_N}\mathbb{E}(\boldsymbol{Z'uu'Z''}|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W_N Z'X}
\end{aligned}
$$

$$
\begin{aligned}
[\boldsymbol{X'ZW_N Z'X}]^{-1'} &= [\boldsymbol{X'ZW_N Z'X}]'^{-1} \\
&= [\boldsymbol{X'Z''W_N' Z'X''}]^{-1} \\
&= [\boldsymbol{X'ZW_N Z'X}]^{-1}
\end{aligned}
$$

$$
\begin{aligned}
Var(\hat{\boldsymbol{\beta}}_{pgmm}|\boldsymbol{X},\boldsymbol{Z}) &= Var([\boldsymbol{X'ZW_N Z'X}]^{-1}\boldsymbol{X'ZW_N Z'y}|\boldsymbol{X},\boldsymbol{Z}) \\
&= [\boldsymbol{X'ZW_N Z'X}]^{-1}Var(\boldsymbol{X'ZW_N Z'y}|\boldsymbol{X},\boldsymbol{Z})[\boldsymbol{X'ZW_N Z'X}]^{-1'} \\
&= [\boldsymbol{X'ZW_N Z'X}]^{-1}\boldsymbol{X'ZW_N}\mathbb{E}(\boldsymbol{Z'uu'Z}|\boldsymbol{X},\boldsymbol{Z})\boldsymbol{W_N Z'X}[\boldsymbol{X'ZW_N Z'X}]^{-1}
\end{aligned}
$$

4 GMM Estimation of Fixed Effect Model

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \alpha_i + \varepsilon_{it}$$
$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i}$$
$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon}$$

4.1 Assumption

α_i is potentially correlated with $\boldsymbol{X}_i$, so $\boldsymbol{u}_i$ is potentially correlated with $\boldsymbol{X}_i$

$\boldsymbol{\varepsilon}_i$ is also potentially correlated with $\boldsymbol{X}_i$, so $\boldsymbol{u}_i$ is potentially correlated with $\boldsymbol{X}_i$

Even after eliminating α_i by using any arbitrary transformers $\boldsymbol{T}$, $\tilde{\boldsymbol{u}}_i := \boldsymbol{T}\boldsymbol{u}_i$ is still potentially correlated with $\tilde{\boldsymbol{X}}_i := \boldsymbol{T}\boldsymbol{X}_i$ because $\boldsymbol{u}_i$ is potentially correlated with $\boldsymbol{X}_i$ due to the potential correlation between $\boldsymbol{\varepsilon}_i$ and $\boldsymbol{X}_i$. Thus, $\tilde{\boldsymbol{X}}_i$ is potentially endogeneous.

If $\tilde{\boldsymbol{X}}_i$ is endogeneous, OLS estimation is inconsistent and biased. We should use IV estimation (for just-identified case) and 2SLS estimation (for over-identified case). IV and 2SLS estimation are special cases of GMM estimation.

4.2 GMM Estimator of Fixed Effect Model

There exists a $\boldsymbol{T}$ such that $\boldsymbol{T}\boldsymbol{e} = \boldsymbol{0}$.

4.2.1 Transformed Model

$$\tilde{\boldsymbol{y}}_i := \boldsymbol{T}\boldsymbol{y}_i = \boldsymbol{T}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{u}_i) = \boldsymbol{T}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{T}\boldsymbol{u}_i := \tilde{\boldsymbol{X}}_i\boldsymbol{\beta} + \tilde{\boldsymbol{u}}_i$$
$$\tilde{\boldsymbol{u}}_i := \boldsymbol{T}\boldsymbol{u}_i = \boldsymbol{T}(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i) = \boldsymbol{T}\boldsymbol{e}\alpha_i + \boldsymbol{T}\boldsymbol{\varepsilon}_i = \boldsymbol{0} + \boldsymbol{T}\boldsymbol{\varepsilon}_i = \boldsymbol{T}\boldsymbol{\varepsilon}_i = \tilde{\boldsymbol{\varepsilon}}_i$$

it is obvious that $\tilde{\boldsymbol{u}}_i = \boldsymbol{T}\boldsymbol{\varepsilon}_i$ is correlated with $\tilde{\boldsymbol{X}}_i := \boldsymbol{T}\boldsymbol{X}_i$ if $\boldsymbol{\varepsilon}_i$ is correlated with $\boldsymbol{X}_i$

If $\boldsymbol{T} = \boldsymbol{Q} = \boldsymbol{I}_T - T^{-1}\boldsymbol{e}\boldsymbol{e}'$

$$\tilde{\boldsymbol{y}}_i = \tilde{\boldsymbol{X}}_i\boldsymbol{\beta} + \tilde{\boldsymbol{\varepsilon}}_i$$
$$(\boldsymbol{y}_i - \boldsymbol{e}\bar{y}_i) = (\boldsymbol{X}_i - \boldsymbol{e}\bar{\boldsymbol{x}}'_i)\boldsymbol{\beta} + (\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)$$
$$(y_{it} - \bar{y}_i) = (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + (\varepsilon_{it} - \bar{\varepsilon}_i)$$

Under weak form of weak/sequential exogeneity assumption $E(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}$ for $s \leq t$

for $s \leq t$, we have

$$\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) = \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) - \mathbb{E}(\boldsymbol{z}_{is}\bar{\varepsilon}_i)$$
$$= \boldsymbol{0} - \mathbb{E}(\boldsymbol{z}_{is}\sum_{t=1}^{T}\varepsilon_{it}/T)$$
$$= -\frac{1}{T}\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1} + \cdots + \boldsymbol{z}_{is}\varepsilon_{i,s-1} + \boldsymbol{z}_{is}\varepsilon_{is} + \cdots + \boldsymbol{z}_{is}\varepsilon_{iT})$$
$$= -\frac{1}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{is}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{iT}))$$
$$= -\frac{1}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \boldsymbol{0} + \cdots + \boldsymbol{0})$$
$$= -\frac{1}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}))$$

so $E(\boldsymbol{z}_{it}(\varepsilon_{it} - \bar{\varepsilon}_i))$ is not necessarily equal to zero under weak form of weak/sequential exogeneity assumption. If weak form of strong/strict exogeneity is assumed $E(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}\ \forall s$, then $E(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) = \boldsymbol{0}\ \forall s$. So, $\boldsymbol{z}_{is}, s = 1, \cdots, T$ satisfy the exclusion

restriction (exogeneity) requirement of valid instrument since $Cov(\boldsymbol{z}_{is}, \varepsilon_{it} - \bar{\varepsilon}_i) = \underbrace{\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i))}_{\boldsymbol{0}} - \mathbb{E}(\boldsymbol{z}_{is})\mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i) =$

$-\mathbb{E}(\boldsymbol{z}_{is})(\underbrace{\mathbb{E}(\varepsilon_{it})}_{0} - T^{-1}\sum_{t=1}^{T}\underbrace{\mathbb{E}(\varepsilon_{it})}_{0}) = \boldsymbol{0} \; \forall s$ (additionally assume $\mathbb{E}(\varepsilon_{it}) = 0$). So, we have

$$\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) = \boldsymbol{0} \qquad \text{for } \forall s$$
$$\Longleftrightarrow \; \mathbb{E}(\boldsymbol{Z}_i'(\boldsymbol{\varepsilon}_i - \boldsymbol{e}\bar{\varepsilon}_i)) = \boldsymbol{0}$$
$$\Longleftrightarrow \; \mathbb{E}(\boldsymbol{Z}_i'\tilde{\boldsymbol{\varepsilon}}_i) = \boldsymbol{0}$$

We can then apply IV estimation in GMM framework.

If $\boldsymbol{T} = \boldsymbol{\Delta}$

$$\tilde{\boldsymbol{y}}_i = \tilde{\boldsymbol{X}}_i\boldsymbol{\beta} + \tilde{\boldsymbol{\varepsilon}}_i$$
$$\boldsymbol{\Delta}\boldsymbol{y}_i = \boldsymbol{\Delta}\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{\Delta}\boldsymbol{\varepsilon}_i$$
$$(y_{it} - y_{i,t-1}) = (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})'\boldsymbol{\beta} + (\varepsilon_{it} - \varepsilon_{i,t-1})$$

Under weak form of weak/exogeneity exogeneity assumption $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}$ for $s \le t$

for $s < t$, we have

$$\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \varepsilon_{i,t-1})) = \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) - \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,t-1})$$
$$= \boldsymbol{0} - \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,t-1}) \qquad \text{as } s < t \implies s \le t$$
$$= \boldsymbol{0} \qquad \text{as } s < t \iff s \le t-1$$

so, $\boldsymbol{z}_{is}$ for $s < t$ satisfy the exclusion restriction (exogeneity) requirement of valid instrument since $Cov(\boldsymbol{z}_{is}, \varepsilon_{it} - \varepsilon_{i,t-1}) = 0$ for $s < t$ (additionally assume $\mathbb{E}(\varepsilon_{it}) = 0$). Equivalently,

$$\boldsymbol{Z}_i = \begin{pmatrix} t=2; \boldsymbol{z}_{i1}' & \boldsymbol{0} & \cdots & & \boldsymbol{0} \\ \vdots & t=3; \begin{pmatrix}\boldsymbol{z}_{i1}' & \boldsymbol{z}_{i2}'\end{pmatrix} & \vdots & & \vdots \\ \vdots & \vdots & \ddots & & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & t=T; \begin{pmatrix}\boldsymbol{z}_{i1}' & \cdots & \boldsymbol{z}_{i,T-1}'\end{pmatrix} \end{pmatrix}$$

So, we have

$$\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \varepsilon_{i,t-1})) = \boldsymbol{0} \qquad \text{for } s < t$$
$$\Longleftrightarrow \; \mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Delta}\boldsymbol{\varepsilon}_i) = \boldsymbol{0}$$
$$\Longleftrightarrow \; \mathbb{E}(\boldsymbol{Z}_i'\tilde{\boldsymbol{\varepsilon}}_i) = \boldsymbol{0}$$

We can then apply IV estimation in GMM framework.

5   GMM Estimation of Random Effect Model

$$y_{it} = \boldsymbol{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it}$$

$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i}$$

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon}$$

5.1   Assumption

α_i is not correlated with $\boldsymbol{X}_i$

$\boldsymbol{\varepsilon}_i$ is potentially correlated with $\boldsymbol{X}_i$, so $\boldsymbol{u}_i$ is potentially correlated with $\boldsymbol{X}_i$ Thus, $\boldsymbol{X}_i$ is potentially endogeneous.

If $\boldsymbol{X}_i$ is endogeneous, OLS estimation is inconsistent and biased. We should use IV estimation (for just-identified case) and 2SLS estimation (for over-identified case). IV and 2SLS estimations are special cases of GMM estimation.

assume

$$\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{Z}_i) = \boldsymbol{0}$$

which is stronger than $\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{Z}_i) = \boldsymbol{0}$ implies $\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{u}_i) = \boldsymbol{0}$

and assume

$$Var(\boldsymbol{u}_i|\boldsymbol{Z}_i) = \boldsymbol{\Omega}_i = \begin{pmatrix} \sigma_\alpha^2 + \sigma_\varepsilon^2 & \cdots & \sigma_\alpha^2 \\ \vdots & \ddots & \vdots \\ \sigma_\alpha^2 & \cdots & \sigma_\alpha^2 + \sigma_\varepsilon^2 \end{pmatrix}$$

5.1.1   Optimal Moment Condition

$$\begin{aligned} \boldsymbol{D}_i &= \mathbb{E}(\frac{\partial \boldsymbol{u}_i'}{\partial \boldsymbol{\beta}}|\boldsymbol{Z}_i)Var(\boldsymbol{u}_i|\boldsymbol{Z}_i)^{-1} \\ &= \mathbb{E}(\frac{\partial(\boldsymbol{Z}_i\boldsymbol{\beta})'}{\partial \boldsymbol{\beta}}|\boldsymbol{Z}_i)\boldsymbol{\Omega}_i^{-1} \\ &= \mathbb{E}(\boldsymbol{Z}_i'|\boldsymbol{Z}_i)\boldsymbol{\Omega}_i^{-1} \\ &= \boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1} \end{aligned}$$

optimal unconditional moment is:

$$\mathbb{E}(\boldsymbol{D}_i\boldsymbol{u}_i) = \boldsymbol{0}$$
$$\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1}\boldsymbol{u}_i) = \boldsymbol{0}$$
$$\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) = \boldsymbol{0}$$
$$\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i'^{-1/2}\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) = \boldsymbol{0}$$
$$\mathbb{E}(\boldsymbol{Z}_i'\boldsymbol{\Omega}_i^{-1/2'}\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) = \boldsymbol{0}$$
$$\mathbb{E}((\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{Z}_i)'\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) = \boldsymbol{0}$$
$$\sigma_\varepsilon^2\mathbb{E}((\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{Z}_i)'\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) = \sigma_\varepsilon^2\boldsymbol{0}$$
$$\mathbb{E}((\sigma_\varepsilon\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{Z}_i)'\sigma_\varepsilon\boldsymbol{\Omega}_i^{-1/2}\boldsymbol{u}_i) = \boldsymbol{0}$$

this implies that the model should be transformed by $\sigma_\varepsilon\boldsymbol{\Omega}_i^{-1/2}$

5.2 GMM Estimator of Random Effect Model

5.2.1 Transformed Model

$$\sigma_\varepsilon \boldsymbol{\Omega}^{-1/2} \boldsymbol{y}_i = \sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + (\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)) = \sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}(\boldsymbol{X}_i\boldsymbol{\beta} + \boldsymbol{u}_i) = \sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}\boldsymbol{X}_i\boldsymbol{\beta} + \sigma_\varepsilon \boldsymbol{\Omega}^{-1/2}\boldsymbol{u}_i$$

$$(\boldsymbol{y}_i - \lambda\boldsymbol{e}\bar{y}_i) = (\boldsymbol{X}_i - \lambda\boldsymbol{e}\bar{\boldsymbol{x}}_i')\boldsymbol{\beta} + [(1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)] \qquad\qquad \lambda = 1 - \psi = 1 - \frac{\sigma_\varepsilon}{\sqrt{T\sigma_\alpha^2 + \sigma_\varepsilon^2}}$$

$$(y_{it} - \lambda\bar{y}_i) = (\boldsymbol{x}_{it} - \lambda\bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + [(1-\lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)]$$

Under weak form of weak/sequential exogeneity assumption $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}$ for $s \leq t$

for $s \leq t$, we have

$$
\begin{aligned}
\mathbb{E}(\boldsymbol{z}_{is}[(1-\lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)]) &= \mathbb{E}(\boldsymbol{z}_{is}(1-\lambda)\alpha_i + \boldsymbol{z}_{is}(\varepsilon_{it} - \lambda\bar{\varepsilon}_i)) \\
&= (1-\lambda)\mathbb{E}(\boldsymbol{z}_{is}\alpha_i) + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) - \lambda\mathbb{E}(\boldsymbol{z}_{is}\bar{\varepsilon}_i) \\
&= (1-\lambda)\boldsymbol{0} + \boldsymbol{0} - \lambda E(\boldsymbol{z}_{is}\sum_{t=1}^{T}\varepsilon_{it}/T) \\
&= -\frac{\lambda}{T}\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1} + \cdots + \boldsymbol{z}_{is}\varepsilon_{i,s-1} + \boldsymbol{z}_{is}\varepsilon_{is} + \cdots + \boldsymbol{z}_{is}\varepsilon_{iT}) \\
&= -\frac{\lambda}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{is}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{iT})) \\
&= -\frac{\lambda}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}) + \boldsymbol{0} + \cdots + \boldsymbol{0}) \\
&= -\frac{\lambda}{T}(\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i1}) + \cdots + \mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{i,s-1}))
\end{aligned}
$$

so $\mathbb{E}(\boldsymbol{z}_{it}(\varepsilon_{it} - \bar{\varepsilon}_i))$ is not necessarily equal to zero under weak form of weak/sequential exogeneity assumption.

If weak form of strong/strict exogeneity assumption is assumed $\mathbb{E}(\boldsymbol{z}_{is}\varepsilon_{it}) = \boldsymbol{0}\ \forall s$, then $\mathbb{E}(\boldsymbol{z}_{is}(\varepsilon_{it} - \bar{\varepsilon}_i)) = \boldsymbol{0}\ \forall s$ so, $\boldsymbol{z}_{is},\ s = 1, \cdots, T$ satisfy the exclusion restriction (exogeneity) requirement of valid instrument.

So, we have

$$\mathbb{E}(\boldsymbol{z}_{is}[(1-\lambda)\alpha_i + (\varepsilon_{it} - \lambda\bar{\varepsilon}_i)]) = \boldsymbol{0} \qquad\qquad \text{for } \forall s$$

$$\Longleftrightarrow \mathbb{E}(\boldsymbol{Z}_i'[(1-\lambda)\boldsymbol{e}\alpha_i + (\boldsymbol{\varepsilon}_i - \lambda\boldsymbol{e}\bar{\varepsilon}_i)]) = \boldsymbol{0}$$

We can then apply IV estimation in GMM framework.

6 Dynamic Linear Panel Model

6.1 Assumption

6.1.1 Weak/Sequential Exogeneity

For $t = 2, \cdots, T$

$$\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i) = 0$$

This implies

$$\mathbb{E}(y_{is}\varepsilon_{it}) = 0, \ \mathbb{E}(\varepsilon_{it}) = 0 \quad and \quad \mathbb{E}(\alpha_i \varepsilon_{it}) = 0 \qquad \qquad \text{for } s < t$$

and

$$Cov(y_{is}, \varepsilon_{it}) = 0 \quad and \quad Cov(\alpha_i, \varepsilon_{it}) = 0 \qquad \qquad \text{for } s < t$$

It is because

$$
\begin{aligned}
Cov(y_{is}, \varepsilon_{it}) &= \mathbb{E}(y_{is}\varepsilon_{it}) - \mathbb{E}(y_{is})\mathbb{E}(\varepsilon_{it}) \\
&= \mathbb{E}(\mathbb{E}(y_{is}\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)) - \mathbb{E}(y_{is})\mathbb{E}(\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)) \\
&= \mathbb{E}(y_{is}\underbrace{\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)}_{0}) - \mathbb{E}(y_{is})\mathbb{E}(\underbrace{\mathbb{E}(\varepsilon_{it}|y_{i,t-1}, \cdots y_{i1}, \alpha_i)}_{0}) \qquad \text{as } s < t \\
&= 0
\end{aligned}
$$

6.2 Model

6.2.1 No Transformation

$$y_{it} = \gamma y_{i,t-1} + \boldsymbol{x}'_{it}\boldsymbol{\beta} + \underbrace{(\alpha_i + \varepsilon_{it})}_{u_{it}}$$

$$
\begin{aligned}
Cov(y_{i,t-1}, \alpha_i) &= Cov(\gamma y_{i,t-2} + \boldsymbol{x}'_{i,t-1}\boldsymbol{\beta} + \alpha_i + \varepsilon_{i,t-1}, \alpha_i) \\
&= \gamma Cov(y_{i,t-2}, \alpha_i) + Cov(\boldsymbol{x}'_{i,t-1}\boldsymbol{\beta}, \alpha_i) + Var(\alpha_i) + \underbrace{Cov(\varepsilon_{i,t-1}, \alpha_i)}_{0} \\
&= \gamma Cov(y_{i,t-2}, \alpha_i) + \boldsymbol{\beta}' Cov(\boldsymbol{x}_{i,t-1}, \alpha_i) + Var(\alpha_i) \\
&\neq 0 \qquad \qquad \qquad \qquad \text{assume } Cov(\boldsymbol{x}_{i,t-1}, \alpha_i) \neq 0 \text{ and } Var(\alpha_i) > 0
\end{aligned}
$$

so that

$$
\begin{aligned}
Cov(y_{i,t-1}, u_{it}) &= Cov(y_{i,t-1}, \alpha_i + \varepsilon_{it}) \\
&= \underbrace{Cov(y_{i,t-1}, \alpha_i)}_{\neq 0} + \underbrace{Cov(y_{i,t-1}, \varepsilon_{it})}_{0} \\
&\neq 0
\end{aligned}
$$

The necessary condition for OLS estimator to be unbiased is $\mathbb{E}(u_{it}|y_{i,t-1}, \boldsymbol{x}_{it}) = 0$. As $\mathbb{E}(u_{it}|y_{i,t-1}, \boldsymbol{x}_{it}) = 0 \implies Cov(y_{i,t-1}, u_{it}) = 0$. As a result, $Cov(y_{i,t-1}, u_{it}) \neq 0 \implies \mathbb{E}(u_{it}|y_{i,t-1}, \boldsymbol{x}_{it}) \neq 0$. Thus, OLS estimator is biased.

6.2.2 Special case: no $\boldsymbol{x}_{it}$

$$y_{it} = \gamma y_{i,t-1} + \underbrace{(\alpha_i + \varepsilon_{it})}_{u_{it}}$$

The necessary condition for OLS estimator to be consistent is $\mathbb{E}(y_{i,t-1}u_{it}) = 0$. However,

$$
\begin{aligned}
\mathbb{E}(y_{i,t-1}u_{it}) &= \mathbb{E}(y_{i,t-1}(\alpha_i + \varepsilon_{it})) \\
&= \mathbb{E}(y_{i,t-1}\alpha_i) + \underbrace{\mathbb{E}(y_{i,t-1}\varepsilon_{it})}_{0} > 0
\end{aligned}
$$

$$
\begin{aligned}
\mathbb{E}(y_{i,t-1}\alpha_i) &= \mathbb{E}((\gamma y_{i,t-2} + \alpha_i + \varepsilon_{i,t-1})\alpha_i) \\
&= \gamma\mathbb{E}(y_{i,t-2}\alpha_i) + \mathbb{E}(\alpha_i^2) + \mathbb{E}(\varepsilon_{i,t-1}\alpha_i) \\
&= \gamma\mathbb{E}((\gamma y_{i,t-3} + \alpha_i + \varepsilon_{i,t-2})\alpha_i) + \mathbb{E}(\alpha_i^2) + \mathbb{E}(\mathbb{E}(\varepsilon_{i,t-1}\alpha_i|y_{i,t-2},\cdots,y_{i1},\alpha_i)) \\
&= \gamma^2\mathbb{E}(y_{i,t-3}\alpha_i) + \gamma\mathbb{E}(\alpha_i^2) + \gamma\mathbb{E}(\varepsilon_{i,t-2}\alpha_i) + \mathbb{E}(\alpha_i^2) + \mathbb{E}(\alpha_i\underbrace{\mathbb{E}(\varepsilon_{i,t-1}|y_{i,t-2},\cdots,y_{i1},\alpha_i)}_{0}) \\
&= \gamma^2\mathbb{E}(y_{i,t-3}\alpha_i) + \gamma\mathbb{E}(\alpha_i^2) + \mathbb{E}(\alpha_i^2) \\
&\cdots \\
&= \gamma^{t-2}\mathbb{E}(y_{i,t-(t-2+1)}) + \gamma^{t-2-1}\mathbb{E}(\alpha_i^2) + \cdots + \mathbb{E}(\alpha_i^2) \\
&= \gamma^{t-2}\mathbb{E}(y_{i1}) + \gamma^{t-3}\mathbb{E}(\alpha_i^2) + \cdots + \mathbb{E}(\alpha_i^2) \\
&= \gamma^{t-2}y_{i1} + \gamma^{t-3}Var(\alpha_i) + \cdots + Var(\alpha_i) \qquad\qquad y_{i1} \text{ is initial value and assume } \mathbb{E}(\alpha_i) = 0 \\
&> 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{assume } Var(\alpha_i) > 0, \ y_{i1} > 0 \text{ and } 0 < \gamma < 1
\end{aligned}
$$

Thus, OLS estimator is inconsistent. The necessary condition for OLS estimator to be unbiased is $\mathbb{E}(u_{it}|y_{i,t-1}) = 0$. As $\mathbb{E}(u_{it}|y_{i,t-1}) = 0 \implies \mathbb{E}(y_{i,t-1}u_{it}) = 0$, $\mathbb{E}(y_{i,t-1}u_{it}) \neq 0 \implies \mathbb{E}(u_{it}|y_{i,t-1}) \neq 0$. Thus, OLS estimator is biased. It can also be seen by OVB formula.

$$
\begin{aligned}
\gamma_{short} &= \frac{Cov(y_{it}, y_{i,t-1})}{Var(y_{i,t-1})} \\
&= \frac{Cov(\gamma_{long}y_{i,t-1} + \alpha_i + \varepsilon_{it}, y_{i,t-1})}{Var(y_{i,t-1})} \\
&= \gamma_{long} + \frac{Cov(\alpha_i, y_{i,t-1})}{Var(y_{i,t-1})} + \frac{\overbrace{Cov(\varepsilon_{it}, y_{i,t-1})}^{0}}{Var(y_{i,t-1})} \\
&= \gamma_{long} + \frac{Cov(\alpha_i, y_{i,t-1})}{Var(y_{i,t-1})}
\end{aligned}
$$

$$
\gamma_{short} - \gamma_{long} = \frac{Cov(\alpha_i, y_{i,t-1})}{Var(y_{i,t-1})} > 0 \qquad\qquad\qquad\qquad \text{if } Var(y_{i,t-1}) > 0
$$

$$
Cov(\alpha_i, y_{i,t-1}) = \mathbb{E}(\alpha_i y_{i,t-1}) - \mathbb{E}(\alpha_i)\mathbb{E}(y_{i,t-1}) > 0 \qquad\qquad \text{see above for } \mathbb{E}(\alpha_i y_{i,t-1}) > 0 \text{ and assume } \mathbb{E}(\alpha_i) = 0
$$

Thus, OLS estimator is biased upward / over-estimate.

6.2.3   Within Transformation

$$
y_{it} - \bar{y}_i = \gamma(y_{i,t-1} - \bar{y}_{i,-1}) + (\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i)'\boldsymbol{\beta} + (\varepsilon_{it} - \bar{\varepsilon}_i)
$$

$$
Cov(y_{i,t-1}, \bar{\varepsilon}_i) = Cov(\gamma y_{i,t-2} + \boldsymbol{x}_{i,t-1}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{i,t-1}, T^{-1}\sum_{t=1}^{T}\varepsilon_{it})
$$

$$
\neq 0 \qquad\qquad\qquad\qquad \text{since } \varepsilon_{i,t-1} \text{ is correlated with } T^{-1}\sum_{t=1}^{T}\varepsilon_{it}
$$

so that

$$
Cov(y_{i,t-1} - \bar{y}_{i,-1}, \varepsilon_{it} - \bar{\varepsilon}_i) \neq 0
$$

The necessary condition for FE estimator to be unbiased is $\mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i | y_{i,t-1} - \bar{y}_{i,-1}, \boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) = 0$. As $\mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i | y_{i,t-1} - \bar{y}_{i,-1}, \boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) = 0 \implies Cov(y_{i,t-1} - \bar{y}_{i,-1}, \varepsilon_{it} - \bar{\varepsilon}_i) = 0$. As a result, $Cov(y_{i,t-1} - \bar{y}_{i,-1}, \varepsilon_{it} - \bar{\varepsilon}_i) \neq 0 \implies \mathbb{E}(\varepsilon_{it} - \bar{\varepsilon}_i | y_{i,t-1} - \bar{y}_{i,-1}, \boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i) \neq 0$. Thus, FE estimator is biased.

6.2.4 Special case: no $\boldsymbol{x}_{it}$

$$y_{it} - \bar{y}_i = \gamma(y_{i,t-1} - \bar{y}_{i,-1}) + (\varepsilon_{it} - \bar{\varepsilon}_i)$$

The bias is called Nickell bias / dynamic panel bias. If $\gamma > 0$, the bias must be negative. The bias converges to zero when $T \to \infty$

6.2.5 First Difference Transformation

$$\tilde{\boldsymbol{y}}_i = \tilde{\boldsymbol{X}}_i \boldsymbol{\delta} + \tilde{\boldsymbol{\varepsilon}}_i$$

$$\begin{pmatrix} y_{i3} - y_{i2} \\ \vdots \\ y_{iT} - y_{i,T-1} \end{pmatrix} = \begin{pmatrix} y_{i2} - y_{i1} & (\boldsymbol{x}_{i3} - \boldsymbol{x}_{i2})' \\ \vdots & \\ y_{i,T-1} - y_{i,T-2} & (\boldsymbol{x}_{iT} - \boldsymbol{x}_{i,T-1})' \end{pmatrix} \begin{pmatrix} \gamma \\ \boldsymbol{\beta} \end{pmatrix} + \begin{pmatrix} \varepsilon_{i3} - \varepsilon_{i2} \\ \vdots \\ \varepsilon_{iT} - \varepsilon_{i,T-1} \end{pmatrix}$$

$$y_{it} - y_{i,t-1} = \gamma(y_{i,t-1} - y_{i,t-2}) + (\boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1})'\boldsymbol{\beta} + (\varepsilon_{it} - \varepsilon_{i,t-1}) \qquad\qquad t \geq 3$$

$$\begin{aligned}
Cov(y_{i,t-1} - y_{i,t-2}, \varepsilon_{it} - \varepsilon_{i,t-1}) &= Cov(y_{i,t-1}, \varepsilon_{it}) - Cov(y_{i,t-1}, \varepsilon_{i,t-1}) - Cov(y_{i,t-2}, \varepsilon_{it}) + Cov(y_{i,t-2}, \varepsilon_{i,t-1}) \\
&= 0 - Cov(y_{i,t-1}, \varepsilon_{i,t-1}) - 0 + 0 \qquad\qquad \text{as } Cov(y_{is}, \varepsilon_{it}) = 0 \text{ for } s < t \\
&= -Cov(\gamma y_{i,t-2} + \boldsymbol{x}'_{i,t-1}\boldsymbol{\beta} + \alpha_i + \varepsilon_{i,t-1}, \varepsilon_{i,t-1}) \\
&= -\gamma \underbrace{Cov(y_{i,t-2}, \varepsilon_{i,t-1})}_{0} - \boldsymbol{\beta}' \underbrace{Cov(\boldsymbol{x}_{i,t-1}, \varepsilon_{i,t-1})}_{0} - \underbrace{Cov(\alpha_i, \varepsilon_{i,t-1})}_{0} - Var(\varepsilon_{i,t-1}) \\
&< 0 \qquad\qquad \text{assume } Var(\varepsilon_{i,t-1}) > 0
\end{aligned}$$

The necessary condition for FD estimator to be unbiased is $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}|y_{i,t-1} - y_{i,t-2}, \boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1}) = 0$. As $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}|y_{i,t-1} - y_{i,t-2}, \boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1}) = 0 \implies Cov(y_{i,t-1} - y_{i,t-2}, \varepsilon_{it} - \varepsilon_{i,t-1}) = 0$. As a result, $Cov(y_{i,t-1} - y_{i,t-2}, \varepsilon_{it} - \varepsilon_{i,t-1}) \neq 0 \implies \mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}|y_{i,t-1} - y_{i,t-2}, \boldsymbol{x}_{it} - \boldsymbol{x}_{i,t-1}) \neq 0$. Thus, FD estimator is biased.

6.2.6 Special case: no $\boldsymbol{x}_{it}$

$$y_{it} - y_{i,t-1} = \gamma(y_{i,t-1} - y_{i,t-2}) + (\varepsilon_{it} - \varepsilon_{i,t-1})$$

The necessary condition for FD estimator to be consistent is $\mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) = 0$. However,

$$\begin{aligned}
\mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) &= \mathbb{E}(y_{i,t-1}\varepsilon_{it}) - \mathbb{E}(y_{i,t-1}\varepsilon_{i,t-1}) - \mathbb{E}(y_{i,t-2}\varepsilon_{it}) + \mathbb{E}(y_{i,t-2}\varepsilon_{i,t-1}) \\
&= 0 - \mathbb{E}(y_{i,t-1}\varepsilon_{i,t-1}) - 0 + 0 \qquad\qquad \text{as } \mathbb{E}(y_{is}\varepsilon_{it}) = 0 \text{ for } s < t \\
&= -\mathbb{E}((\gamma y_{i,t-2} + \alpha_i + \varepsilon_{i,t-1})\varepsilon_{i,t-1}) \\
&= -\gamma \underbrace{\mathbb{E}(y_{i,t-2}\varepsilon_{i,t-1})}_{0} - \underbrace{\mathbb{E}(\alpha_i \varepsilon_{i,t-1})}_{0} - \mathbb{E}(\varepsilon^2_{i,t-1}) \\
&= -Var(\varepsilon_{i,t-1}) \qquad\qquad \text{as } \mathbb{E}(\varepsilon_{i,t-1}) = 0 \\
&< 0 \qquad\qquad \text{assume } Var(\varepsilon_{i,t-1}) > 0
\end{aligned}$$

Thus, FD estimator is inconsistent. The necessary condition for FD estimator to be unbiased is $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}|y_{i,t-1} - y_{i,t-2}) = 0$. As $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}|y_{i,t-1} - y_{i,t-2}) = 0 \implies \mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) = 0$, $\mathbb{E}((y_{i,t-1} - y_{i,t-2})(\varepsilon_{it} - \varepsilon_{i,t-1})) \neq 0 \implies \mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}|y_{i,t-1} - y_{i,t-2}) \neq 0$. Thus, FD estimator is biased.

Thus, IV estimation (for just-identified case) or 2SLS estimation (for over-identified case) is applied. IV and 2SLS estimations are special cases of GMM estimation.

Under weak/sequential exogeneity, $Cov(y_{is}, \varepsilon_{it}) = 0$ for $s < t$. This implies for $s < t - 1 \iff s \leq t - 2$

$$\begin{aligned}
Cov(y_{is}, \varepsilon_{it} - \varepsilon_{it-1}) &= Cov(y_{is}, \varepsilon_{it}) - Cov(y_{is}, \varepsilon_{i,t-1}) \\
&= 0 - Cov(y_{is}, \varepsilon_{i,t-1}) \qquad\qquad \text{as } s < t - 1 \implies s < t \\
&= 0 \qquad\qquad \text{as } s < t - 1
\end{aligned}$$

Note that $Cov(y_{is}, \varepsilon_{it} - \varepsilon_{i,t-1}) = 0 \implies \mathbb{E}(y_{is}(\varepsilon_{it} - \varepsilon_{i,t-1})) = 0$ as $\mathbb{E}(\varepsilon_{it} - \varepsilon_{i,t-1}) = 0$ under weak/sequential exogeneity. So, y_{is} for $s \leq t-2$ satisfy the exclusion restriction (exogeneity) requirement of valid instrument. i.e.,

$$\tilde{z}'_{i3} = (y_{i1}, \Delta x'_{i3}) \qquad \text{at } t = 3$$
$$\tilde{z}'_{i4} = (y_{i1}, y_{i2}, \Delta x'_{i4}) \qquad \text{at } t = 4$$
$$\cdots$$
$$\tilde{z}'_{iT} = (y_{i1}, \cdots, y_{i,T-2}, \Delta x'_{iT}) \qquad \text{at } t = T$$

That is, $\tilde{z}'_{it} = [y_{i1}, \cdots, y_{i,t-2}, \Delta x'_{it}]$. $\boldsymbol{Z}_i = \begin{pmatrix} \tilde{z}'_{i3} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \tilde{z}'_{i4} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \tilde{z}'_{iT} \end{pmatrix}$

So, we have

$$\mathbb{E}(\tilde{z}_{it}(\varepsilon_{it} - \varepsilon_{i,t-1})) = \boldsymbol{0}$$
$$\iff \mathbb{E}(\boldsymbol{Z}'_i \boldsymbol{\Delta \varepsilon}_i) = \boldsymbol{0}$$

Note that $\tilde{z}'_{it} = (z'_{i1}, \cdots, z'_{it})$. Not to confuse with the z_{is} defined before. We can then apply IV estimation in GMM framework.

6.2.7 Anderson-Hsiao Estimator

Anderson and Hsiao (1981) considers a special case y_{is} for $s = t-2$ i.e., $y_{i,t-2}$ as the instrument since they not only satisfy the exclusion restriction (exogeneity) requirement but also satisfy the relevancy requirement of valid instrument i.e., correlates with $y_{i,t-1} - y_{i,t-2}$. Thus, $\tilde{z}'_{it} = [y_{i,t-2}, \Delta x'_{it}]$

$$\boldsymbol{Z}_i = \begin{pmatrix} (y_{i1} \quad \Delta x'_{i3}) & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & (y_{i2} \quad \Delta x'_{i4}) & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & (y_{i,T-2} \quad \Delta x'_{iT}) \end{pmatrix}$$

and

$$\tilde{z}'_{it} = [\underbrace{\Delta y_{i,t-2}}_{y_{i,t-2} - y_{i,t-3}}, \Delta x'_{it}]$$

$$\boldsymbol{Z}_i = \begin{pmatrix} (\Delta y_{i2} \quad \Delta x'_{i4}) & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & (\Delta y_{i3} \quad \Delta x'_{i5}) & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & (\Delta y_{i,T-2} \quad \Delta x'_{iT}) \end{pmatrix}$$

As only one instrument is used at each t, the number of moments is equal to the number of parameters i.e., $r = K$. In such case, GMM estimation = MM estimation = IV estimation.

$$\hat{\boldsymbol{\delta}}^{pgmm}_{AH} = [\sum_{i=1}^{N} \boldsymbol{Z}'_i \tilde{\boldsymbol{X}}_i]^{-1} \sum_{i=1}^{N} \boldsymbol{Z}'_i \tilde{\boldsymbol{y}}_i = \hat{\boldsymbol{\delta}}^{piv}_{AH}$$

6.2.8 Arellano-Bond Estimator

Arellano and Bond (1991) considers all the possible cases i.e., y_{is} for $s \leq t-2$. Except $t = 3$, more than one instruments are used, number of moments is larger than the number of parameters i.e., $r > K$. GMM estimation is 2SLS estimation if

$$\boldsymbol{W}_N = (\sum_{i=1}^{N} \boldsymbol{Z}_i' \boldsymbol{Z}_i)^{-1}.$$

$$\tilde{\boldsymbol{z}}_{it}' = [y_{i1}, \cdots, y_{i,t-2}, \Delta \boldsymbol{x}_{it}']$$

$$\boldsymbol{Z}_i = \begin{pmatrix} \begin{pmatrix} y_{i1} & \Delta \boldsymbol{x}_{i3}' \end{pmatrix} & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \begin{pmatrix} y_{i1} & y_{i2} & \Delta \boldsymbol{x}_{i4}' \end{pmatrix} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \begin{pmatrix} y_{i1} & \cdots & y_{i,T-2} & \Delta \boldsymbol{x}_{iT}' \end{pmatrix} \end{pmatrix}$$

$$\hat{\boldsymbol{\delta}}_{AB}^{pgmm} = [(\sum_{i=1}^{N} \tilde{\boldsymbol{X}}_i' \boldsymbol{Z}_i) \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i' \tilde{\boldsymbol{X}}_i)]^{-1} (\sum_{i=1}^{N} \tilde{\boldsymbol{X}}_i' \boldsymbol{Z}_i) \boldsymbol{W}_N (\sum_{i=1}^{N} \boldsymbol{Z}_i' \tilde{\boldsymbol{y}}_i)$$

if $\boldsymbol{W}_N = (\sum_{i=1}^{N} \boldsymbol{Z}_i' \boldsymbol{Z}_i)^{-1}$, $\hat{\boldsymbol{\delta}}_{AB}^{pgmm} = \hat{\boldsymbol{\delta}}_{AB}^{2SLS}$

if $\boldsymbol{W}_N = \hat{\boldsymbol{S}}^{-1}$, $\hat{\boldsymbol{\delta}}_{AB}^{pgmm} = \hat{\boldsymbol{\delta}}_{AB}^{opgmm}$

$$\tilde{\boldsymbol{z}}_{it}' = [y_{i1}, \cdots, y_{i,t-2}, \Delta \boldsymbol{x}_{it}']$$

7   Pooled Model and Clustered Standard Error

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \alpha_i + \varepsilon_{it} \qquad \text{Level 1}$$

$$\begin{pmatrix} y_{i1} \\ \vdots \\ y_{iT} \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}'_{i1} \\ \vdots \\ \boldsymbol{x}'_{iT} \end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}\alpha_i + \begin{pmatrix} \varepsilon_{i1} \\ \vdots \\ \varepsilon_{iT} \end{pmatrix}$$

$$\boldsymbol{y}_i = \boldsymbol{X}_i\boldsymbol{\beta} + \underbrace{(\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i)}_{\boldsymbol{u}_i} \qquad \text{Level 2}$$

$$\begin{pmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_N \end{pmatrix} = \begin{pmatrix} \boldsymbol{X}_1 \\ \vdots \\ \boldsymbol{X}_N \end{pmatrix}\boldsymbol{\beta} + \begin{pmatrix} \boldsymbol{e} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{e} \end{pmatrix}\begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{pmatrix} + \begin{pmatrix} \boldsymbol{\varepsilon}_1 \\ \vdots \\ \boldsymbol{\varepsilon}_N \end{pmatrix}$$

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + (\boldsymbol{I}_N \otimes \boldsymbol{e})\boldsymbol{\alpha} + \boldsymbol{\varepsilon} \qquad \text{Level 3}$$

where α_i is unobserved heterogeneity, $\boldsymbol{\varepsilon}_i$ is idiosyncratic error, $\boldsymbol{u}_i$ is composite error.

If $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0$, OLS estimator is likely to be unbiased and consistent.
$\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies \mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \mathbb{E}(\boldsymbol{X}'_i\boldsymbol{e}\alpha_i + \boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{X}'_i\boldsymbol{e}\mathbb{E}(\alpha_i|\boldsymbol{X}) + \mathbb{E}(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \boldsymbol{0}$. Thus, the necessary condition for OLS estimator to be unbiased is satisfied if $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0$

$\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i) = \boldsymbol{0} \implies \mathbb{E}(\boldsymbol{X}'_i\boldsymbol{u}_i) = \boldsymbol{0}$ as $\mathbb{E}(\boldsymbol{X}'_i\boldsymbol{u}_i) = \mathbb{E}(\mathbb{E}(\boldsymbol{X}'_i\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}'_i\mathbb{E}(\boldsymbol{u}_i|\boldsymbol{X}_i)) = \mathbb{E}(\boldsymbol{X}'_i\boldsymbol{0}) = \boldsymbol{0}$. Thus, the necessary condition for OLS estimator to be consistent is satisfied if $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0$.

$\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies \mathbb{E}(\alpha_i\boldsymbol{X}_i) = \boldsymbol{0}$ and $\mathbb{E}(\alpha_i) = 0$. Thus, $\mathbb{E}(\alpha_i|\boldsymbol{X}_i) = 0 \implies Cov(\alpha_i, \boldsymbol{X}_i) = \boldsymbol{0}$ as $Cov(\alpha_i, \boldsymbol{X}_i) = \mathbb{E}(\alpha_i\boldsymbol{X}_i) - \mathbb{E}(\alpha_i)\mathbb{E}(\boldsymbol{X}_i) = \boldsymbol{0}$.

$$\hat{\boldsymbol{\beta}}^{ols}_{pooled} = [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{y}_i \qquad \text{Level 2}$$

$$= [\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}y_{it} \qquad \text{Level 1}$$

As pooled model does not perform any transformation before OLS estimation, so $\boldsymbol{Q} = \boldsymbol{I}$.

$$Var(\hat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{I}'\boldsymbol{I}\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{I}'Var(\boldsymbol{I}\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{I}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{I}'\boldsymbol{I}\boldsymbol{X}_i]^{-1}$$

$$= [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N} \boldsymbol{X}'_iVar(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i)\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}$$

If ε_{it} is homoskedasticity and serially uncorrelated across t i.e., $Var(\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i) = \sigma^2_\varepsilon\boldsymbol{I}_T$ and independence across i and with strict exogeneity. We have $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim iid\,[\boldsymbol{0}, \sigma^2_\varepsilon\boldsymbol{I}_T]$

$$= \sigma^2_\varepsilon[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}$$

$$= \sigma^2_\varepsilon[\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}$$

If $\boldsymbol{\varepsilon}_i|\boldsymbol{X}_i \sim inid\,[\boldsymbol{0}, \boldsymbol{\Omega}_i]$

$$= [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N} \boldsymbol{X}'_i\overbrace{\mathbb{E}[\boldsymbol{\varepsilon}_i\boldsymbol{\varepsilon}'_i|\boldsymbol{X}_i]}^{\boldsymbol{\Omega}_i}\boldsymbol{X}_i[\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}$$

$$= [\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T} \boldsymbol{x}_{it}\mathbb{E}[\varepsilon_{it}\varepsilon_{is}|\boldsymbol{X}_i]\boldsymbol{x}'_{is}[\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}$$

7.1 Petersen (2009) RFS - Simulation Result

7.1.1 Only individual fixed effect

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \alpha_i + \varepsilon_{it}$$

If there is only α_i (individual fixed effect) and α_i is not correlated with $\boldsymbol{x}_{it}$ (so no OVB), OLS estimator is unbiased and clustered standard error clustered by individual is unbiased. In contrast, conventional standard error, White standard error, Newey-West standard error, Fama-Macbeth standard error are biased downward (over-rejection).

7.1.2 Only time fixed effect

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \gamma_t + \varepsilon_{it}$$

If there is only γ_t (individual time effect) and γ_t is not correlated with $\boldsymbol{x}_{it}$ (so no OVB), OLS estimator is unbiased and Fama-Macbeth standard error and clustered standard error clustered by time (only if T is large) is unbiased. In contrast, conventional standard error are biased downward (over-rejection).

7.1.3 Both individual and time fixed effect

$$y_{it} = \boldsymbol{x}'_{it}\boldsymbol{\beta} + \alpha_i + \gamma_t + \varepsilon_{it}$$

Clustered standard error clustered by both individual and time is unbiased. Cameron, Gelbach, and Miller (2006), and Thompson (2006) suggests clustered standard error clustered by both individual and time = Clustered standard error clustered by individual + Clustered standard error clustered by time - White standard error. Simulation result seems work.

7.2 MHE's suggestions for tackling clustering problem

7.2.1 1. Block bootstrapping

7.2.2 2. Aggregation

$$
\begin{aligned}
y_{it} &= \beta_0 + \beta_1 x_i + w'_{it}\delta + \alpha_i + \varepsilon_{it} \\
&= \underbrace{(\beta_0 + \beta_1 x_i + \alpha_i)}_{\mu_i} + w'_{it}\delta + \varepsilon_{it}
\end{aligned}
$$

$$
\begin{aligned}
\mu_i &= \beta_0 + \beta_1 x_i + \alpha_i \\
\hat{\mu}_i &= \beta_0 + \beta_1 x_i + (\alpha_i - \mu_i + \hat{\mu}_i)
\end{aligned}
$$

7.2.3 3. Clustered standard error

Clustered standard error is

$$\widehat{Var}(\hat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{i=1}^{N} \boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}\sum_{i=1}^{N}\boldsymbol{X}'_i\widehat{\boldsymbol{\Omega}}_i\boldsymbol{X}_i[\sum_{i=1}^{N}\boldsymbol{X}'_i\boldsymbol{X}_i]^{-1}$$

$$\widehat{\boldsymbol{\Omega}}_i = \widehat{\boldsymbol{\varepsilon}}_i\widehat{\boldsymbol{\varepsilon}}'_i = \begin{pmatrix} \hat{\varepsilon}_{i1}^2 & \hat{\varepsilon}_{i1}\hat{\varepsilon}_{i2} & \cdots & \hat{\varepsilon}_{i1}\hat{\varepsilon}_{iT} \\ \vdots & \hat{\varepsilon}_{i2}^2 & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\varepsilon}_{iT}\hat{\varepsilon}_{i1} & \cdots & \hat{\varepsilon}_{iT}\hat{\varepsilon}_{i,T-1} & \hat{\varepsilon}_{iT}^2 \end{pmatrix}$$

$$\widehat{\boldsymbol{\Omega}} = \begin{pmatrix} \widehat{\boldsymbol{\Omega}}_1 & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \widehat{\boldsymbol{\Omega}}_2 & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \widehat{\boldsymbol{\Omega}}_N \end{pmatrix}$$

$$\widehat{Var}(\hat{\boldsymbol{\beta}}^{ols}_{pooled}|\boldsymbol{X}_i) = [\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{s=1}^{T}\boldsymbol{x}_{it}\hat{\varepsilon}_{it}\hat{\varepsilon}_{is}\boldsymbol{x}'_{is}[\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{x}_{it}\boldsymbol{x}'_{it}]^{-1}$$

If N (the number of cluster) is small, it is biased. However, we can adjust it by Bell & McCaffrey (2002)'s Bias-Reduced Linearization (BRL) adjustment, and using t-distribution with $N-K$ degree of freedom, instead of standard normal distribution.

In BRL adjustment, we replace $\widehat{\varepsilon}_i$ by

$$\tilde{\varepsilon}_i = \boldsymbol{A}_i \widehat{\varepsilon}_i$$

where $\boldsymbol{A}_i' \boldsymbol{A}_i = (\boldsymbol{I}_T - \boldsymbol{H}_i)^{-1}$ where $\boldsymbol{H}_i = \boldsymbol{X}_i (\boldsymbol{X}'\boldsymbol{X})^{-1} \boldsymbol{X}_i'$ the projection/hat matrix.

There are many possible $\boldsymbol{A}_i$, Bell & McCaffrey (2002) uses eigen-decomposition of the inverse of the residual marker $\boldsymbol{I}_T - \boldsymbol{H}_i$ i.e.,

$$
\begin{aligned}
(\boldsymbol{I}_T - \boldsymbol{H}_i)^{-1} &= \boldsymbol{P}\boldsymbol{\Lambda}\boldsymbol{P}' \\
&= \boldsymbol{P}\boldsymbol{\Lambda}^{1/2}\boldsymbol{\Lambda}^{1/2}\boldsymbol{P}' \\
&= \boldsymbol{P}\boldsymbol{\Lambda}^{1/2}\boldsymbol{\Lambda}^{1/2'}\boldsymbol{P}' \\
&= \boldsymbol{P}\boldsymbol{\Lambda}^{1/2}(\boldsymbol{P}\boldsymbol{\Lambda}^{1/2})' \\
&= \boldsymbol{A}'\boldsymbol{A}''
\end{aligned}
$$

where $\boldsymbol{P}$ is a matrix in which vectors are eigenvectors; $\boldsymbol{\Lambda}$ is a diagonal matrix with eigenvalues items.

$$\tilde{\varepsilon}_i = \boldsymbol{A}_i \widehat{\varepsilon}_i$$

8 References

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