

Estimation and Inference of Nonlinear Autoregressive Distributed Lag Models with Time Trend by Ordinary Least Squares

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Abstract

This study examines the large-sample behavior of an ordinary least squares (OLS) estimator within a correctly specified nonlinear autoregressive distributed lag (NARDL) model for nonstationary data. Although the OLS estimator suffers from an asymptotically singular matrix problem, it remains consistent for unknown model parameters and asymptotically follows a mixed normal distribution. Additionally, we examine the large-sample behavior of the standard Wald test, as defined by the OLS estimator, for asymmetries in long- and short-run NARDL parameters, and enhance this analysis with a super-consistent long-run parameter estimator. We then confirm the theory on the Wald test using Monte Carlo simulations. Finally, using U.S. GDP and exogenous fiscal shock data, we demonstrate use of the OLS estimator and show statistical evidence of long- and short-run symmetries between the effects of tax increases and decreases on U.S. GDP.

Key Words: Nonlinear autoregressive distributed lag model; OLS estimation; Singular matrix; Limit distribution; Wald test; Exogenous fiscal shocks; GDP.

JEL Classifications: C12, C13, C22, E62.

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1 Introduction

The nonlinear autoregressive distributed lag (NARDL) model is widely used to estimate the asymmetric cointegrating relationship between nonstationary variables. Since [Shin, Yu, and Greenwood-Nimmo \(2014\)](#) introduced the NARDL model, researchers have revisited many long-run relationships, and modified linear ones using different slope coefficients based on the signs of the variables. For example, [Borenstein, Cameron, and Gilbert \(1997\)](#) identified the so-called rockets and feathers in gasoline prices, showing that upward cost shocks in crude oil prices pass through faster than downward shocks, thus affecting other economic variables asymmetrically. [Chesnes \(2016\)](#) empirically confirms this feature using the NARDL model.

Despite its popularity, estimating the NARDL model using ordinary least squares (OLS) lacks theoretical foundation. [Cho, Greenwood-Nimmo, and Shin \(2026\)](#) noted that OLS suffers from an asymptotically singular matrix problem, and since then, no theoretical justification has emerged for estimating the NARDL parameter using OLS. Currently, many empirical studies continue to estimate the unknown parameter using OLS, without an established theory.

In this study, we revisit OLS and provide its large-sample theory. Although OLS suffers from the problem of an asymptotically singular matrix, we find that it consistently estimates the unknown parameter. Furthermore, we establish a theoretical basis for applying Wald test principle to OLS by deriving its asymptotic distribution, which allows us to test for the NARDL hypothesis. OLS asymptotically follows a mixed normal distribution under some mild regularity conditions, validating the use of OLS for empirical analysis.

This study addresses a gap in the literature concerning NARDL estimation, although it is not the first to address the asymptotically singular matrix problem associated with NARDL. [Cho et al. \(2026\)](#) explained and resolved this problem by using a two-step procedure for estimating the NARDL parameter, termed two-step NARDL (2SNARDL). They separately estimate the long- and short-run parameters, following the method used by [Engle and Granger \(1987\)](#), which avoids the asymptotically singular matrix problem. We provide theoretical grounds to compare these two estimators by deriving the limit distribution of OLS and showing that the parameter targeted by OLS is estimated at the same convergence rate as 2SNARDL. From this, if the sample size is sufficiently large, OLS can estimate the parameter more straightforwardly than 2SNARDL. Meanwhile, 2SNARDL is more useful than OLS if the sample size is small and the asymptotic bias ignored by OLS can be efficiently removed.

Singular matrices are common in econometric asymptotics, particularly in multivariate regressions, and do not necessarily indicate the absence of a limit theory; rather, they lead to significant changes in that theory. In time-series analysis involving deterministic trends and nonstationary cointegrated regressors, researchers typically resolve singularity issues by applying multiple rates of convergence in various direc-

tions (see [Phillips, 1995](#), and his subsequent works for early demonstrations). Similarly, singular matrices emerge in the context of maximum-likelihood (ML) and nonlinear least squares (NLS) estimations, letting researchers find the limit distribution using higher-order approximation of the nonlinear model. From this the convergence rate of the estimator becomes slower than the standard case (e.g., [Teräsvirta, 1994](#); [Cho and White, 2007, 2010](#); [Cho and Phillips, 2018](#)).

In the current study's OLS analysis, applying a higher-order approximation to its limit distribution is necessary, but challenging. Unlike ML and NLS, the model is linear, which means the higher-order expansion should directly apply to OLS, rather than the model itself. This task is particularly challenging, because it involves applying the higher-order expansion to the inverse matrix within OLS. Because the dimension of the matrix is arbitrary, approximating it using a higher-order expansion is not straightforward.

We address this issue by indirectly obtaining the asymptotic distribution of OLS. For this, we represent OLS as a transformation of other primitive estimators that do not suffer from a singular matrix problem, and then we derive their weak limits to achieve the desired limit distribution. This process elaborates on the Frisch-Waugh-Lovell (FWL) projection method in [Park and Phillips \(1988, 1989\)](#) so that OLS can be represented by the primitive estimators without omitting any of its elements, identifying a channel through which the unknown parameters and the primitive estimators affect the limit distribution. Using this we isolate the singular matrix problem and show that the convergence rate of OLS depends on the unknown parameter values.

The indirectly obtained limit distribution is useful for inferring the NARDL parameter. We can develop a test methodology using this limit distribution. In addition, using the limit distributions of the primitive estimators, we can establish an additional Wald test to compensate for the slower convergence rate of OLS. The primitive estimators prove to be super-consistent for the long-run parameter, which is also the same convergence rate as the long-run 2SNARDL estimator.

The limit theory of OLS guides proper empirical data analysis. In this demonstration, we analyze the empirical data provided by [Romer and Romer \(2010\)](#) to examine the long- and short-run relationships between U.S. GDP and fiscal exogenous shocks. [Romer and Romer \(2010\)](#) measure legislated exogenous tax changes related to the U.S. GDP using narrative records such as presidential speeches and *Congressional reports*. By applying the NARDL model, we determine the long- and short-run relationships between tax increases and decreases in relation to the U.S. GDP. This empirical project also serves to illustrate our methodology in a standard setting.

We conduct the empirical project not only for demonstration, but also to identify how the long- and short-run relationships between U.S. GDP and tax decreases differ from those with tax increases. According to [Romer and Romer \(2010\)](#), exogenous tax changes are classified into those aimed at deficit reduction and

those intended for long-run growth. All tax changes for deficit reduction relate to tax increases, while most changes for long-run growth involve tax decreases. The NARDL model, which we use, separates shocks into negative and positive ones and estimates their possibly different effects on the dependent variable. By applying the NARDL model, we analyze the long- and short-run relationships between the tax changes for deficit reduction and those for long-run growth in terms of U.S. GDP. Our investigation shows that the long- and short-run parameters are indeed symmetric, meaning that the tax changes for deficit reduction and those for long-run growth affect the U.S. GDP symmetrically.

The remainder of this paper is structured as follows. Section 2 provides an overview of the NARDL model and discusses the asymptotically singular matrix problem associated with OLS. Section 3 defines primitive estimators and presents OLS as a bilinear transform of the primitive estimators. Section 4 discusses the limit distribution of OLS. Section 5 examines the large-sample properties of the standard Wald test for the NARDL hypothesis, and Section 6 presents Monte Carlo simulations for the Wald tests. Section 7 presents the empirical illustration. Finally, Section 8 concludes the paper. All mathematical proofs are available in the Online Supplement, in which we also provide other simulation evidence for OLS and empirical supplements.

Before moving to the next section, we present the notation used throughout this paper. We provide the weak limit of an estimator by a stochastic integral. Denoting the weak limit by $\int \mathcal{B}$ or $\int d\mathcal{B}$ means $\int_0^1 \mathcal{B}(u)du$ or $\int_0^1 d\mathcal{B}(u)$, respectively, where $\mathcal{B}(\cdot)$ is a Brownian motion.

2 Motivation and the NARDL Model in the Literature

This section briefly summarizes NARDL and motivates the current study.

2.1 NARDL and Error-Correction Models

We consider a NARDL(p, q) process augmented by a time trend:

$$y_t = \alpha_{0*} + \xi_* t + \sum_{j=1}^p \phi_{j*} y_{t-j} + \sum_{j=0}^q (\boldsymbol{\theta}_{j*}^+ \mathbf{x}_{t-j}^+ + \boldsymbol{\theta}_{j*}^- \mathbf{x}_{t-j}^-) + e_t, \quad (1)$$

where $\mathbf{x}_t \in \mathbb{R}^k$ ($k \in \mathbb{N}$), $\mathbf{x}_t^+ := \sum_{j=1}^t \Delta \mathbf{x}_j^+$, $\mathbf{x}_t^- := \sum_{j=1}^t \Delta \mathbf{x}_j^-$, $\Delta \mathbf{x}_t^+ := \max[\mathbf{0}, \Delta \mathbf{x}_t]$, $\Delta \mathbf{x}_t^- := \min[\mathbf{0}, \Delta \mathbf{x}_t]$, $\{e_t, \mathcal{F}_t\}$ is a martingale difference array (MDA), and \mathcal{F}_t is the smallest σ -algebra driven by $\{y_{t-1}, \mathbf{x}_t^+, \mathbf{x}_t^-, y_{t-2}, \mathbf{x}_{t-1}^+, \mathbf{x}_{t-1}^-, \dots\}$ such that $\Delta \mathbf{x}_t$ is a stationary process, and Δ denotes the differencing operator, so that $\Delta \mathbf{x}_t := \mathbf{x}_t - \mathbf{x}_{t-1}$. Here, the max and min operators applied to a vector operate element-wise. The NARDL process in (1) is defined by introducing the asymmetric effect to the autoregressive distributed lag (ARDL) process proposed by Pesaran and Shin (1998). By supposing that the response of

dependent variable y_t to the positive and negative parts of \mathbf{x}_t is possibly different, the NARDL process generalizes the ARDL process. If $\boldsymbol{\theta}_{j*}^+ = \boldsymbol{\theta}_{j*}^-$ for each j , the NARDL process reduces to the ARDL process. In addition, the NARDL process in (1) is more general than those defined by Shin et al. (2014) and Cho, Greenwood-Nimmo, and Shin (2023b), because the latter do not allow for a time trend on the right side.

The NARDL process is closely related to an error-correction representation. We first rewrite (1) as follows:

$$\Delta y_t = \rho_* y_{t-1} + \boldsymbol{\theta}_*^{+'} \mathbf{x}_{t-1}^+ + \boldsymbol{\theta}_*^{-'} \mathbf{x}_{t-1}^- + \xi_*(t-1) + \alpha_* + \sum_{j=1}^{p-1} \varphi_{j*} \Delta y_{t-j} + \sum_{j=0}^{q-1} \left(\boldsymbol{\pi}_{j*}^{+'} \Delta \mathbf{x}_{t-j}^+ + \boldsymbol{\pi}_{j*}^{-'} \Delta \mathbf{x}_{t-j}^- \right) + e_t,$$

where ρ_* , $\boldsymbol{\theta}_*^+$, $\boldsymbol{\theta}_*^-$, φ_{j*} ($j = 1, 2, \dots, p-1$), $\boldsymbol{\pi}_{j*}^+$, and $\boldsymbol{\pi}_{j*}^-$ ($j = 0, 1, \dots, q-1$) are defined by the parameters in (1), as given in Cho et al. (2023b). Specifically, $\rho_* := \sum_{j=1}^p \phi_{j*} - 1$, $\boldsymbol{\theta}_*^+ := \sum_{j=0}^q \boldsymbol{\theta}_{j*}^+$, $\boldsymbol{\theta}_*^- := \sum_{j=0}^q \boldsymbol{\theta}_{j*}^-$, $\boldsymbol{\pi}_{0*}^+ := \boldsymbol{\theta}_{0*}^+$, $\boldsymbol{\pi}_{0*}^- := \boldsymbol{\theta}_{0*}^-$, and for $\ell = 1, 2, \dots, p-1$ and $j = 1, 2, \dots, q-1$, $\varphi_{\ell*} := -\sum_{i=\ell+1}^p \phi_{i*}$, $\boldsymbol{\pi}_{j*}^+ := -\sum_{i=j+1}^q \boldsymbol{\theta}_{i*}^+$, $\boldsymbol{\pi}_{j*}^- := -\sum_{i=j+1}^q \boldsymbol{\theta}_{i*}^-$, and $\alpha_* = \alpha_{0*} + \xi_*$. By plugging these parameters into (2), the NARDL(p, q) process in (1) is obtained. For notational simplicity, we further rewrite this as

$$\Delta y_t = \rho_* y_{t-1} + \boldsymbol{\theta}_*^{'} \ddot{\mathbf{x}}_{t-1} + \xi_*(t-1) + \alpha_* + \boldsymbol{\kappa}_*^{'} \mathbf{z}_{2t} + e_t \quad (2)$$

by letting $\boldsymbol{\theta}_* := [\boldsymbol{\theta}_*^{+'}, \boldsymbol{\theta}_*^{-'}]'$, $\ddot{\mathbf{x}}_{t-1} := [\mathbf{x}_{t-1}^+, \mathbf{x}_{t-1}^-]'$, $\boldsymbol{\kappa}_* := [\boldsymbol{\varphi}_*^{'}, \boldsymbol{\pi}_*^{'}]'$, and $\mathbf{z}_{2t} := [\Delta \mathbf{y}_{t-1}', \Delta \tilde{\mathbf{x}}_t']'$, such that

$$\begin{aligned} \boldsymbol{\varphi}_* &:= [\varphi_{1*}, \dots, \varphi_{p-1*}]', & \Delta \mathbf{y}_{t-1} &:= [\Delta y_{t-1}, \dots, \Delta y_{t-p+1}]', \\ \boldsymbol{\pi}_* &:= [\boldsymbol{\pi}_*^{+'}, \boldsymbol{\pi}_*^{-'}]', & \boldsymbol{\pi}_*^+ &:= [\boldsymbol{\pi}_{0*}^+, \dots, \boldsymbol{\pi}_{q-1*}^+]', & \boldsymbol{\pi}_*^- &:= [\boldsymbol{\pi}_{0*}^-, \dots, \boldsymbol{\pi}_{q-1*}^-]', \\ \Delta \tilde{\mathbf{x}}_t &:= [\Delta \tilde{\mathbf{x}}_t^+, \Delta \tilde{\mathbf{x}}_t^{-'}]', & \Delta \tilde{\mathbf{x}}_t^+ &:= [\Delta \mathbf{x}_t^+, \dots, \Delta \mathbf{x}_{t-q+1}^+]', & \text{and } \Delta \tilde{\mathbf{x}}_t^- &:= [\Delta \mathbf{x}_t^-, \dots, \Delta \mathbf{x}_{t-q+1}^-]'. \end{aligned}$$

Here, if y_{t-1} is cointegrated with $\ddot{\mathbf{x}}_{t-1}$, (2) can be rewritten into the following error-correction form:

$$\Delta y_t = \rho_* u_{t-1} + \gamma_* + \boldsymbol{\kappa}_*^{'} \mathbf{z}_{2t} + e_t, \quad (3)$$

such that the cointegration error is defined as $u_{t-1} := y_{t-1} - \boldsymbol{\beta}_*^{'} \ddot{\mathbf{x}}_{t-1} - \zeta_*(t-1) - \nu_*$ with $\boldsymbol{\beta}_* := [\boldsymbol{\beta}_*^{+'}, \boldsymbol{\beta}_*^{-'}]'$, $\boldsymbol{\beta}_*^+ := -(\boldsymbol{\theta}_*^+ / \rho_*)$, $\boldsymbol{\beta}_*^- := -(\boldsymbol{\theta}_*^- / \rho_*)$, and $\zeta_* := -(\xi_* / \rho_*)$. Here, the intercept ν_* is introduced so that $\mathbb{E}[u_t] = 0$, and u_t is assumed to be stationary and possibly correlated with $\Delta \mathbf{y}_{t-1}$ and $\Delta \tilde{\mathbf{x}}_t$. From this, it follows that $\gamma_* = \alpha_* + \rho_* \nu_*$.

The NARDL process captures an asymmetric cointegrating relationship between nonstationary processes. If we let $\boldsymbol{\mu}_* := [\boldsymbol{\mu}_*^{+'}, \boldsymbol{\mu}_*^{-'}]'$, $\boldsymbol{\mu}_*^+ := \mathbb{E}[\Delta \mathbf{x}_t^+]$ and $\boldsymbol{\mu}_*^- := \mathbb{E}[\Delta \mathbf{x}_t^-]$, then $\boldsymbol{\mu}_*^+ + \boldsymbol{\mu}_*^- \equiv \mathbb{E}[\Delta \mathbf{x}_t]$

by construction. Therefore, if we further let $\mathbf{s}_t^+ := \Delta \mathbf{x}_t^+ - \boldsymbol{\mu}_*^+$ and $\mathbf{s}_t^- := \Delta \mathbf{x}_t^- - \boldsymbol{\mu}_*^-$, it follows that

$$\ddot{\mathbf{x}}_t = \boldsymbol{\mu}_* t + \mathbf{m}_t \quad \text{by letting} \quad \mathbf{m}_t := [\mathbf{m}_t^{+'}, \mathbf{m}_t^{-'}]', \quad \mathbf{m}_t^+ := \sum_{j=1}^t \mathbf{s}_j^+ \quad \text{and} \quad \mathbf{m}_t^- := \sum_{j=1}^t \mathbf{s}_j^-. \quad (4)$$

From (4), $\ddot{\mathbf{x}}_t$ is clearly a unit-root process with nonzero time trends. Moreover, Δy_t is not necessarily distributed around zero, even when \mathbf{x}_t is a unit-root process without a time trend. From (3), we have

$$\delta_* := \mathbb{E}[\Delta y_t] = \frac{1}{\varrho_*} \left[\gamma_* + \sum_{j=0}^{q-1} \boldsymbol{\pi}_{j*} \boldsymbol{\mu}_* \right], \quad \text{where} \quad \boldsymbol{\pi}_{j*} := [\boldsymbol{\pi}_{j*}^{+'}, \boldsymbol{\pi}_{j*}^{-'}] \quad \text{and} \quad \varrho_* := 1 - \sum_{j=1}^{p-1} \varphi_{j*},$$

so that if $d_t := \Delta y_t - \delta_*$, then

$$y_t = \delta_* t + \sum_{j=1}^t d_j. \quad (5)$$

This fact implies that y_t is a unit-root process with a deterministic time trend, which has further implications. First, even when $\mathbb{E}[\mathbf{x}_t] = \mathbf{0}$, the NARDL model captures a cointegrating relationship between the variables without and with time trend, viz., \mathbf{x}_t and y_t . Second, the NARDL model includes the time trend in (2) as an explanatory variable by noting that the trend in y_t could also be influenced by exogenous factors other than the NARDL effect. If the estimated coefficient of the time trend is insignificant, it signals that the trend in y_t is solely sourced from the NARDL effect.

2.2 OLS for NARDL and Asymptotic Singular Matrix

Shin et al. (2014) estimate (2) by OLS without distinguishing the long- and short-run equation, which is now very popular in the empirical literature. For this examination, we first let

$$\mathbf{z}_t := \left[\begin{array}{c|c} \mathbf{z}'_{1t} & \mathbf{z}'_{2t} \end{array} \right]' := \left[\begin{array}{c|c|c} y_{t-1} & \mathbf{r}'_{t-1} & \mathbf{z}'_{2t} \end{array} \right]' := \left[\begin{array}{c|c|c|c|c} y_{t-1} & \ddot{\mathbf{x}}'_{t-1} & (t-1) & 1 & \mathbf{z}'_{2t} \end{array} \right]',$$

so that $\mathbf{r}_{t-1} = [\ddot{\mathbf{x}}'_{t-1}, (t-1), 1]'$. Here, $\mathbf{z}_t \in \mathbb{R}^{2+p+2k(1+q)}$ is partitioned into two variables such that $\mathbf{z}_{1t} \in \mathbb{R}^{3+2k}$ and $\mathbf{z}_{2t} \in \mathbb{R}^{p+2kq-1}$. Next, we let $\boldsymbol{\alpha}_* := \left[\begin{array}{c|c|c|c} \rho_* & \boldsymbol{\theta}'_* & \xi_* & \alpha_* \\ \hline & & & \boldsymbol{\kappa}'_* \end{array} \right]'$. From this, the OLS estimator is written as

$$\hat{\boldsymbol{\alpha}}_T := \left[\begin{array}{c|c|c|c} \hat{\rho}_T & \hat{\boldsymbol{\theta}}'_T & \hat{\xi}_T & \hat{\alpha}_T \\ \hline & & & \hat{\boldsymbol{\kappa}}'_T \end{array} \right]' := \left(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}'_t \right)^{-1} \sum_{t=1}^T \mathbf{z}_t \Delta y_t.$$

For later purposes, we partition $\hat{\boldsymbol{\theta}}_T$ and $\hat{\boldsymbol{\kappa}}_T$ into $[\hat{\boldsymbol{\theta}}_T^{+'}, \hat{\boldsymbol{\theta}}_T^{-'}]'$ and $[\hat{\boldsymbol{\varphi}}_T', \hat{\boldsymbol{\pi}}_T']' \equiv [\hat{\boldsymbol{\varphi}}_T', \hat{\boldsymbol{\pi}}_T^{+'}, \hat{\boldsymbol{\pi}}_T^{-'}]'$, respectively.

Despite its popularity, there is no theoretical foundation for the OLS. This is mainly attributed to the

asymptotically singular matrix problem. Even under mild regularity conditions, the OLS estimator suffers from an asymptotically singular matrix problem. For this discussion, we impose the following conditions, which are standard in the literature:

- Assumption 1.** (i) $\{(\Delta y_t, \Delta \mathbf{x}'_t, u_t)' \in \mathbb{R}^{k+2} : t = \dots, -1, 0, 1, \dots\}$ is a strictly stationary ϕ -mixing process of size $-r/(2(r-1))$ or α -mixing process of size $-r/(r-2)$ and $r > 2$;
- (ii) $\mathbb{E}[|\Delta x_{ti}|^r] < \infty$ ($i = 1, 2, \dots, k$), $\mathbb{E}[|u_t|^r] < \infty$, $\mathbb{E}[|e_t|^2] < \infty$, and $\delta_* \neq 0$, where x_{ti} is the i -th row element of \mathbf{x}_t ;
- (iii) $\Sigma_* := \lim_{T \rightarrow \infty} \text{var}[T^{-1/2} \sum_{t=1}^T \mathbf{w}_t]$ is positive definite, where

$$\mathbf{w}_t := \begin{bmatrix} \mathbf{w}'_{1t} \\ \mathbf{w}'_{2t} \end{bmatrix} := \begin{bmatrix} \mathbf{s}'_{t-1} & u_{t-1} \\ e_t & e_t u_{t-1} & e_t \mathbf{z}'_{2t} \end{bmatrix}'$$

and $\mathbf{s}_{t-1} := [\mathbf{s}_{t-1}^+, \mathbf{s}_{t-1}^-]'$;

- (iv) for some α_* with $\rho_* < 0$, Δy_t is generated by (2) such that $|L_*| > 1$, where $1 - \sum_{j=1}^p \phi_{j*} L_*^j \equiv 0$;
- (v) $\{e_t, \mathcal{F}_t\}$ is an MDA such that $\mathbb{E}[e_t^2 | \mathcal{F}_t] = \sigma_e^2$. □

- Remarks.** (a) Under the same assumption, we investigate the limit behavior of the OLS estimator below.
- (b) Assumptions 1 (i and ii) assume mixing and moment conditions to apply the functional central limit theorem (FCLT) to a partial-sum data process. The FCLT is popular for deriving the limit distribution of the OLS applied to estimate a cointegrating relationship (e.g., Phillips and Hansen, 1990; Phillips, 1991; White, 2001, chapter 7).
- (c) Assumption 1 (iv) assumes $\rho_* < 0$ for a cointegrating relationship between y_t and $\tilde{\mathbf{x}}_t$. If no cointegrating relationship exists, so that if $\beta_* = \mathbf{0}$ and $\zeta_* = 0$, then it follows from (3) that

$$y_t = \alpha_* + \sum_{j=1}^p \phi_{j*} y_{t-j} + \pi_*' \Delta \tilde{\mathbf{x}}_t + e_t.$$

Assumption 1 (iv), however, implies that y_t is a stationary process, contradicting the assumption that y_t is a unit-root process. From this, it is necessary to assume $\rho_* = 0$ for $(\beta_*', \zeta_*)' = \mathbf{0}$. In this study, we assume the cointegrating relationship established by (3).

- (d) Although it is not our main interest, Pesaran, Shin, and Smith (2001) and Banerjee, Dolado, and Mestre (1998) have previously examined estimating the unknown parameter by OLS under $\rho_* = 0$. They assumed a linear model and developed a testing methodology for $\rho_* = 0$. Their methodology is applicable even in the context of NARDL, because assuming no cointegration under the condition of linearity is equivalent to assuming $\beta_* = \mathbf{0}$ and $\zeta_* = 0$.
- (e) Assumption 1 (v) is a standard condition for the error term in the ARDL and NARDL processes (e.g.,

We now show how the asymptotically singular matrix problem is associated with the OLS. For this, we provide the following lemma.

Lemma 1. *Under Assumption 1,*

(i)

$$\mathbf{D}_1^{-1} \left(\sum_{t=1}^T \mathbf{z}_{1t} \mathbf{z}'_{1t} \right) \mathbf{D}_1^{-1} \xrightarrow{\mathbb{P}} \mathbf{M}_{11} := \left[\begin{array}{c|c} \begin{bmatrix} \frac{1}{3} \delta_* \\ \frac{1}{3} \boldsymbol{\mu}_* \\ \frac{1}{3} \\ \frac{1}{2} \end{bmatrix} & \begin{bmatrix} \frac{1}{2} \delta_* \\ \frac{1}{2} \boldsymbol{\mu}_* \\ 1 \end{bmatrix} \\ \hline [\delta_*, \boldsymbol{\mu}'_*, 1] & \end{array} \right],$$

where $\mathbf{D}_1 := \text{diag}[T^{3/2} \mathbf{I}_{2+2k}, T^{1/2}]$;

(ii) $\mathbf{D}_2^{-1} \left(\sum_{t=1}^T \mathbf{z}_{2t} \mathbf{z}'_{2t} \right) \mathbf{D}_2^{-1} \xrightarrow{\mathbb{P}} \mathbf{M}_{22} := \mathbb{E}[\mathbf{z}_{2t} \mathbf{z}'_{2t}]$, where $\mathbf{D}_2 := T^{1/2} \mathbf{I}_{p+2kq-1}$;

(iii)

$$\mathbf{D}_2^{-1} \left(\sum_{t=1}^T \mathbf{z}_{2t} \mathbf{z}'_{1t} \right) \mathbf{D}_1^{-1} \xrightarrow{\mathbb{P}} \mathbf{M}_{21} := \left[\begin{array}{c|c} \begin{bmatrix} \frac{1}{2} \delta_* \boldsymbol{\nu}_{p-1} \\ \frac{1}{2} \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* \end{bmatrix} & \begin{bmatrix} \frac{1}{2} \delta_* \boldsymbol{\nu}_{p-1} \\ \frac{1}{2} \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* \end{bmatrix} \\ \hline [\delta_*, \boldsymbol{\mu}'_*, 1] & 2 \end{array} \right],$$

where for each $\ell \in \mathbb{N}$, $\boldsymbol{\nu}_\ell := [1, 1, \dots, 1]' \in \mathbb{R}^\ell$;

(iv)

$$\mathbf{D}^{-1} \left(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}'_t \right) \mathbf{D}^{-1} \xrightarrow{\mathbb{P}} \mathbf{M} := \begin{bmatrix} \mathbf{M}_{11} & \mathbf{M}_{12} \\ \mathbf{M}_{21} & \mathbf{M}_{22} \end{bmatrix},$$

which is singular, where $\mathbf{D} := \text{diag}[\mathbf{D}_1, \mathbf{D}_2]$ and $\mathbf{M}_{12} := \mathbf{M}'_{21}$. \square

Here, \mathbf{M} is singular because its first $(1 + 2k)$ columns are proportional to the $(2 + 2k)$ -th column.

Remarks. (a) Lemma 1 clearly implies that the theoretical foundation of the OLS cannot be established without tackling the asymptotically singular matrix problem. The asymptotically singular matrix problem arises from the deterministic time trend in the regressors. Specifically, $\mathbb{E}[\Delta y_{t-1}] \neq 0$ by (5), so that y_{t-1} is an integrated series with a deterministic time trend. Likewise, both \mathbf{x}_{t-1}^+ and \mathbf{x}_{t-1}^- are integrated series with deterministic time trends. Therefore, all of y_{t-1} , $\ddot{\mathbf{x}}_{t-1}$, and $(t-1)$ are driven by the time trend, leading to the asymptotically singular matrix problem. This aspect is also evident from Lemma 1. The first $(2 + 2k)$ columns of \mathbf{M} are proportional to each other, and they are the terms involved with y_{t-1} , $\ddot{\mathbf{x}}_{t-1}$, and $(t-1)$.

(b) Cho et al. (2026) note the asymptotically singular matrix and estimate the unknown long-run parameters by first removing the trends from y_{t-1} and $\ddot{\mathbf{x}}_{t-1}$, proposing 2SNARDL estimation. We prove Lemma 1 in the Online Supplement by extending lemma 1 of Cho et al. (2026). Their lemma demon-

- strates another singular matrix problem by supposing no time trend in (1). Lemma 1 verifies that augmenting the time trend on the right side is not helpful in eliminating the singular matrix problem.
- (c) We can easily verify the asymptotically singular matrix problem by conducting simple Monte Carlo simulations. By denoting the model and data-generating process (DGP) conditions for Table 3, we compute the minimum diagonal element and determinant of $\mathbf{D}^{-1}(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}_t') \mathbf{D}^{-1}$ for $T = 25, 50, 75, 100, 125, \dots, 475, \text{ and } 500$. After iterating 10000 independent experiments, Figure 1 (a) draws a scatter diagram between T and the average of the 10000 minimum diagonal elements. From this, we can see that the minimum diagonal element converges to a finite number, indicating that $\mathbf{D}^{-1}(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}_t') \mathbf{D}^{-1} = O_{\mathbb{P}}(1)$. Meanwhile, Figure 1 (b) draws a scatter diagram between T and the average of the 10000 determinants $\times 10^{12}$. This second figure shows that the determinant converges to zero, meaning that $\mathbf{D}^{-1}(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}_t') \mathbf{D}^{-1}$ is asymptotically singular. This corroborates Lemma 1.
- (d) Singular matrices often appear in econometric asymptotics, especially in multivariate regressions. These matrices do not necessarily indicate the absence of a limit theory; rather, they typically lead to significant changes in that theory. In time-series analysis, when dealing with deterministic trends and nonstationary cointegrated regressors, researchers use multiple rates of convergence in different directions to address this issue (e.g., Phillips, 1995, and his subsequent works). In the cases of ML and NLS estimations, researchers obtain the limit distribution by applying higher-order approximations to nonlinear models, resulting in a slower convergence rate compared to the standard case (e.g., Teräsvirta, 1994; Cho and White, 2007, 2010; Cho and Phillips, 2018).
- (e) In the current context, it is not straightforward to apply a higher-order expansion to OLS. The model is already linear, unlike ML and NLS. This means that it is necessary to apply the higher-order expansion to OLS itself. However, given that the dimension of $(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}_t')^{-1}$ is determined by $k, p, \text{ and } q$, and they can be given arbitrarily, the task becomes challenging. \square

3 An Alternative Representation of the OLS Estimator

Owing to the complexity of the higher-order expansion, we use a different approach to obtain the desired limit distribution. We represent the OLS estimator as a transformation of other primitive estimators that do not suffer from an asymptotic singularity problem.

3.1 Alternative Representation

We achieve the alternative representation in two steps. First, we estimate the long- and short-run parameters using OLS and represent the OLS estimator $\hat{\alpha}_T$ as a bilinear transformation of the long- and short-run OLS

estimators. Next, we express the long- and short-run OLS estimators as other bilinear transformations of further primitive estimators that do not suffer from an asymptotically singular matrix problem.

3.1.1 First Step: Representing OLS Estimator by Long- and Short-Run Estimators

We estimate the long-run parameter using OLS. That is, after specifying the long-run equation

$$y_{t-1} = \mathbf{r}'_{t-1} \mathbf{v}_* + u_{t-1} = \boldsymbol{\beta}'_* \ddot{\mathbf{x}}_{t-1} + \zeta_*(t-1) + \nu_* + u_{t-1} \quad (6)$$

by letting $\mathbf{v}_* := [\boldsymbol{\beta}'_*, \zeta_*, \nu_*]'$, we let the long-run OLS estimator be

$$\tilde{\mathbf{v}}_T := [\tilde{\boldsymbol{\beta}}'_T, \tilde{\zeta}_T, \tilde{\nu}_T]' := \left(\sum_{t=1}^T \mathbf{r}_{t-1} \mathbf{r}'_{t-1} \right)^{-1} \sum_{t=1}^T \mathbf{r}_{t-1} y_{t-1}.$$

For later purposes, we let $\tilde{u}_{t-1} := y_{t-1} - \mathbf{r}'_{t-1} \tilde{\mathbf{v}}_T$ and partition $\tilde{\boldsymbol{\beta}}_T$ such that $\tilde{\boldsymbol{\beta}}_T \equiv [\tilde{\boldsymbol{\beta}}_T^+, \tilde{\boldsymbol{\beta}}_T^-]'$.

We next estimate the short-run parameter by letting $\boldsymbol{\omega}_* := [\rho_*, \boldsymbol{\eta}'_*, \psi_*, \gamma_*, \boldsymbol{\kappa}'_*]'$, such that $\boldsymbol{\eta}_* := \boldsymbol{\theta}_* + \rho_* \boldsymbol{\beta}_*$ and $\psi_* := \xi_* + \rho_* \zeta_*$, and $\dot{\mathbf{z}}_t := [u_{t-1}, \mathbf{r}'_{t-1}, \mathbf{z}'_{2t}]'$ to specify the error-correction model

$$\Delta y_t = \dot{\mathbf{z}}'_t \boldsymbol{\omega}_* + e_t = \rho_* u_{t-1} + \boldsymbol{\eta}'_* \ddot{\mathbf{x}}_{t-1} + \psi_*(t-1) + \gamma_* + \boldsymbol{\kappa}'_* \mathbf{z}_{2t} + e_t. \quad (7)$$

We obtain this equation by combining (2) and (6) and estimate the parameters in (7) by

$$\tilde{\boldsymbol{\omega}}_T := [\tilde{\rho}_T, \tilde{\boldsymbol{\eta}}'_T, \tilde{\psi}_T, \tilde{\gamma}_T, \tilde{\boldsymbol{\kappa}}'_T]' := \left(\sum_{t=1}^T \tilde{\mathbf{z}}_t \tilde{\mathbf{z}}'_t \right)^{-1} \sum_{t=1}^T \tilde{\mathbf{z}}_t \Delta y_t, \quad \text{where } \tilde{\mathbf{z}}_t := [\tilde{u}_{t-1}, \mathbf{r}'_{t-1}, \mathbf{z}'_{2t}]',$$

estimating the short-run parameter $\boldsymbol{\omega}_*$. Note that $\tilde{\boldsymbol{\omega}}_T$ is obtained by replacing u_{t-1} with \tilde{u}_{t-1} . For later purposes, we partition $\boldsymbol{\eta}_*$ into $[\boldsymbol{\eta}_*^+, \boldsymbol{\eta}_*^-]'$.

The long- and short-run OLS estimators have a regular relationship in terms of the OLS estimator $\hat{\boldsymbol{\alpha}}_T$. The following proposition reveals the relationship:

Proposition 1. *Under Assumption 1, $\hat{\boldsymbol{\alpha}}_T = \mathbf{R}_T \tilde{\boldsymbol{\omega}}_T$, where*

$$\mathbf{R}_T := \begin{bmatrix} \mathbf{R}_T^{11} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_{p+2kq-1} \end{bmatrix}, \quad \text{and} \quad \mathbf{R}_T^{11} := \begin{bmatrix} 1 & \mathbf{0}_{1 \times (2+2k)} \\ -\tilde{\mathbf{v}}_T & \mathbf{I}_{2+2k} \end{bmatrix}. \quad \square$$

Remarks. (a) By Proposition 1, the OLS estimator $\hat{\boldsymbol{\alpha}}_T$ is now represented as a bilinear transformation

between the long- and short-run OLS estimators \tilde{v}_T and $\tilde{\omega}_T$. That is,

$$\hat{\alpha}_T = [\tilde{\rho}_T, -\tilde{\rho}_T \tilde{\beta}'_T + \tilde{\eta}'_T, -\tilde{\rho}_T \tilde{\zeta}_T + \tilde{\psi}_T, -\tilde{\rho}_T \tilde{\nu}_T + \tilde{\gamma}_T, \tilde{\kappa}'_T]'$$

If both \tilde{v}_T and $\tilde{\omega}_T$ are consistent for v_* and ω_* , respectively, it follows that

$$\hat{\alpha}_T \xrightarrow{\mathbb{P}} [\rho_*, -\rho_* \beta'_* + \eta'_*, -\rho_* \zeta_* + \psi_*, -\rho_* \nu_* + \gamma_*, \kappa'_*]' = [\rho_*, \theta_*, \xi_*, \alpha_*, \kappa'_*]'$$

by noting that $\eta_* = \mathbf{0}$ and $\psi_* = 0$.

- (b) Proposition 1 follows by applying Lemma A.2 in the Online Supplement. By letting y_t , \mathbf{x}_t , \mathbf{z}_t , and \mathbf{w}_t of Lemma A.2 be Δy_t , y_{t-1} , \mathbf{r}_{t-1} , and \mathbf{z}_{2t} of (7), respectively, Proposition 1 follows. Here, \hat{v}_t in Lemma A.2 corresponds to \tilde{u}_{t-1} . Lemma A.2 is established by elaborating on the FWL projection method in Park and Phillips (1988, 1989). It complements the FWL method by augmenting a representation for the estimator ignored by FWL, so that the OLS estimator $\hat{\alpha}_T$ could be written without omitting any of its element as given in Proposition 1. By this feature, we call Lemma A.2 the augmented FWL (AFWL). For the goal to derive the joint limit distribution of $\hat{\alpha}_T$, it is important to derive the joint limit distributions of the long- and short-run OLS estimators without omitting any of its element, but FWL omits the representation of the coefficient, if its variable is concentrated out. For this reason, we complement FWL using AFWL and provide the alternative representation for $\hat{\alpha}_T$. \square

3.1.2 Second Step: Representing Long- and Short-Run Estimators by Primitive Estimators

Although Proposition 1 represents $\hat{\alpha}_T$ as a bilinear transformation between the long- and short-run OLS estimators, they both suffer from asymptotically singular matrix problems. It is mainly because \tilde{v}_T and $\tilde{\omega}_T$ are defined by regressors including \tilde{x}_{t-1} and $(t-1)$ that are driven by the time trend; see Lemma A.3 in the Online Supplement. Therefore, we again represent both estimators using other primitive estimators that do not suffer from an asymptotically singular matrix problem.

Long-Run Estimator We first represent the long-run OLS estimator \tilde{v}_T using other estimators. Note that both (4) and (6) imply that

$$y_{t-1} = \mathbf{r}'_{t-1} \mathbf{v}_* + u_{t-1} = \beta'_* \mathbf{m}_{t-1} + \vartheta_*(t-1) + \nu_* + u_{t-1}, \quad \text{where } \vartheta_* := \beta'_* \boldsymbol{\mu}_* + \zeta_*. \quad (8)$$

This representation is obtained by collecting the deterministic time trend $(t-1)$ and the remainder \mathbf{m}_{t-1} in (4) as regressors. However, \mathbf{m}_{t-1} is unobservable. So, we first predict it by estimating the unknown

parameters μ_* in (4):

$$\ddot{\mu}_T := \left(\sum_{t=1}^T (t-1)^2 \right)^{-1} \sum_{t=1}^T (t-1) \ddot{\mathbf{x}}_{t-1}, \quad \text{obtaining} \quad \ddot{\mathbf{m}}_{t-1} := \ddot{\mathbf{x}}_{t-1} - (t-1) \ddot{\mu}_T,$$

and regressing y_{t-1} against $\ddot{\mathbf{r}}_{t-1} := [\ddot{\mathbf{m}}'_{t-1}, (t-1), 1]'$, to obtain

$$\ddot{\mathbf{v}}_T := [\ddot{\beta}'_T, \ddot{\vartheta}_T, \ddot{\nu}_T]' := \left(\sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}'_{t-1} \right)^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} y_{t-1}, \quad \text{estimating} \quad \ddot{\mathbf{v}}_* := [\beta'_*, \vartheta_*, \nu_*]'$$

For later purposes, we partition $\ddot{\beta}_T$ such that $\ddot{\beta}_T \equiv [\ddot{\beta}_T^+, \ddot{\beta}_T^-]'$ and let $\ddot{u}_{t-1} := y_{t-1} - \ddot{\mathbf{r}}'_{t-1} \ddot{\mathbf{v}}_T$.

The interrelationship between the long-run OLS and primitive estimators is stated in the following proposition:

Proposition 2. *Given Assumption 1, $\tilde{\mathbf{v}}_T := [\tilde{\beta}'_T, \tilde{\zeta}_T, \tilde{\nu}_T]' = \mathbf{P}_T \ddot{\mathbf{v}}_T = [\ddot{\beta}'_T, \ddot{\vartheta}_T - \ddot{\mu}'_T \ddot{\beta}_T, \ddot{\nu}_T]'$, where*

$$\mathbf{P}_T := \begin{bmatrix} \mathbf{I}_{2k} & \mathbf{0} \\ \mathbf{P}_T^{21} & \mathbf{I}_2 \end{bmatrix} \quad \text{and} \quad \mathbf{P}_T^{21} := \begin{bmatrix} -\ddot{\mu}'_T \\ \mathbf{0}_{1 \times 2k} \end{bmatrix}. \quad \square$$

Remarks. (a) By Proposition 2, the long-run OLS estimator $\tilde{\mathbf{v}}_T$ is represented as a bilinear transformation between the primitive estimators, $\ddot{\mu}_T$ and $\ddot{\mathbf{v}}_T$. This representation is particularly useful, because neither $\ddot{\mu}_T$ nor $\ddot{\mathbf{v}}_T$ suffers from an asymptotically singular matrix problem; see Lemma 2 below.

(b) If both $\ddot{\mu}_T$ and $\ddot{\mathbf{v}}_T$ are consistent for μ_* and $\ddot{\mathbf{v}}_*$, respectively,

$$\tilde{\mathbf{v}}_T = [\ddot{\beta}'_T, \ddot{\vartheta}_T - \ddot{\mu}'_T \ddot{\beta}_T, \ddot{\nu}_T]' \xrightarrow{\mathbb{P}} [\beta'_*, \vartheta_* - \mu'_* \beta_*, \nu_*]' = [\beta'_*, \zeta_*, \nu_*]' =: \mathbf{v}_*$$

by noting that $\vartheta_* := \beta'_* \mu_* + \zeta_*$, leading to the consistency of $\tilde{\mathbf{v}}_T$ for \mathbf{v}_* . Furthermore, $\tilde{u}_{t-1} = \ddot{u}_{t-1}$ using the definition of $\ddot{\mathbf{m}}_{t-1} := \ddot{\mathbf{x}}_{t-1} - (t-1) \ddot{\mu}_T$.

(c) Proposition 2 is also established by AFWL. If we let y_{t-1} , $\ddot{\mathbf{x}}'_{t-1}$, $(t-1)$, and 1 be y_t , \mathbf{x}_t , \mathbf{z}_t , and \mathbf{w}_t , respectively, in Lemma A.2, then Proposition 2 follows. \square

Short-Run Estimator Next, we represent the short-run OLS estimator $\tilde{\omega}_T$ as a bilinear transformation between two other estimators that do not suffer from an asymptotically singular matrix problem. This representation is parallel to the one for the long-run OLS estimator. As both $\ddot{\mathbf{x}}_{t-1}$ and $(t-1)$ on the right side of (7) are driven by the deterministic trend, we reparameterize (7) using (4):

$$\Delta y_t = \rho_* u_{t-1} + \eta'_* \mathbf{m}_{t-1} + \varsigma_*(t-1) + \gamma_* + \kappa'_* \mathbf{z}_{2t} + e_t, \quad \text{where} \quad \varsigma_* := \mu'_* \eta_* + \psi_*. \quad (9)$$

Here, the coefficient of $(t-1)$ is obtained as ς_* by collecting the coefficients of the time trends in $\ddot{\mathbf{x}}_{t-1}$ and $(t-1)$, but the coefficient of \mathbf{m}_{t-1} keeps the same as that of $\ddot{\mathbf{x}}_{t-1}$ on the right side of (7).

We estimate the unknown parameters in (9) by OLS. For this, we replace u_{t-1} and \mathbf{m}_{t-1} in (9) with \ddot{u}_{t-1} and $\ddot{\mathbf{m}}_{t-1}$, respectively as they are unobservable. By letting $\ddot{\mathbf{z}}_t := [\ddot{u}_{t-1} \mid \ddot{\mathbf{r}}'_{t-1} \mid \mathbf{z}'_{2t}]'$, the parameter estimator is obtained as follows:

$$\begin{aligned} \ddot{\boldsymbol{\tau}}_T &:= [\ddot{\rho}_T \mid \ddot{\boldsymbol{\tau}}'_{1T} \mid \ddot{\boldsymbol{\kappa}}'_T]' := [\ddot{\rho}_T \mid \ddot{\boldsymbol{\eta}}'_T \quad \ddot{\zeta}_T \quad \ddot{\gamma}_T \mid \ddot{\boldsymbol{\kappa}}'_T]' := \left(\sum_{t=1}^T \ddot{\mathbf{z}}_t \ddot{\mathbf{z}}'_t \right)^{-1} \sum_{t=1}^T \ddot{\mathbf{z}}_t \Delta y_t, \quad \text{estimating} \\ \boldsymbol{\tau}_* &:= [\rho_* \mid \boldsymbol{\tau}'_{1*} \mid \boldsymbol{\kappa}'_*]' := [\rho_* \mid \boldsymbol{\eta}'_* \quad \varsigma_* \quad \gamma_* \mid \boldsymbol{\kappa}'_*]'. \end{aligned}$$

Here, for later purposes, we let $\ddot{\boldsymbol{\eta}}_T \equiv [\ddot{\boldsymbol{\eta}}_T^{+'}, \ddot{\boldsymbol{\eta}}_T^{-'}]'$ and $\ddot{\boldsymbol{\kappa}}_T \equiv [\ddot{\boldsymbol{\varphi}}'_T, \ddot{\boldsymbol{\pi}}'_T]' \equiv [\ddot{\boldsymbol{\varphi}}'_T, \ddot{\boldsymbol{\pi}}_T^{+'}, \ddot{\boldsymbol{\pi}}_T^{-'}]'$. In addition, we separately estimate ψ_* by $\ddot{\psi}_T := -\ddot{\boldsymbol{\mu}}'_T \ddot{\boldsymbol{\eta}}_T + \ddot{\zeta}_T$ by applying the plug-in principle to $\varsigma_* := \boldsymbol{\mu}'_* \boldsymbol{\eta}_* + \psi_*$.

The interrelationship between the short-run OLS and primitive estimators, $\tilde{\boldsymbol{\omega}}_T$ and $\ddot{\boldsymbol{\tau}}_T$, is stated in the following proposition:

Proposition 3. *Given Assumption 1, $\tilde{\boldsymbol{\omega}}_T = \mathbf{Q}_T \ddot{\boldsymbol{\tau}}_T$, where*

$$\mathbf{Q}_T := \begin{bmatrix} \mathbf{I}_{1+2k} & \mathbf{0} \\ \mathbf{Q}_T^{21} & \mathbf{I}_{p+2kq+1} \end{bmatrix} \quad \text{and} \quad \mathbf{Q}_T^{21} := \begin{bmatrix} 0 & -\ddot{\boldsymbol{\mu}}'_T \\ \mathbf{0}_{(p+2kq) \times 1} & \mathbf{0}_{(p+2kq) \times 2k} \end{bmatrix}. \quad \square$$

Remarks. (a) By Proposition 3, the short-run OLS estimator $\tilde{\boldsymbol{\omega}}_T$ is represented as a bilinear transformation between $\ddot{\boldsymbol{\mu}}_T$ and $\ddot{\boldsymbol{\tau}}_T$, which do not suffer from asymptotically singular matrix problems; see Lemma 2 below.

(b) If both $\ddot{\boldsymbol{\mu}}_T$ and $\ddot{\boldsymbol{\tau}}_T$ are consistent for $\boldsymbol{\mu}_*$ and $\boldsymbol{\tau}_*$, respectively, it follows that

$$\begin{aligned} \tilde{\boldsymbol{\omega}}_T &= [\ddot{\rho}_T, \ddot{\boldsymbol{\eta}}'_T, -\ddot{\boldsymbol{\mu}}'_T \ddot{\boldsymbol{\eta}}_T + \ddot{\zeta}_T, \ddot{\gamma}_T, \ddot{\boldsymbol{\kappa}}'_T]' \\ &\xrightarrow{\mathbb{P}} [\rho_*, \boldsymbol{\eta}'_*, -\boldsymbol{\mu}'_* \boldsymbol{\eta}_* + \varsigma_*, \gamma_*, \boldsymbol{\kappa}'_*]' = [\rho_*, \boldsymbol{\eta}'_*, \psi_*, \gamma_*, \boldsymbol{\kappa}'_*]' =: \boldsymbol{\omega}_* \end{aligned}$$

by noting that $\varsigma_* := \boldsymbol{\mu}'_* \boldsymbol{\eta}_* + \psi_*$.

(c) As before, Proposition 3 is established by AFWL. By letting Δy_t , $\ddot{\mathbf{x}}_{t-1}$, $(t-1)$, and $[\ddot{u}_{t-1}, 1, \mathbf{z}'_{2t}]'$ be y_t , \mathbf{x}_t , \mathbf{z}_t , and \mathbf{w}_t , respectively, in Lemma A.2, Proposition 3 follows. \square

OLS Estimator Using the alternative representations for the long- and short-run OLS estimators, we now represent the OLS estimator $\hat{\boldsymbol{\alpha}}_T$ as a transform of the primitive estimators: $\ddot{\boldsymbol{\mu}}_T$, $\ddot{\mathbf{v}}_T$, and $\ddot{\boldsymbol{\tau}}_T$. The following proposition reveals it:

Proposition 4. Given Assumption 1, $\widehat{\alpha}_T = \mathbf{T}_T \ddot{\tau}_T$, where $\mathbf{T}_T := \mathbf{R}_T \mathbf{Q}_T$ such that

$$\mathbf{R}_T \mathbf{Q}_T = \mathbf{T}_T := \begin{bmatrix} \mathbf{T}_T^{11} & \mathbf{0} \\ \mathbf{T}_T^{21} & \mathbf{I}_{p+2kq+1} \end{bmatrix}, \quad \mathbf{T}_T^{11} := \begin{bmatrix} 1 & \mathbf{0}_{1 \times 2k} \\ -\widetilde{\beta}_T & \mathbf{I}_{2k} \end{bmatrix} \quad \text{and}$$

$$\mathbf{T}_T^{21} := \begin{bmatrix} -\widetilde{\zeta}_T & -\ddot{\mu}'_T \\ -\widetilde{\nu}_T & \mathbf{0}_{1 \times 2k} \\ \mathbf{0}_{(p+2kq-1) \times 1} & \mathbf{0}_{(p+2kq-1) \times 2k} \end{bmatrix}. \quad \square$$

Remarks. (a) Proposition 4 follows by combining Propositions 1 and 3, in which we demonstrated that $\widehat{\alpha}_T = \mathbf{R}_T \widetilde{\omega}_T$ and $\widetilde{\omega}_T = \mathbf{Q}_T \ddot{\tau}_T$, respectively, so that

$$\widehat{\alpha}_T = \left[\ddot{\rho}_T, -\ddot{\rho}_T \ddot{\beta}'_T + \ddot{\eta}'_T, -\ddot{\rho}_T (\ddot{\vartheta}_T - \ddot{\mu}'_T \ddot{\beta}_T) - \ddot{\mu}'_T \ddot{\eta}_T + \ddot{\zeta}_T, -\ddot{\rho}_T \ddot{\nu}_T + \ddot{\gamma}_T, \ddot{\kappa}'_T \right]' \quad (10)$$

by further noting Proposition 2: $[\widetilde{\beta}'_T, \widetilde{\zeta}_T, \widetilde{\nu}_T]' = [\ddot{\beta}'_T, \ddot{\vartheta}_T - \ddot{\mu}'_T \ddot{\beta}_T, \ddot{\nu}_T]'$. An alternative representation of $\widehat{\alpha}_T$ is now provided without omitting any of its elements.

(b) If $\ddot{\mu}_T, \ddot{\nu}_T$ and $\ddot{\tau}_T$ are consistent for μ_*, ν_* and τ_* , respectively, then

$$\begin{aligned} \widehat{\alpha}_T &\xrightarrow{\mathbb{P}} [\rho_*, -\rho_* \beta'_* + \eta'_*, -\rho_* \zeta_* - \mu'_* \eta_* + \varsigma_*, -\rho_* \nu_* + \gamma_*, \kappa'_*]' \\ &= [\rho_*, -\rho_* \beta'_*, -\rho_* \zeta_*, -\rho_* \nu_* + \gamma_*, \kappa'_*]' = [\rho_*, \theta'_*, \xi_*, \alpha_*, \kappa'_*]' =: \alpha_*, \end{aligned} \quad (11)$$

where the first equality holds because $\zeta_* = \vartheta_* - \mu'_* \beta_*$, $\eta_* = \mathbf{0}$ and $\varsigma_* = 0$. In addition, the second equality holds by the definitions of β_* , ζ_* , and γ_* . From this, the consistence of $\widehat{\alpha}_T$ can be established.

(c) By Proposition 4, we can obtain the weak limit of $\widehat{\alpha}_T$ using the weak limits of the primitive estimators: $\ddot{\mu}_T, \ddot{\nu}_T$, and $\ddot{\tau}_T$; see Theorem 1.

(d) The convergence rate of the OLS estimator $\widehat{\alpha}_T$ is slower than \mathbf{D} in Lemma 1. For example, for the long-run OLS estimator $\widehat{\theta}_T$, we have $\widehat{\theta}_T = -\ddot{\rho}_T \ddot{\beta}_T + \ddot{\eta}_T$ from (10), and the convergence rates of $\ddot{\rho}_T$ and $(\ddot{\beta}_T, \ddot{\eta}_T)$ are $T^{1/2}$ and T , respectively, by Lemmas 3 and 4 given below. From this, if for $j = 1, 2, \dots, k$, $\theta_{j*}^\pm \neq 0$, then the convergence rate of $\widehat{\theta}_T$ is determined as $T^{1/2}$, which is slower than $T^{3/2}$ given in \mathbf{D} . Similar arguments apply to the other elements in $\widehat{\alpha}_T$. This slower convergence rate is the same effect as expected when the asymptotic distribution of an estimator is obtained by a higher-order expansion (e.g., Teräsvirta, 1994; Cho and White, 2007, 2010; Cho and Phillips, 2018). Theorem 1 below elaborates on the convergence rates under various parameter conditions. \square

3.2 Nonsingular Primitive Estimators

We now show that the primitive estimators $\tilde{\mathbf{r}}_T$ and $\tilde{\mathbf{v}}_T$ do not suffer from an asymptotically singular matrix problem by deriving their limit distributions. By the definition of $\tilde{\boldsymbol{\mu}}_T$, it does not suffer from an asymptotic singularity. We therefore focus on the limit distributions of $\tilde{\mathbf{r}}_T$ and $\tilde{\mathbf{v}}_T$. For this we let

$$\mathcal{B}(\cdot) := [\mathcal{B}_s(\cdot)', \mathcal{B}_u(\cdot), \mathcal{B}_e(\cdot), \mathcal{B}_{ue}(\cdot), \mathcal{B}_{ze}(\cdot)']' := \boldsymbol{\Sigma}_*^{1/2} \mathcal{W}(\cdot),$$

where $\mathcal{W}(\cdot)$ is a vector of $(2 + p + 2k(1 + q))$ independent standard Wiener processes, and $\boldsymbol{\Sigma}_*$ is the global covariance matrix given in Assumption 1. Here, $\mathcal{B}(\cdot)$ is the Brownian motion obtained by applying FCLT to $\mathbf{B}_T(\cdot) := T^{-1/2} \sum_{t=1}^{\lfloor(\cdot)T\rfloor} \mathbf{w}_t$; see Lemma B.1 in the Online Supplement. For later purposes, we also partition $\mathbf{B}_T(\cdot)$ in parallel to $\mathcal{B}(\cdot)$:

$$\mathbf{B}_T(\cdot) := [\mathbf{B}_{sT}(\cdot)', B_{uT}(\cdot), B_{eT}(\cdot), B_{ueT}(\cdot), \mathbf{B}_{zeT}(\cdot)']' := \frac{1}{\sqrt{T}} \sum_{t=1}^{\lfloor(\cdot)T\rfloor} [s'_{t-1}, u_{t-1}, e_t, u_{t-1}e_t, \mathbf{z}'_{2t}e_t]'$$

by noting that $\mathbf{w}_t := [s'_{t-1}, u_{t-1}, e_t, u_{t-1}e_t, \mathbf{z}'_{2t}e_t]'$.

The following lemma shows that neither $\tilde{\mathbf{r}}_T$ nor $\tilde{\mathbf{v}}_T$ suffers from an asymptotically singular matrix problem.

Lemma 2. *Given Assumption 1,*

(i) $T^{-1/2} \left(\sum_{t=1}^T \ddot{u}_{t-1} \ddot{\mathbf{r}}_{t-1} \right) \ddot{\mathbf{D}}_1^{-1} \Rightarrow \mathbf{M}_{1u} := \mathbf{0}_{(2k+2) \times 1}$, where $\ddot{\mathbf{D}}_1 := \text{diag}[T\mathbf{I}_{2k}, T^{3/2}, T^{1/2}]$;

(ii)

$$\ddot{\mathbf{D}}_1^{-1} \left(\sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}'_{t-1} \right) \ddot{\mathbf{D}}_1^{-1} \Rightarrow \mathcal{M}_{11} := \begin{bmatrix} \int \bar{\mathcal{B}}_s \bar{\mathcal{B}}_s' & \mathbf{0}_{2k \times 1} & \int \widetilde{\mathcal{B}}_s \\ \mathbf{0}_{1 \times 2k} & \frac{1}{3} & \frac{1}{2} \\ \int \widetilde{\mathcal{B}}_s' & \frac{1}{2} & 1 \end{bmatrix},$$

where $\bar{\mathcal{B}}_s(\cdot) := \mathcal{B}_s(\cdot) - 3(\cdot) \int r \mathcal{B}_s$ and $\widetilde{\mathcal{B}}_s(\cdot) := \mathcal{B}_s(\cdot) - \frac{3}{2}(\cdot) \int r \mathcal{B}_s$;

(iii) $\ddot{\mathbf{D}}_2^{-1} \left(\sum_{t=1}^T \ddot{u}_{t-1} \mathbf{z}_{2t} \right) \ddot{\mathbf{D}}_2^{-1} \xrightarrow{\mathbb{P}} \mathbf{M}_{2u} := \mathbb{E}[u_{t-1} \mathbf{z}_{2t}]$, where $\ddot{\mathbf{D}}_2 := T^{1/2} \mathbf{I}_{p+2kq-1}$;

(iv)

$$\ddot{\mathbf{D}}_2^{-1} \left(\sum_{t=1}^T \mathbf{z}_{2t} \ddot{\mathbf{r}}'_{t-1} \right) \ddot{\mathbf{D}}_2^{-1} \Rightarrow \mathcal{M}_{21} := \begin{bmatrix} \delta_* \boldsymbol{\nu}_{p-1} \int \widetilde{\mathcal{B}}_s' & \frac{1}{2} \delta_* \boldsymbol{\nu}_{p-1} & \delta_* \boldsymbol{\nu}_{p-1} \\ \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* \int \widetilde{\mathcal{B}}_s' & \frac{1}{2} \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* & \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* \end{bmatrix};$$

(v) $\ddot{\mathbf{D}}_2^{-1} \left(\sum_{t=1}^T \mathbf{z}_{2t} \mathbf{z}'_{2t} \right) \ddot{\mathbf{D}}_2^{-1} \xrightarrow{\mathbb{P}} \mathbf{M}_{22}$; and

(vi)

$$\ddot{\mathbf{D}}^{-1} \left(\sum_{t=1}^T \ddot{\mathbf{z}}_t \ddot{\mathbf{z}}_t' \right) \ddot{\mathbf{D}}^{-1} \Rightarrow \mathcal{M} := \begin{bmatrix} \sigma_u^2 & \mathbf{M}_{u1} & \mathbf{M}_{u2} \\ \mathbf{M}_{1u} & \mathcal{M}_{11} & \mathcal{M}_{12} \\ \mathbf{M}_{2u} & \mathcal{M}_{21} & \mathbf{M}_{22} \end{bmatrix},$$

where $\ddot{\mathbf{D}} := \text{diag}[T^{1/2}, \ddot{\mathbf{D}}_1, \ddot{\mathbf{D}}_2]$, $\mathcal{M}_{12} := \mathcal{M}'_{21}$, $\mathbf{M}_{u1} := \mathbf{M}'_{1u}$, $\mathbf{M}_{u2} := \mathbf{M}'_{2u}$, and $\sigma_u^2 := \mathbb{E}[u_t^2]$. \square

Both weak limits \mathcal{M}_{11} and \mathcal{M} given in Lemmas 2 (ii and vi) are nonsingular almost surely, meaning that the weak limits of $(\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}_{t-1}' \ddot{\mathbf{D}}_1^{-1})^{-1}$ and $(\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{\mathbf{z}}_t \ddot{\mathbf{z}}_t' \ddot{\mathbf{D}}^{-1})^{-1}$ are obtained as \mathcal{M}_{11}^{-1} and \mathcal{M}^{-1} , respectively, where the inverse matrices are those within the long- and short-run OLS estimators, $\ddot{\mathbf{v}}_T := (\sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}_{t-1}')^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} y_{t-1}$ and $\ddot{\mathbf{r}}_T := (\sum_{t=1}^T \ddot{\mathbf{z}}_t \ddot{\mathbf{z}}_t')^{-1} \sum_{t=1}^T \ddot{\mathbf{z}}_t \Delta y_t$. From this, it follows that neither $\ddot{\mathbf{v}}_T$ nor $\ddot{\mathbf{r}}_T$ suffers from an asymptotically singular matrix problem.

4 Limit Distribution of the OLS Estimator

In this section, we derive the limit distribution of $\hat{\alpha}_T$ using the weak limits of the primitive estimators. We proceed in three steps. First, we derive the weak limits of $\tilde{\mathbf{v}}_T$ and $\ddot{\mathbf{v}}_T$. Second, we conduct the same procedure for the primitive estimator $\ddot{\mathbf{r}}_T$. Finally, we derive the weak limit of $\hat{\alpha}_T$.

4.1 Weak Limit of the Long-Run OLS Estimator

We derive the weak limits of $\ddot{\mathbf{v}}_T$ and $\tilde{\mathbf{v}}_T$ using Proposition 2: $\tilde{\mathbf{v}}_T = \mathbf{P}_T \ddot{\mathbf{v}}_T$. Here,

$$\mathbf{P}_T \xrightarrow{\mathbb{P}} \mathbf{P} := \begin{bmatrix} \mathbf{I}_{2k} & \mathbf{0} \\ \mathbf{P}^{21} & \mathbf{I}_2 \end{bmatrix} \quad \text{with} \quad \mathbf{P}^{21} := \begin{bmatrix} -\boldsymbol{\mu}'_* \\ \mathbf{0}_{1 \times 2k} \end{bmatrix},$$

as $\ddot{\mathbf{m}}_T$ is consistent for $\boldsymbol{\mu}_*$. Next, we obtain the limit distribution of the primitive estimator $\ddot{\mathbf{v}}_T$. For this, we note that $\mathbf{m}_{t-1} = \ddot{\mathbf{m}}_{t-1} + (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*)(t-1)$ and rewrite (8) as

$$y_{t-1} = \ddot{\mathbf{r}}_{t-1}' \bar{\mathbf{v}}_{T*} + u_{t-1} = \boldsymbol{\beta}'_* \ddot{\mathbf{m}}_{t-1} + \vartheta_{T*}(t-1) + \nu_* + u_{t-1}, \quad \text{where} \quad \bar{\mathbf{v}}_{T*} := [\boldsymbol{\beta}'_*, \vartheta_{T*}, \nu_*]' \quad (12)$$

with $\vartheta_{T*} := \boldsymbol{\beta}'_*(\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) + \vartheta_*$. This rearranges (8) so that the right-hand side variables in the long-run equation are the same as the regressors employed for $\ddot{\mathbf{v}}_T$. From this, it follows that

$$\ddot{\mathbf{v}}_T := \left(\sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}_{t-1}' \right)^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} y_{t-1} = \bar{\mathbf{v}}_{T*} + \left(\sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}_{t-1}' \right)^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} u_{t-1}. \quad (13)$$

Using this, we derive the weak limits of $\tilde{\mathbf{v}}_T$ and $\ddot{\mathbf{v}}_T$ as follows:

Lemma 3. Let $\boldsymbol{\varrho}_{m*} := \lim_{T \rightarrow \infty} T^{-1} \sum_{t=1}^T \sum_{\tau=1}^{t-1} \mathbb{E}[s_\tau u_t]$. Given Assumption 1,

(i) $\ddot{\mathbf{D}}_1(\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*}) \Rightarrow \mathcal{L} := [\mathcal{L}'_1, \mathcal{L}_2, \mathcal{L}_3]'$ where

$$\mathcal{L} := \begin{bmatrix} \mathcal{S}_1 \\ \mathcal{S}_2 \\ \mathcal{S}_3 \end{bmatrix} := \begin{bmatrix} \int \mathcal{B}_s d\mathcal{B}_u - 3 \int r \mathcal{B}_s \int r d\mathcal{B}_u + \boldsymbol{\varrho}_{m*} \\ \int r d\mathcal{B}_u \\ \int d\mathcal{B}_u \end{bmatrix},$$

such that \mathcal{L}_1 and $\mathcal{S}_1 \in \mathbb{R}^{2k}$; and

(ii) $\ddot{\mathbf{D}}_\dagger(\tilde{\mathbf{v}}_T - \mathbf{v}_*) \Rightarrow [\mathcal{L}'_1, -\boldsymbol{\mu}'_* \mathcal{L}_1, \mathcal{L}_3]'$, where $\ddot{\mathbf{D}}_\dagger := \text{diag}[T\mathbf{I}_{2k}, T, T^{1/2}]$. \square

Remarks. (a) By Lemma 3, none of $(\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*})$ and $(\tilde{\mathbf{v}}_T - \mathbf{v}_*)$ follows a mixed normal distribution, and \mathcal{S}_1 is influenced by the asymptotic bias $\boldsymbol{\varrho}_{m*}$. This bias corresponds to that arising when estimating a cointegrating relationship by OLS (e.g., [Engle and Granger, 1987](#); [Phillips and Hansen, 1990](#)).

(b) We prove Lemma 3 (i) by noting that $\ddot{\mathbf{D}}_1(\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*}) = (\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}'_{t-1} \ddot{\mathbf{D}}_1^{-1})^{-1} \ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} u_{t-1}$ and focusing on the weak limit of $\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} u_{t-1}$. Lemma 2 (ii) already derives the weak limit of $(\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}'_{t-1} \ddot{\mathbf{D}}_1^{-1})^{-1}$. Next, we note that $\tilde{\mathbf{v}}_T - \mathbf{v}_* = (\mathbf{P}_T - \mathbf{P})(\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*}) + \mathbf{P}(\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*}) + (\mathbf{P}_T - \mathbf{P})(\bar{\mathbf{v}}_{T*} - \bar{\mathbf{v}}_*) + \mathbf{P}(\bar{\mathbf{v}}_{T*} - \bar{\mathbf{v}}_*) + (\mathbf{P}_T - \mathbf{P})\bar{\mathbf{v}}_*$ and prove Lemma 3 (ii) by examining each component on the right side. As a result, it follows that $\tilde{\mathbf{v}}_T - \mathbf{v}_* = \mathbf{P}(\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*}) + O_{\mathbb{P}}(T^{-3/2})$ and $\ddot{\mathbf{D}}_\dagger(\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*}) = O_{\mathbb{P}}(1)$.

(c) The consistency of the estimators follows from Lemma 3: $\ddot{\mathbf{v}}_T - \bar{\mathbf{v}}_{T*} \xrightarrow{\mathbb{P}} \mathbf{0}$ and $\tilde{\mathbf{v}}_T \xrightarrow{\mathbb{P}} \mathbf{v}_*$. We also have $\bar{\mathbf{v}}_{T*} \xrightarrow{\mathbb{P}} \bar{\mathbf{v}}_* := [\boldsymbol{\beta}'_*, \vartheta_*, \nu_*]'$, because $\vartheta_{T*} := \boldsymbol{\beta}'_*(\dot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) + \vartheta_* \xrightarrow{\mathbb{P}} \vartheta_*$. This further implies that $\mathbf{P}_T \xrightarrow{\mathbb{P}} \mathbf{P}$, so that $\tilde{\mathbf{v}}_T = \mathbf{P}_T \ddot{\mathbf{v}}_T \rightarrow \mathbf{P} \bar{\mathbf{v}}_* = [\boldsymbol{\beta}'_*, \zeta_*, \nu_*]'$.

(d) By Lemma 3 (ii), the weak limits of $\tilde{\boldsymbol{\beta}}_T$ and $\tilde{\zeta}_T$ are linearly correlated. This feature confirms that the long-run OLS estimator $\tilde{\mathbf{v}}_T$ suffers from the asymptotically singularity, although $\ddot{\mathbf{v}}_T$ does not.

(e) 2SNARDL estimates the long- and short-run parameters separately, and the convergence rate of the long-run 2SNARDL estimator is T , which is also the same as the convergence rate of $\ddot{\boldsymbol{\beta}}_T$ in $\ddot{\mathbf{v}}_T$. Meanwhile, the convergence rate of the OLS estimator for $\boldsymbol{\theta}_*$ depends on the unknown parameters. \square

4.2 Weak Limit of the Short-Run OLS Estimator

We derive the weak limit of the primitive estimator $\ddot{\boldsymbol{\tau}}_T$. For this purpose, we first rewrite (9) as

$$\begin{aligned} \Delta y_t = \boldsymbol{\tau}'_{T*} \ddot{\mathbf{z}}_t + e_t = \rho_* \ddot{u}_{t-1} + (\boldsymbol{\eta}_* + \rho_*(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*))' \ddot{\mathbf{m}}_{t-1} + (\psi_* + \boldsymbol{\eta}'_* \ddot{\boldsymbol{\mu}}_T + \rho_*(\ddot{\vartheta}_T - \vartheta_{T*}))(t-1) \\ + (\gamma_* + \rho_*(\ddot{\nu}_T - \nu_*)) + \boldsymbol{\kappa}'_* \mathbf{z}_{2t} + e_t, \end{aligned}$$

where

$$\begin{aligned}\tau_{T*} &:= [\rho_*, \tau'_{1T}, \kappa_*']' \quad \text{and} \\ \tau_{1T} &:= [(\boldsymbol{\eta}_* + \rho_*(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*))', \psi_* + \boldsymbol{\eta}'_* \ddot{\boldsymbol{\mu}}_T + \rho_*(\ddot{\vartheta}_T - \vartheta_{T*}), \gamma_* + \rho_*(\ddot{\nu}_T - \nu_*)']' .\end{aligned}$$

This equality is established by noting that

$$u_{t-1} = \ddot{u}_{t-1} + (\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*)' \ddot{\mathbf{m}}_{t-1} + (\ddot{\vartheta}_T - \vartheta_{T*})(t-1) + (\ddot{\nu}_T - \nu_*),$$

which follows from (12) and the definition of $\ddot{u}_{t-1} := y_{t-1} - \ddot{\mathbf{r}}'_{t-1} \ddot{\nu}_T$. This representation is obtained so that the right-hand side variables in the short-run equation are the same as the regressors employed for $\ddot{\tau}_T$. That is, we can decompose the primitive estimator $\ddot{\tau}_T$ into τ_{T*} and a remainder using this representation:

$$\ddot{\tau}_T := \left(\sum_{t=1}^T \ddot{z}_t \ddot{z}'_t \right)^{-1} \sum_{t=1}^T \ddot{z}_t \Delta y_t = \tau_{T*} + \left(\sum_{t=1}^T \ddot{z}_t \ddot{z}'_t \right)^{-1} \sum_{t=1}^T \ddot{z}_t e_t. \quad (14)$$

We now provide the weak limit of the primitive estimator $\ddot{\tau}_T$ in the following lemma:

Lemma 4. *Given Assumption 1,*

- (i) $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_{T*}) \Rightarrow \mathcal{D} := [\mathcal{D}_1, \mathcal{D}'_2, \mathcal{D}_3, \mathcal{D}_4, \mathcal{D}'_5]' := \mathcal{M}^{-1} \mathcal{J}$, where $\mathcal{J} := [\int d\mathcal{B}_{ue}, \int \ddot{\mathcal{B}}'_s d\mathcal{B}_e, \int r d\mathcal{B}_e, \int d\mathcal{B}_e, \int d\mathcal{B}'_{ze}]'$;
- (ii) $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_*) \Rightarrow \mathcal{D} - \rho_*[0, \mathcal{L}', \mathbf{0}']'$. □

Remarks. (a) From the definition of \mathcal{D} , the primitive estimator $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_{T*})$ asymptotically follows a mixed normal distribution, but $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_*)$ does not. Lemma 2 (i) already shows that the weak limit \mathcal{L} does not follow a mixed normal distribution, and the limit distribution of $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_*)$ is formed by both \mathcal{D} and \mathcal{L} .

- (b) We prove Lemma 4 by examining the limit behavior of each component on the right side of (14). Because Lemma 2 (vi) already shows that $\ddot{\mathbf{D}}^{-1}(\sum_{t=1}^T \ddot{z}_t \ddot{z}'_t) \ddot{\mathbf{D}}^{-1} \Rightarrow \mathcal{M}$, we focus on showing that $\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t e_t \Rightarrow \mathcal{J}$. In addition, we note that $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_{T*}) = \ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_*) + [0, -\rho_* T(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*)', -\rho_* T^{3/2}(\ddot{\vartheta}_T - \vartheta_{T*}), -\rho_* T^{1/2}(\ddot{\nu}_T - \nu_*), \mathbf{0}']'$, and exploit Lemmas 3 (ii) and 4 (i) to prove Lemma 4 (ii).
- (c) Unlike the weak limit of the long-run OLS estimator $\tilde{\nu}_T$, the weak limit of $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_*)$ cannot be written as a linear combination of other weak limits. This corroborates that the primitive estimator $\ddot{\tau}_T$ does not suffer from an asymptotically singular matrix problem.
- (d) Because Lemma 4 assumes that $\rho_* < 0$, we cannot use the weak limit in Lemma 4 (ii) to derive the null limit distribution of the t -statistic testing $\rho_* = 0$. □

4.3 Weak Limit of the OLS Estimator

We finally derive the weak limit of the OLS estimator $\widehat{\alpha}_T$. For this derivation, we first note that

$$(\widehat{\alpha}_T - \alpha_*) = (\mathbf{T}_T - \mathbf{T})\tau_* + \mathbf{T}(\ddot{\tau}_T - \tau_*) + (\mathbf{T}_T - \mathbf{T})(\ddot{\tau}_T - \tau_*), \quad (15)$$

by (10) and (11), where \mathbf{T} is the probability limit of \mathbf{T}_T . That is,

$$\mathbf{T} := \begin{bmatrix} \mathbf{T}^{11} & \mathbf{0} \\ \mathbf{T}^{21} & \mathbf{I}_{p+2kq+1} \end{bmatrix}, \quad \mathbf{T}^{11} := \begin{bmatrix} 1 & \mathbf{0}_{1 \times 2k} \\ -\beta_* & \mathbf{I}_{2k} \end{bmatrix}, \quad \mathbf{T}^{21} := \begin{bmatrix} -\zeta_* & -\boldsymbol{\mu}'_* \\ -\nu_* & \mathbf{0}_{1 \times 2k} \\ \mathbf{0}_{(p+2kq-1) \times 1} & \mathbf{0}_{(p+2kq-1) \times 2k} \end{bmatrix}.$$

Here, the weak limits of \mathbf{T}_T and $\ddot{\tau}_T$ are already provided in Lemmas 3 and 4, respectively. Using these weak limits, we derive the weak limit of the OLS estimator $\widehat{\alpha}_T$.

Before stating the weak limit, we note that (15) identifies the channel through which the unknown parameters and primitive estimators affect the weak limit. It is difficult to identify *a priori* how they affect the limit distribution of $\widehat{\alpha}_T$, but (15) represents $\widehat{\alpha}_T$ as a transformation of the unknown parameters and the primitive estimators for the long- and short-run OLS estimators, enabling us to identify how they affect the weak limit. For example, if for each $j = 1, 2, \dots, k$, $\beta_{j*}^\pm \neq 0$ and $\zeta_* \neq 0$, we can rewrite (15) as

$$\sqrt{T}(\widehat{\alpha}_T - \alpha_*) = \mathbf{c}_* \sqrt{T}(\ddot{\rho}_T - \rho_*) + \sqrt{T} \mathbf{d}_T + o_{\mathbb{P}}(1), \quad (16)$$

where $\mathbf{c}_* := [1, -\beta_*', -\zeta_*, -\nu_*, \mathbf{0}']'$ and $\mathbf{d}_T := [0, \mathbf{0}'_{2k \times 1}, 0, \{(\dot{\gamma}_T - \gamma_*) - \rho_*(\dot{\nu}_T - \nu_*)\}, (\ddot{\kappa}_T - \kappa_*)']'$. This representation implies that the weak limit is determined by the weak limits of $\ddot{\rho}_T$ and \mathbf{d}_T . However, if β_* or ζ_* is zero, we cannot use (16) to find the weak limit, because the estimator corresponding to β_* or ζ_* is asymptotically negligible. That is, $\sqrt{T}(\widehat{\theta}_T - \theta_*) = o_{\mathbb{P}}(1)$ or $\sqrt{T}(\widehat{\xi}_T - \xi_*) = o_{\mathbb{P}}(1)$, respectively. For such a case, we have to exploit the next-order terms to derive the weak limit of $(\widehat{\theta}_T - \theta_*)$, demonstrating that the weak limit depends on the parameter value condition on β_* and ζ_* .

In the following theorem, we collect the weak limits obtained under various parameter conditions. For notational simplicity, we let $\mathcal{D}_2 \equiv [\mathcal{D}_2^+, \mathcal{D}_2^-]'$. Recall that \mathcal{D}_2 is the weak limit of $\ddot{\eta}_T - (\eta_* + \rho_*(\ddot{\beta}_T - \beta_*))$.

Theorem 1. *Given Assumption 1,*

- (i) *if for each $j = 1, 2, \dots, k$, $\beta_{j*}^\pm \neq 0$ and $\zeta_* \neq 0$, then $\sqrt{T}(\widehat{\alpha}_T - \alpha_*) \Rightarrow \mathbf{c}_* \mathcal{D}_1 + [0, \mathbf{0}'_{2k \times 1}, 0, \mathcal{D}_4, \mathcal{D}_5]'$;*
- (ii) *if $\beta_*^+ = \mathbf{0}$, but for each $j = 1, 2, \dots, k$, $\beta_{j*}^- \neq 0$ and $\zeta_* \neq 0$, then $\ddot{\mathbf{D}}_+(\widehat{\alpha}_T - \alpha_*) \Rightarrow [\mathcal{D}_1, \mathcal{D}_2^+, -\beta_*^{-\prime} \mathcal{D}_1, -\zeta_* \mathcal{D}_1, \mathcal{D}_4 - \nu_* \mathcal{D}_1, \mathcal{D}_5]'$, where $\ddot{\mathbf{D}}_+ := \text{diag}[T^{1/2}, T \mathbf{I}_k, T^{1/2} \mathbf{I}_{k+2}, \ddot{\mathbf{D}}_2]$;*

- (iii) if $\beta_*^- = \mathbf{0}$, but for each $j = 1, 2, \dots, k$, $\beta_{j*}^+ \neq 0$ and $\zeta_* \neq 0$, then $\ddot{\mathbf{D}}_-(\hat{\alpha}_T - \alpha_*) \Rightarrow [\mathcal{D}_1, -\beta_*^{+'} \mathcal{D}_1, \mathcal{D}_2^{-'}, -\zeta_* \mathcal{D}_1, \mathcal{D}_4 - \nu_* \mathcal{D}_1, \mathcal{D}'_5]'$, where $\ddot{\mathbf{D}}_- := \text{diag}[T^{1/2} \mathbf{I}_{k+1}, T \mathbf{I}_k, T^{1/2} \mathbf{I}_2, \ddot{\mathbf{D}}_2]$; and
- (iv) if for each $j = 1, 2, \dots, k$, $\beta_{j*}^\pm \neq 0$, but $\zeta_* = 0$, then $\ddot{\mathbf{D}}_\odot(\hat{\alpha}_T - \alpha_*) \Rightarrow [\mathcal{D}_1, -\beta_*' \mathcal{D}_1, -\mu_*' \mathcal{D}_2, \mathcal{D}_4 - \nu_* \mathcal{D}_1, \mathcal{D}'_5]'$, where $\ddot{\mathbf{D}}_\odot := \text{diag}[T^{1/2} \mathbf{I}_{2k+1}, T, T^{1/2}, \ddot{\mathbf{D}}_2]$. \square

Remarks. (a) The limit distribution of $\hat{\alpha}_T$ is determined by \mathcal{D} under all the parameter value conditions in Theorem 1, so that it asymptotically follows a mixed normal distribution by Lemma 4. The OLS estimator is formed by the primitive estimators \ddot{v}_T and \ddot{r}_T , none of which follows a mixed normal distribution asymptotically, but $\hat{\alpha}_T$ follows a mixed normal distribution.

- (b) Although the time trend and nonstationary regressors are included as regressors, the convergence rate of $\hat{\alpha}_T$ in Theorem 1 (i) is slower than \mathbf{D} in Lemma 1. Again, this slower convergence rate is the same effect as expected when the asymptotic distribution of an estimator is obtained by a higher-order expansion (e.g., Teräsvirta, 1994; Cho and White, 2007, 2010; Cho and Phillips, 2018).
- (c) We prove Theorem 1 (i) by deriving the weak limit of each component on the right side of (15). For example, we first derive the following for the long-run OLS estimator $\hat{\theta}_T$:

$$(\hat{\theta}_T - \theta_*) = -\beta_*(\ddot{\rho}_T - \rho_*) + (\ddot{\eta}_T - \eta_*) - \rho_*(\ddot{\beta}_T - \beta_*). \quad (17)$$

Lemmas 3 and 4 verify that $(\ddot{\rho}_T - \rho_*) = O_{\mathbb{P}}(T^{-1/2})$ and $(\ddot{\eta}_T - \eta_*) - \rho_*(\ddot{\beta}_T - \beta_*) = O_{\mathbb{P}}(T^{-1})$, respectively. Using these, we derive that $\sqrt{T}(\hat{\theta}_T - \theta_*) \Rightarrow -\beta_* \mathcal{D}_1$.

- (d) 2SNARDL has the same convergence rate as the OLS estimator when it is transformed to estimate the parameter targeted by OLS. 2SNARDL estimates ν_* and τ_* separately, and Cho, Greenwood-Nimmo, and Shin (2023a) show that the 2SNARDL for β_* and ρ_* has convergence rate T and \sqrt{T} , respectively. Thus, their product estimates θ_* with convergence rate \sqrt{T} , which is identical to that of $\hat{\theta}_T$ under Theorem 1 (i). Section A.4.1 in the Online Supplement corroborates this by simulation.
- (e) By Theorem 1 (i), the weak limit of $(\hat{\rho}_T, \hat{\theta}_T', \hat{\xi}_T)'$ is $(1, \beta_*', -\zeta_*)' \mathcal{D}_1$, indicating that the estimates are linearly correlated at the limit. This result confirms the asymptotically singular matrix problem and demonstrates how the convergence rate of $\hat{\alpha}_T$ is determined.
- (f) Despite the asymptotic singularity problem associated with $\hat{\alpha}_T$, its weak limit given in Theorem 1 (i) is determined by \mathcal{D}_1 , \mathcal{D}_4 , and \mathcal{D}_5 . This implies the following. First, the OLS estimator follows a mixed normal distribution, so that if the standard t -test applies to $\hat{\alpha}_T$, it follows a mixed normal distribution under the null hypothesis and the condition in Theorem 1 (i). We verify this by simulation in the Online Supplement; see Section A.4.2. Second, \mathcal{D}_1 is the weak limit of the second coefficient obtained by regressing Δy_t against $(1, \ddot{u}_{t-1}, z'_{2t})'$. Thus, the null weak limit of the t -statistic testing

ρ_* (< 0) is equivalent to those of the t -statistics testing the long-run parameters β_* and ξ_* .

- (g) If the zero coefficient conditions in Theorems 1 (ii, iii, and iv) are imposed, the limit distribution of the OLS estimator has to be determined by the next-order term in (15) as mentioned above. Specifically, if $\beta_*^+ = \mathbf{0}$, (17) implies that $T(\widehat{\theta}_T^+ - \theta_*^+) = T\{(\ddot{\eta}_T^+ - \eta_*^+) - \rho_*(\ddot{\beta}_T^+ - \beta_*^+)\} \Rightarrow \mathcal{D}_2^+$ by Lemma 4 (i). In parallel, if $\beta_*^- = \mathbf{0}$, then $T(\widehat{\theta}_T^- - \theta_*^-) = T\{(\ddot{\eta}_T^- - \eta_*^-) - \rho_*(\ddot{\beta}_T^- - \beta_*^-)\} \Rightarrow \mathcal{D}_2^-$; and if $\zeta_* = 0$, then $T(\widehat{\xi}_T - \xi_*) = -\mu_*' T\{(\ddot{\eta}_T - \eta_*) - \rho_*(\ddot{\beta}_T - \beta_*)\} + O_{\mathbb{P}}(T^{-1/2}) \Rightarrow -\mu_*' \mathcal{D}_2$, meaning that the weak limits of $\widehat{\theta}_T$ and $\widehat{\xi}_T$ are determined by \mathcal{D}_2 . Given that \mathcal{D}_2 follows a mixed normal distribution, if the standard t -test applies to $\widehat{\theta}_T$ or $\widehat{\xi}_T$, its null weak limit also follows a mixed normal distribution.
- (h) There is a caveat to Theorems 1 (i, ii, iii, and iv). If $\beta_* = \mathbf{0}$ and $\zeta_* = 0$ simultaneously, then $\rho_* = 0$, by the remark below Assumption 1, which contradicts the assumption that $\rho_* < 0$. Theorems 1 (i, ii, iii, and iv) assume an environment in which at least one of β_*^+ , β_*^- , and ζ_* is nonzero.
- (i) As a remark relevant to (h), Pesaran et al. (2001) and Banerjee et al. (1998) provide the asymptotic critical values of the F - and t -statistics testing $\rho_* = 0$, showing that their null limit distributions cannot be approximated by a mixed normal distribution. This implies that the limit distributions of $\widehat{\alpha}_T$ under the conditions in Theorem 1 are different from that under $\beta_* = \mathbf{0}$ and $\zeta_* = 0$.
- (j) For empirical application, the following procedure is applicable. First, it is necessary to test $\rho_* = 0$ using Pesaran et al.'s (2001) F -test or Banerjee et al.'s (1998) t -test as a preliminary procedure. Second, if ρ_* turns out to be negative, we can estimate the unknown coefficients by OLS. The null limit distribution of the t -test is mixed normal for each parameter except for the t -statistic testing $\rho_* = 0$. Third, when a joint hypothesis is tested, we can apply standard Wald test principle to the OLS estimator. By Theorem 1, the standard Wald test defined by OLS is asymptotically mixed chi-squared unless the joint hypothesis is involved with testing $\rho_* = 0$. The second and third steps are the same as for a standard regression analysis. Finally, when estimating the long-run parameter, we recommend using the primitive estimator \check{v}_T or 2SNARDL. \square

Before closing this section, we note that NARDL model can also be estimated by instrumental variable (IV) estimation by overcoming singular matrix problems similarly to OLS (e.g., Phillips and Hansen, 1990). We leave this as a future research topic.

5 Hypotheses Testing

In this section, we develop a testing methodology by Wald test principle. In particular, we suppose that a cointegrating relationship holds between y_t and \ddot{x}_t by supposing that $\theta_*^+ \neq \mathbf{0}$ and/or $\theta_*^- \neq \mathbf{0}$.

Our main interest is in testing the symmetry conditions. The NARDL process reduces to the ARDL

process if $\theta_*^+ = \theta_*^-$ and $\pi_*^+ = \pi_*^-$. Under the ARDL process condition, it is inefficient to estimate the parameters in NARDL, making it necessary to test the symmetry conditions. We specify the following three hypothesis systems:

$$\begin{aligned} \mathcal{H}'_0 : \theta_*^+ = \theta_*^- \quad \text{vs.} \quad \mathcal{H}'_1 : \theta_*^+ \neq \theta_*^-; \\ \mathcal{H}''_0 : \pi_*^+ = \pi_*^- \quad \text{vs.} \quad \mathcal{H}''_1 : \pi_*^+ \neq \pi_*^-; \\ \mathcal{H}'''_0 : \theta_*^+ = \theta_*^- \quad \text{and} \quad \pi_*^+ = \pi_*^- \quad \text{vs.} \quad \mathcal{H}'''_1 : \theta_*^+ \neq \theta_*^- \quad \text{or} \quad \pi_*^+ \neq \pi_*^-. \end{aligned}$$

Here, \mathcal{H}'_0 and \mathcal{H}''_0 are provided to test the long- and short-run symmetries, respectively, and \mathcal{H}'''_0 hypothesizes both symmetries jointly.

Testing \mathcal{H}'_0 versus \mathcal{H}'_1 We first apply Wald test principle to test \mathcal{H}'_0 . The standard Wald test applied to OLS is defined as follows:

$$W_T^{(1)} := \hat{\alpha}'_T \hat{\mathbf{R}}'_1 \left(\widehat{\mathbf{W}}_T^{(1)} \right)^{-1} \hat{\mathbf{R}}_1 \hat{\alpha}_T, \quad \text{where} \quad \widehat{\mathbf{W}}_T^{(1)} := \hat{\sigma}_{e,T}^2 \hat{\mathbf{R}}_1 \left(\sum_{t=1}^T z_t z_t' \right)^{-1} \hat{\mathbf{R}}'_1,$$

$\hat{\sigma}_{e,T}^2 := T^{-1} \sum_{t=1}^T (\Delta y_t - z_t' \hat{\alpha}_T)^2$, and $\hat{\mathbf{R}}_1 := [\mathbf{0}_{k \times 1}, \mathbf{I}_k, -\mathbf{I}_k, \mathbf{0}_{k \times (1+p+2kq)}]$. As we assume that $\theta_*^+ \neq \mathbf{0}$ and/or $\theta_*^- \neq \mathbf{0}$, we cannot suppose the environment assumed in Theorems 1 (ii or iii) under the null. Furthermore, we cannot directly apply the limit distribution of the OLS estimator in Theorems 1 (i and iv) to obtain the null limit distribution of the test. Note that $\hat{\mathbf{R}}_1 \hat{\alpha}_T = (\hat{\theta}_T^+ - \hat{\theta}_T^-)$, so that $\sqrt{T}(\hat{\theta}_T^+ - \hat{\theta}_T^-) \Rightarrow (\beta_*^- - \beta_*^+) \mathcal{D}_1$. Thus, $\sqrt{T}(\hat{\theta}_T^+ - \hat{\theta}_T^-)$ is asymptotically negligible under the null. The null limit behavior has to be obtained by the next-order term of $(\hat{\theta}_T^+ - \hat{\theta}_T^-)$. Specifically, (10) implies that

$$\begin{aligned} (\hat{\theta}_T^+ - \hat{\theta}_T^-) &= (\ddot{\eta}_T^+ - \ddot{\eta}_T^-) - \ddot{\rho}_T (\tilde{\beta}_T^+ - \tilde{\beta}_T^-) \\ &= (\ddot{\eta}_T^+ - \ddot{\eta}_T^-) - (\eta_*^+ - \eta_*^-) - \rho_* (\tilde{\beta}_T^+ - \tilde{\beta}_T^-) - (\ddot{\rho}_T - \rho_*) (\tilde{\beta}_T^+ - \tilde{\beta}_T^-) \\ &= (\ddot{\eta}_T^+ - \ddot{\eta}_T^-) - (\eta_{T*}^+ - \eta_{T*}^-) + o_{\mathbb{P}}(T^{-1}) \end{aligned} \tag{18}$$

under \mathcal{H}'_0 , where $\eta_{T*} := \eta_* + \rho_* (\tilde{\beta}_T - \beta_*)$, and (18) is established by letting $\eta_{T*} := [\eta_{T*}^+, \eta_{T*}^-]'$ and noting that $\tilde{\beta}_T = \beta_T$. Therefore, the null limit distribution of $W_T^{(1)}$ is determined not by Theorem 1 (i or iv), but by Lemma 4. All these imply $(\hat{\theta}_T^+ - \hat{\theta}_T^-) = O_{\mathbb{P}}(T^{-1})$, so that if we let $\mathbf{R}_1 := [\mathbf{0}_{k \times 1}, \mathbf{I}_k, -\mathbf{I}_k, \mathbf{0}_{k \times (1+p+2kq)}]$, $T(\hat{\theta}_T^+ - \hat{\theta}_T^-) \Rightarrow \mathbf{R}_1 \mathcal{D}$ under \mathcal{H}'_0 by Lemma 4. However, its alternative behavior is differently determined. From $\hat{\mathbf{R}}_1 \hat{\alpha}_T = (\hat{\theta}_T^+ - \hat{\theta}_T^-)$, its divergence rate is determined by Theorem 1 (i or iv), meaning that $\hat{\mathbf{R}}_1 \hat{\alpha}_T = O_{\mathbb{P}}(T^{-1/2})$. Therefore, the convergence and divergence rates of the test basis are unbalanced between \mathcal{H}'_0 and \mathcal{H}'_1 , respectively.

We supplement the unbalanced rates by applying Wald test principle to the primitive estimator $\check{\nu}_T$. This is mainly because the primitive estimator $\check{\nu}_T$ enables us to define another Wald test using the next-order terms. Because testing \mathcal{H}'_0 is equivalent to testing

$$\mathbb{H}'_0 : \beta_*^+ - \beta_*^- = \mathbf{0},$$

we apply Wald test principle to the primitive estimator $\check{\beta}_T$. If we let $\check{\mathbf{R}}_1 := [\mathbf{I}_k, -\mathbf{I}_k, \mathbf{0}_{k \times 2}]$, $\check{\mathbf{R}}_1 \check{\nu}_{T*} = \beta_*^+ - \beta_*^-$, which we can estimate by $\check{\beta}_T^+ - \check{\beta}_T^- = \check{\mathbf{R}}_1 \check{\nu}_T$. Using this, we define another Wald test:

$$\mathcal{W}_T^{(1)} := \check{\nu}'_T \check{\mathbf{D}}_1 \check{\mathbf{R}}'_1 (\check{\mathbf{W}}_T^{(1)})^{-1} \check{\mathbf{R}}_1 \check{\mathbf{D}}_1 \check{\nu}_T, \quad \text{where} \quad \check{\mathbf{W}}_T^{(1)} := \check{\sigma}_{u,T}^2 \check{\mathbf{R}}_1 \check{\mathbf{D}}_1 \left(\sum_{t=1}^T \check{r}_{t-1} \check{r}'_{t-1} \right)^{-1} \check{\mathbf{D}}_1 \check{\mathbf{R}}'_1$$

and $\check{\sigma}_{u,T}^2 := T^{-1} \sum_{t=1}^T \check{u}_t^2$. Here, $(\check{\beta}_T^+ - \check{\beta}_T^-)$ and $(\hat{\theta}_T^+ - \hat{\theta}_T^-)$ are different by the presence of $(\check{\eta}_T^+ - \check{\eta}_T^-)$ and $\check{\rho}_T$ as given in (18) such that $(\tilde{\beta}_T^+ - \tilde{\beta}_T^-) = (\check{\beta}_T^+ - \check{\beta}_T^-)$. Furthermore, $(\check{\beta}_T^+ - \check{\beta}_T^-) = O_{\mathbb{P}}(T^{-1})$ under both hypotheses, letting the convergence and divergence rates of $\mathcal{W}_T^{(1)}$ be identical under both \mathcal{H}'_0 and \mathcal{H}'_1 .

Testing \mathcal{H}''_0 versus \mathcal{H}''_1 We next apply Wald test principle to test \mathcal{H}''_0 . The Wald test principle applied to $\hat{\alpha}_T$ delivers the following test:

$$W_T^{(2)} := \hat{\alpha}'_T \hat{\mathbf{R}}'_2 (\hat{\mathbf{W}}_T^{(2)})^{-1} \hat{\mathbf{R}}_2 \hat{\alpha}_T, \quad \text{where} \quad \hat{\mathbf{W}}_T^{(2)} := \hat{\sigma}_{e,T}^2 \hat{\mathbf{R}}_2 \left(\sum_{t=1}^T z_t z'_t \right)^{-1} \hat{\mathbf{R}}'_2$$

and $\hat{\mathbf{R}}_2 := [\mathbf{0}_{kq \times (2+p+2k)}, \mathbf{I}_{kq}, -\mathbf{I}_{kq}]$, so that it follows that $\hat{\mathbf{R}}_2 \hat{\alpha}_T = \hat{\pi}_T^+ - \hat{\pi}_T^-$ and $\sqrt{T} \hat{\mathbf{R}}_2 \hat{\alpha}_T \Rightarrow \hat{\mathbf{R}}_2 \mathcal{D}$ using the limit distribution in Theorem 1.

We define another supplementary Wald test using the primitive estimator. From Proposition 4, it follows that $\hat{\kappa}_T = \check{\kappa}_T$. That is, the short-run OLS and its primitive estimator are identical, so that we can test \mathcal{H}''_0 by using $\check{\tau}_T$. By Lemma 2 (vi), $\check{\tau}_T$ is not associated with an asymptotically singular matrix problem. We define the following Wald test:

$$\mathcal{W}_T^{(2)} := \check{\tau}'_T \check{\mathbf{D}} \hat{\mathbf{R}}'_2 (\check{\mathbf{W}}_T^{(2)})^{-1} \hat{\mathbf{R}}_2 \check{\mathbf{D}} \check{\tau}_T, \quad \text{where} \quad \check{\mathbf{W}}_T^{(2)} := \check{\sigma}_{e,T}^2 \hat{\mathbf{R}}_2 \check{\mathbf{D}} \left(\sum_{t=1}^T \check{z}_t \check{z}'_t \right)^{-1} \check{\mathbf{D}} \hat{\mathbf{R}}'_2.$$

Although the test basis of the Wald test $\mathcal{W}_T^{(2)}$ is the same as that of $W_T^{(2)}$, from the fact that $\hat{\pi}_T^+ - \hat{\pi}_T^- = \hat{\pi}_T^+ - \hat{\pi}_T^-$, the weight matrix of $\mathcal{W}_T^{(2)}$ is different from $W_T^{(2)}$. The weight matrix $\check{\mathbf{W}}_T^{(2)}$ is more relevant to the test basis, because $\check{\tau}_T$ is obtained by regressing Δy_t on \check{z}_t .

Testing \mathcal{H}_0''' versus \mathcal{H}_1''' Finally, we apply Wald test principle to $\hat{\alpha}_T$ as follows:

$$W_T^{(3)} := \hat{\alpha}'_T \hat{\mathbf{R}}'_3 (\widehat{\mathbf{W}}_T^{(3)})^{-1} \hat{\mathbf{R}}_3 \hat{\alpha}_T, \quad \text{where} \quad \widehat{\mathbf{W}}_T^{(3)} := \hat{\sigma}_{e,T}^2 \hat{\mathbf{R}}_3 \left(\sum_{t=1}^T z_t z_t' \right)^{-1} \hat{\mathbf{R}}'_3$$

and $\hat{\mathbf{R}}_3 := \text{diag}[\hat{\mathbf{R}}_1, \hat{\mathbf{R}}_2]$, so that $\hat{\mathbf{R}}_3 \hat{\alpha}_T = (\hat{\boldsymbol{\theta}}_T^{+'} - \hat{\boldsymbol{\theta}}_T^{-'}, \hat{\boldsymbol{\pi}}_T^{+'} - \hat{\boldsymbol{\pi}}_T^{-'})'$. Here, the null weak limit of $\hat{\mathbf{R}}_3 \hat{\alpha}_T$ is obtained by combining the fact that $T(\hat{\boldsymbol{\theta}}_T^+ - \hat{\boldsymbol{\theta}}_T^-) \Rightarrow \mathbf{R}_1 \mathcal{D}$ and $\sqrt{T}(\hat{\boldsymbol{\pi}}_T^+ - \hat{\boldsymbol{\pi}}_T^-) \Rightarrow \hat{\mathbf{R}}_2 \mathcal{D}$ under \mathcal{H}_0''' . Therefore, if we let $\mathbf{R}_3 := \text{diag}[\mathbf{R}_1, \hat{\mathbf{R}}_2]$, $(T(\hat{\boldsymbol{\theta}}_T^+ - \hat{\boldsymbol{\theta}}_T^-), \sqrt{T}(\hat{\boldsymbol{\pi}}_T^+ - \hat{\boldsymbol{\pi}}_T^-))' \Rightarrow \mathbf{R}_3 \mathcal{D}$ under \mathcal{H}_0''' . However, $\hat{\mathbf{R}}_3 \hat{\alpha}_T = O_{\mathbb{P}}(T^{-1/2})$ under \mathcal{H}_1''' because $(\hat{\boldsymbol{\theta}}_T^{+'} - \hat{\boldsymbol{\theta}}_T^{-'})' = O_{\mathbb{P}}(T^{-1/2})$ as discussed above.

We define another supplementary Wald test and overcome the unbalanced convergence and divergence rates of $W_T^{(3)}$ between \mathcal{H}_0''' and \mathcal{H}_1''' . For this, we first reformulate \mathcal{H}_0''' against \mathcal{H}_1''' into

$$\mathbb{H}_0''' : \beta_*^+ = \beta_*^- \quad \text{and} \quad \pi_*^+ = \pi_*^- \quad \text{vs.} \quad \mathbb{H}_1''' : \beta_*^+ \neq \beta_*^- \quad \text{or} \quad \pi_*^+ \neq \pi_*^-,$$

and define the following supplementary Wald test:

$$\mathcal{W}_T^{(3)} := \check{\boldsymbol{\delta}}_T' \bar{\mathbf{D}} \check{\mathbf{R}}'_3 (\check{\mathbf{W}}_T^{(3)})^{-1} \check{\mathbf{R}}_3 \bar{\mathbf{D}} \check{\boldsymbol{\delta}}_T,$$

where $\check{\boldsymbol{\delta}}_T := (\check{\boldsymbol{v}}_T', \check{\boldsymbol{\tau}}_T')'$, $\bar{\mathbf{D}} := \text{diag}[\bar{\mathbf{D}}_1, \bar{\mathbf{D}}]$, $\check{\mathbf{R}}_3 := \text{diag}[\check{\mathbf{R}}_1, \hat{\mathbf{R}}_2]$, and $\check{\mathbf{W}}_T^{(3)} := \text{diag}[\check{\mathbf{W}}_T^{(1)}, \check{\mathbf{W}}_T^{(2)}]$. The Wald test $\mathcal{W}_T^{(3)}$ is defined by applying Wald test principle to both primitive estimators $\check{\boldsymbol{v}}_T$ and $\check{\boldsymbol{\tau}}_T$ and by noting that $\check{\mathbf{R}}_3 \bar{\mathbf{D}} \check{\boldsymbol{\delta}}_T = (T(\check{\boldsymbol{\beta}}_T^+ - \check{\boldsymbol{\beta}}_T^-)', \sqrt{T}(\check{\boldsymbol{\pi}}_T^+ - \check{\boldsymbol{\pi}}_T^-))'$. It straightforwardly follows that $\mathcal{W}_T^{(3)} = \mathcal{W}_T^{(1)} + \mathcal{W}_T^{(2)}$ from the fact that $\check{\mathbf{W}}_T^{(3)}$ is block-diagonal. From this, its null and alternative limit behaviors are determined by those of $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(2)}$.

We now provide the limit behaviors of the Wald tests. For notational simplicity, we partition \mathbb{H}_0''' into $\mathbb{H}_{01}''' : \beta_*^+ = \beta_*^-$ and $\mathbb{H}_{02}''' : \pi_*^+ = \pi_*^-$. In parallel, we also partition \mathbb{H}_1''' into $\mathbb{H}_{11}''' : \beta_*^+ \neq \beta_*^-$ and $\mathbb{H}_{12}''' : \pi_*^+ \neq \pi_*^-$. These partitions are provided because the power of $\mathcal{W}_T^{(3)}$ depends on the sub-hypotheses from the fact that the divergence rate of $(\check{\boldsymbol{\beta}}_T^+ - \check{\boldsymbol{\beta}}_T^-)$ differs from that of $(\check{\boldsymbol{\pi}}_T^+ - \check{\boldsymbol{\pi}}_T^-)$. We also let $\sigma_e^2 := \mathbb{E}[e_t^2]$. The following theorem summarizes their limit behaviors:

Theorem 2. *Given Assumption 1, if $\boldsymbol{\theta}_*^+ \neq \mathbf{0}$ and/or $\boldsymbol{\theta}_*^- \neq \mathbf{0}$,*

- (i) (a) $W_T^{(1)} \Rightarrow \mathcal{D}' \mathbf{R}'_1 (\sigma_e^2 \mathbf{R}_1 \mathcal{M}^{-1} \mathbf{R}'_1)^{-1} \mathbf{R}_1 \mathcal{D}$ under \mathcal{H}'_0 , where $\mathbf{R}_1 := [\mathbf{0}_{k \times 1}, \mathbf{I}_k, -\mathbf{I}_k, \mathbf{0}_{k \times (1+p+2kq)}]$;
- (b) $W_T^{(2)} \Rightarrow \mathcal{D}' \hat{\mathbf{R}}'_2 (\sigma_e^2 \hat{\mathbf{R}}_2 \mathcal{M}^{-1} \hat{\mathbf{R}}'_2)^{-1} \hat{\mathbf{R}}_2 \mathcal{D}$ under \mathcal{H}''_0 ;
- (c) $W_T^{(3)} \Rightarrow \mathcal{D}' \mathbf{R}'_3 (\sigma_e^2 \mathbf{R}_3 \mathcal{M}^{-1} \mathbf{R}'_3)^{-1} \mathbf{R}_3 \mathcal{D}$ under \mathcal{H}'''_0 , where $\mathbf{R}_3 := \text{diag}[\mathbf{R}_1, \hat{\mathbf{R}}_2]$;
- (ii) (a) for any $c'_T = o(T)$, $\lim_{T \rightarrow \infty} \mathbb{P}(W_T^{(1)} > c'_T) = 1$ under \mathcal{H}'_1 ;
- (b) for any $c'_T = o(T)$, $\lim_{T \rightarrow \infty} \mathbb{P}(W_T^{(2)} > c'_T) = 1$ under \mathcal{H}''_1 ;

- (c) for any $c'_T = o(T)$, $\lim_{T \rightarrow \infty} \mathbb{P}(W_T^{(3)} > c'_T) = 1$ under \mathcal{H}_1''' ;
- (iii) (a) $\mathcal{W}_T^{(1)} \Rightarrow \mathcal{L}' \ddot{\mathbf{R}}_1' (\sigma_u^2 \ddot{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \ddot{\mathbf{R}}_1')^{-1} \ddot{\mathbf{R}}_1 \mathcal{L}$ under \mathbb{H}_0' ;
- (b) $\mathcal{W}_T^{(2)} \Rightarrow \mathcal{D}' \widehat{\mathbf{R}}_2' (\sigma_e^2 \widehat{\mathbf{R}}_2 \mathcal{M}^{-1} \widehat{\mathbf{R}}_2')^{-1} \widehat{\mathbf{R}}_2 \mathcal{D}$ under \mathcal{H}_0'' ;
- (c) $\mathcal{W}_T^{(3)} \Rightarrow \mathcal{L}' \ddot{\mathbf{R}}_1' (\sigma_u^2 \ddot{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \ddot{\mathbf{R}}_1')^{-1} \ddot{\mathbf{R}}_1 \mathcal{L} + \mathcal{D}' \widehat{\mathbf{R}}_2' (\sigma_e^2 \widehat{\mathbf{R}}_2 \mathcal{M}^{-1} \widehat{\mathbf{R}}_2')^{-1} \widehat{\mathbf{R}}_2 \mathcal{D}$ under \mathbb{H}_0''' ; and
- (iv) (a) for any $c_T = o(T^2)$, $\lim_{T \rightarrow \infty} \mathbb{P}(\mathcal{W}_T^{(1)} > c_T) = 1$ under \mathbb{H}_1' ;
- (b) for any $c'_T = o(T)$, $\lim_{T \rightarrow \infty} \mathbb{P}(\mathcal{W}_T^{(2)} > c'_T) = 1$ under \mathcal{H}_1'' ;
- (c) for any $c_T = o(T^2)$ and $c'_T = o(T)$,
- (1) $\lim_{T \rightarrow \infty} \mathbb{P}(\mathcal{W}_T^{(3)} > c_T) = 1$ under $\mathbb{H}_{11}''' \cap \mathbb{H}_{02}'''$;
 - (2) $\lim_{T \rightarrow \infty} \mathbb{P}(\mathcal{W}_T^{(3)} > c'_T) = 1$ under $\mathbb{H}_{01}''' \cap \mathbb{H}_{12}'''$; and
 - (3) $\lim_{T \rightarrow \infty} \mathbb{P}(\mathcal{W}_T^{(3)} > c_T) = 1$ under $\mathbb{H}_{11}''' \cap \mathbb{H}_{12}'''$. □

Remarks. (a) The asymptotic behaviors of $W_T^{(1)}$, $W_T^{(2)}$, and $W_T^{(3)}$ are determined by the weak limit of the primitive estimator $(\ddot{\tau}_T - \tau_{T*})$. For example, it follows from (18) that $(\widehat{\theta}_T^+ - \widehat{\theta}_T^-) = (\theta_*^+ - \theta_*^-) - (\ddot{\rho}_T - \rho_*)(\beta_*^+ - \beta_*^-) + (\ddot{\eta}_T^+ - \eta_{T*}^+) - (\ddot{\eta}_T^- - \eta_{T*}^-) + o_{\mathbb{P}}(T^{-1})$, so that $(\widehat{\theta}_T^+ - \widehat{\theta}_T^-) = (\ddot{\eta}_T^+ - \eta_{T*}^+) - (\ddot{\eta}_T^- - \eta_{T*}^-) + o_{\mathbb{P}}(T^{-1})$ under \mathcal{H}_0' . In other words, $\widehat{\mathbf{R}}_1 \widehat{\alpha}_T = \mathbf{R}_1 (\ddot{\tau}_T - \tau_{T*}) + o_{\mathbb{P}}(T^{-1})$. This fact implies that the null weak limit of $W_T^{(1)}$ is determined by that of $(\ddot{\tau}_T - \tau_{T*})$. Using Lemma 4, Theorem 2 (i.a) reports its weak limit under \mathcal{H}_0' . Meanwhile, the alternative weak limit of the test basis is obtained from $(\widehat{\theta}_T^+ - \widehat{\theta}_T^-) = (\theta_*^+ - \theta_*^-) - (\ddot{\rho}_T - \rho_*)(\beta_*^+ - \beta_*^-) + o_{\mathbb{P}}(T^{-1/2})$ and $(\ddot{\rho}_T - \rho_*) = O_{\mathbb{P}}(T^{-1/2})$. Theorem 2 (ii.a) reports the power behavior of the test implied by this representation. We apply similar arguments to the other Wald tests, $W_T^{(2)}$ and $W_T^{(3)}$ and provide their limit behaviors in Theorem 2 (i.b, i.c, ii.b, and ii.c). Consequently, $W_T^{(1)}$, $W_T^{(2)}$, and $W_T^{(3)}$ asymptotically follow mixed chi-squared distributions under the respective null hypotheses.

- (b) If we partition \mathcal{L}_1 such that $\mathcal{L}_1 \equiv (\mathcal{L}_1^+, \mathcal{L}_1^-)'$, $\ddot{\mathbf{R}}_1 \mathcal{L} = \mathcal{L}_1^+ - \mathcal{L}_1^-$, so that the null weak limit in Theorem 2 (iii.a) is given as $(\mathcal{L}_1^+ - \mathcal{L}_1^-)' (\sigma_u^2 \ddot{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \ddot{\mathbf{R}}_1')^{-1} (\mathcal{L}_1^+ - \mathcal{L}_1^-)$. In parallel, if we let $\mathcal{D}_5 \equiv [\mathcal{D}_5^+, \mathcal{D}_5^-, \mathcal{D}_5^-]'$, such that \mathcal{D}_5^+ , \mathcal{D}_5^+ , and \mathcal{D}_5^- are the weak limits of $\ddot{\varphi}_T$, $\ddot{\pi}_T^+$, and $\ddot{\pi}_T^-$, respectively, then $\widehat{\mathbf{R}}_2 \mathcal{D} = \mathcal{D}_5^+ - \mathcal{D}_5^-$, and so the weak the limit in Theorem 2 (iii.b) can be rewritten as $(\mathcal{D}_5^+ - \mathcal{D}_5^-)' (\sigma_e^2 \widehat{\mathbf{R}}_2 \mathcal{M}^{-1} \widehat{\mathbf{R}}_2')^{-1} (\mathcal{D}_5^+ - \mathcal{D}_5^-)$.
- (c) The test methodology of using the supplementary tests depends on the hypothesis of consideration. We can rewrite the null weak limit of $\mathcal{W}_T^{(1)}$ as $\mathcal{S}' \mathcal{M}_{11}^{-1} \ddot{\mathbf{R}}_1' (\sigma_u^2 \ddot{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \ddot{\mathbf{R}}_1')^{-1} \ddot{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \mathcal{S}$ using the definition of $\mathcal{L} := \mathcal{M}_{11}^{-1} \mathcal{S}$, meaning that $\mathcal{W}_T^{(1)}$ does not follow a mixed chi-squared distribution. This follows from the fact that \mathcal{S} does not follow a mixed normal distribution and is also influenced by the asymptotic bias ϱ_{m*} . The same result also holds for $\mathcal{W}_T^{(3)}$. However, the null weak limit of $\mathcal{W}_T^{(2)}$ is characterized by \mathcal{D} , meaning that its null weak limit follows a mixed chi-squared distribution. For both $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(3)}$, we can test the hypotheses by applying a resampling method; see Section 6.

(d) The divergence speed of $\mathcal{W}_T^{(3)}$ depends on the alternative sub-hypothesis. If \mathbb{H}_0''' is negated only because of the asymmetric long-run parameters: $\beta_*^+ \neq \beta_*^-$, the divergence speed of $\mathcal{W}_T^{(3)}$ is T^2 . In contrast, if only the short-run parameters are asymmetric: $\pi_*^+ \neq \pi_*^-$, its divergence speed is T . If both the long- and short-run parameters are asymmetric, the divergence speed is determined as T^2 . Theorem 2 (iv.c) summarizes these results. \square

Before moving to the next section, we summarize the use of the Wald tests introduced in this section. Table 1 provides their summary. We contain the formulas of the Wald tests along with their null hypotheses and null limit distributions. In case the null limit distribution is mixed chi-squared, the researcher can obtain the asymptotic critical values from the chi-square distribution table. Otherwise, the residual bootstrap is applicable. Section 6 details the residual bootstrap procedure.

6 Monte Carlo Simulations

In this section, we conduct simulations and examine the finite sample properties of the Wald tests.

For our simulation, we assume the following DGP condition:

$$y_{t-1} = \nu_* + \beta_*^+ x_{t-1}^+ + \beta_*^- x_{t-1}^- + \zeta_*(t-1) + u_{t-1} \quad \text{and}$$

$$\Delta y_t = \alpha_* + \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t,$$

where $\Delta x_t = 1/4 + \kappa_* \Delta x_{t-1} + v_t$, and $(e_t, v_t)' \sim \text{IIDN}(\mathbf{0}_2, \mathbf{I}_2)$. By this DGP condition, both y_t and x_t are integrated series with time trends. We also set $(\nu_*, \zeta_*, \alpha_*, \rho_*, \varphi_*) = (0, 0, 0, -1/2, 0)$ throughout the simulation, but adjust the value of $(\beta_*^+, \beta_*^-, \pi_*^+, \pi_*^-)$, depending on the hypotheses of interest. According to the NARDL condition, it must hold that $\theta_*^+ = -\rho_* \beta_*^+$ and $\theta_*^- = -\rho_* \beta_*^-$.

The next procedure applies to define the Wald tests. First, we estimate the unknown parameters using the primitive parameter estimators. Specifically, we estimate $\bar{\nu}_{T*}$ and τ_{T*} separately by specifying the following models:

$$y_t = \beta^+ \ddot{m}_t^+ + \beta^- \ddot{m}_t^- + \vartheta t + \nu + u_t \quad \text{and}$$

$$\Delta y_t = \rho \tilde{u}_{t-1} + \eta^+ \ddot{m}_{t-1}^+ + \eta^- \ddot{m}_{t-1}^- + \varsigma(t-1) + \gamma + \varphi \Delta y_{t-1} + \pi^+ \Delta x_t^+ + \pi^- \Delta x_t^- + e_t,$$

where we set $\ddot{m}_t^+ := x_t^+ - t\ddot{\mu}_T^+$, $\ddot{m}_t^- := x_t^- - t\ddot{\mu}_T^-$, and $\tilde{u}_t := y_t - \mathbf{r}'_t \tilde{\mathbf{v}}_T$, with $\ddot{\mu}_T^+ := (\sum_{t=1}^{T-1} t^2)^{-1} \sum_{t=1}^{T-1} t x_t^+$, $\ddot{\mu}_T^- := (\sum_{t=1}^{T-1} t^2)^{-1} \sum_{t=1}^{T-1} t x_t^-$, $\tilde{\mathbf{v}}_T := (\sum_{t=1}^T \mathbf{r}_{t-1} \mathbf{r}'_{t-1})^{-1} \sum_{t=1}^T \mathbf{r}_{t-1} y_{t-1}$, and $\mathbf{r}_{t-1} := [x_{t-1}^+, x_{t-1}^-, (t-$

1), 1]'. Second, we assume the following hypothesis systems:

$$\mathcal{H}'_0 : \theta_*^+ = \theta_*^- \text{ vs. } \mathcal{H}'_1 : \theta_*^+ \neq \theta_*^-;$$

$$\mathcal{H}''_0 : \pi_*^+ = \pi_*^- \text{ vs. } \mathcal{H}''_1 : \pi_*^+ \neq \pi_*^-;$$

$$\mathcal{H}'''_0 : \theta_*^+ = \theta_*^- \text{ and } \pi_*^+ = \pi_*^- \text{ vs. } \mathcal{H}'''_1 : \theta_*^+ \neq \theta_*^- \text{ or } \pi_*^+ \neq \pi_*^-;$$

$$\mathbb{H}'_0 : \beta_* = 0 \text{ vs. } \mathbb{H}'_1 : \beta_* \neq 0; \text{ and } \mathbb{H}''_0 : \beta_* = 0 \text{ and } \pi_*^+ = \pi_*^- \text{ vs. } \mathbb{H}''_1 : \beta_* \neq 0 \text{ or } \pi_*^+ \neq \pi_*^-.$$

Note that these hypotheses correspond to those in Section 5. Finally, we compute the Wald tests $\mathcal{W}_T^{(1)}$, $\mathcal{W}_T^{(2)}$, $\mathcal{W}_T^{(3)}$, $W_T^{(1)}$, $W_T^{(2)}$, and $W_T^{(3)}$, as stated in Section 5.

We conduct simulations under the following two DGP conditions assuming $\kappa_* = 1/2$. First, we set $\beta_*^+ = \beta_*^- = 1$ and $\pi_*^+ = \pi_*^- = 1/2$ to generate data. This parameter condition satisfies the ARDL condition. From this, we examine the finite sample properties of the Wald tests under the null. Second, we set $\beta_*^+ = 1/4$, $\beta_*^- = -1/4$, $\pi_*^+ = 1/8$, and $\pi_*^- = -1/8$, and use this to examine the power of the tests.

A bootstrap method is used for the testing. Theorem 2 shows that the null limit distributions of the Wald tests $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(3)}$ are not mixed chi-squared. So, we apply the following residual bootstrap procedure:

- S1:** After computing the Wald tests, we estimate the ARDL model by regressing Δy_t against y_{t-1} , x_{t-1} , $(t-1)$, 1 , Δy_{t-1} , and Δx_t . We let the estimated linear coefficient be $(\hat{\rho}_T, \hat{\theta}_T, \hat{\xi}_T, \hat{\alpha}_T, \hat{\varphi}_T, \hat{\pi}_T)$. We also let the residual be $\hat{e}_t := \Delta y_t - \hat{\rho}_T y_{t-1} - \hat{\theta}_T x_{t-1} - \hat{\xi}_T (t-1) - \hat{\alpha}_T - \hat{\varphi}_T \Delta y_{t-1} - \hat{\pi}_T \Delta x_t$.
- S2:** We construct a resampled series as follows. First, we resample \hat{e}_t with replacement and denote it as e_t^b . Next, we let

$$\Delta y_t^b := \hat{\rho}_T y_{t-1}^b + \hat{\theta}_T x_{t-1} + \hat{\xi}_T (t-1) + \hat{\alpha}_T + \hat{\varphi}_T \Delta y_{t-1}^b + \hat{\pi}_T \Delta x_t + e_t^b,$$

where y_t^b is the cumulative sum of Δy_t^b . Note that we do not resample Δx_t here. Using the resampled series, we compute the Wald tests and denote them using the superscript b . For example, we let $\mathcal{W}_T^{(1),b}$ denote the bootstrapped $\mathcal{W}_T^{(1)}$.

- S3:** We iterate the second step B times in total and compute the empirical p -value of the test. For example, we let the empirical p -value be $p_T^{(1)} := B^{-1} \sum_{b=1}^B \mathbb{1}\{\mathcal{W}_T^{(1),b} > \mathcal{W}_T^{(1)}\}$ for $\mathcal{W}_T^{(1)}$. If $p_T^{(1)}$ is less than the significance level, we reject the null hypothesis. \square

This bootstrap procedure can apply even when the null weak limit of the Wald test follows a mixed chi-squared distribution.

We conduct our simulation by the above residual bootstrap procedure. Assuming that $B = 500$, we

independently iterate the above experiment 5000 times for $T = 100, 200, 300, 400,$ and 500 . The simulation results are reported in Tables 2 and 3. We also evaluate the Wald tests by mixed chi-squared distributions and report their empirical rejection rates. The simulation results are summarized as follows:

- (a) Table 2 shows the empirical rejection rates using the null DGP condition allowing $\beta_*^+ = \beta_*^- = 1$ and $\pi_*^+ = \pi_*^- = 1/2$. The left side panel shows the empirical rejection rates obtained by the residual bootstrap method. The rejection rates on the right side are based on the mixed chi-squared distributions. In summary, first, when using the bootstrap method, for each T , the empirical rejection rates are very close to the nominal significance levels. This implies that the bootstrap method effectively controls the test levels. Second, when considering the asymptotic critical values from the mixed chi-squared distribution, we find no significant level distortion for $\mathcal{W}_T^{(2)}$, but both $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(3)}$ do experience level distortions. For the current DGP, $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(3)}$ reject \mathbb{H}'_0 and \mathbb{H}'''_0 more often than the significance levels. This confirms that $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(3)}$ do not follow mixed chi-squared distributions under the null. However, $\mathcal{W}_T^{(2)}$ does not suffer from level distortions, indicating that $\tilde{\pi}_T^+$ and $\tilde{\pi}_T^-$ follow mixed normal distributions, as Lemma 4 (i) establishes. Finally, $W_T^{(1)}$, $W_T^{(2)}$, and $W_T^{(3)}$ suffer no level distortions when using the critical values from the mixed chi-squared distributions.
- (b) Table 3 shows the empirical rejection rates under the alternative DGP. The summary results are as follows. First, with the bootstrap method, the empirical rejection rates of $\mathcal{W}_T^{(1)}$, $\mathcal{W}_T^{(2)}$, and $\mathcal{W}_T^{(3)}$ tend toward 100% as T increases, implying their consistency against \mathbb{H}'_1 , \mathcal{H}''_1 , and \mathbb{H}'''_1 , respectively. Second, when applying the critical values obtained from the mixed chi-squared distribution, the empirical rejection rates of $\mathcal{W}_T^{(1)}$, $\mathcal{W}_T^{(2)}$, and $\mathcal{W}_T^{(3)}$ also converge toward 100% as T increases. However, it is difficult to control their sizes, as shown in Table 2. Third, the standard Wald tests are consistently powerful. Fourth, as in the case of the bootstrap method, $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(3)}$ are more powerful than $W_T^{(1)}$ and $W_T^{(3)}$, respectively, for small T . In contrast, both $\mathcal{W}_T^{(2)}$ and $W_T^{(2)}$ show similar power patterns. \square

Before moving to the empirical section, we describe other simulation experiences on OLS and 2SNARDL. As the two estimators can estimate the same parameter, each has relative advantages over the other. The OLS contains a finite sample bias that is driven by ϱ_{m*} in Lemma 3 and vanishes as T increases, so that the negligible bias affects its finite sample performance. In contrast, 2SNARDL estimates the parameter by removing the bias. On the other hand, 2SNARDL is more involved than OLS. The bias is removed using an asymptotic covariance matrix estimator between Δx_t and u_t , affecting the performance of 2SNARDL. Meanwhile, OLS is straightforward to compute. From this comparison, if T is sufficiently large, OLS can be preferred to 2SNARDL for practical purposes. However, if T is not large 2SNARDL can be preferred over OLS when the bias is successfully removed. Cho et al. (2026) provide simulation results to compare the finite performance of OLS with 2SNARDL.

7 Empirical Application

This section examines the empirical data provided by [Romer and Romer \(2010\)](#) to measure the fiscal policy impact on the GDP of the United States of America. We review the literature and apply the NARDL model to examine the long- and short-run symmetries in the data.

7.1 Literature Review and Empirical Motivation

Estimating the effects of fiscal policy on output is challenging, because many fiscal factors that lead to tax changes are correlated with output, and this lets the OLS estimator suffer from endogenous bias. [Blanchard and Perotti \(2002\)](#) address this by using structural vector autoregression (SVAR). They attempt to solve the bias problem by assuming that policymakers do not respond to shocks contemporaneously, and by using information on the elasticity of revenue to create cyclically adjusted revenues. From this, they estimate that the effect of a tax cut on U.S. GDP is around 1%. However, [Romer and Romer \(2010\)](#) and [Cloyne \(2013\)](#) argue that the structural assumptions used in the SVAR model may be unrealistic in estimating the effect of fiscal policy on output.

[Romer and Romer \(2010\)](#) analyze the effects of tax changes correlated with GDP differently by performing a narrative analysis. They examine the motivations behind each tax change from 1945 to 2007 using sources such as *the Economic Report of the President* and *the Congressional Record*. They categorize legislated tax changes that altered tax liabilities from one quarter to the next into four categories: (i) tax changes to counteract changes in government spending, (ii) tax changes to offset other factors affecting near-term output, (iii) tax changes to address inherited budget deficits, and (iv) tax changes to promote long-term growth. The first two categories, considered countercyclical, are motivated by restoring output growth reduced by other factors, making it difficult to classify them as purely exogenous. In contrast, the last two categories, based on policymakers' perceptions of prudent fiscal policies or focus on increasing long-term growth, may be classified as exogenous. Consequently, they identified 54 exogenous tax changes through narrative analysis during the same period. Using these exogenous fiscal shocks, they develop a time-series model and estimate that GDP would increase by approximately 3% over three years following a tax cut of 1% of GDP. This estimate differs significantly from that of [Blanchard and Perotti \(2002\)](#).

Narrative analysis is widely used to examine the effects of fiscal shocks on GDP. For example, [Cloyne \(2013\)](#) applies this approach to UK legislation and estimates that a 1% tax cut, as a percentage of GDP, increases output by nearly 2.5% over the following three years, similar to findings in the United States of America. [Mertens and Olea \(2018\)](#) use narrative analysis to determine that the short-run tax elasticity of income is approximately 1.2% in the United States of America by analyzing exogenous variations in

the marginal tax rate. Additionally, [Gunter, Riera-Crichton, Vegh, and Vuletin \(2021\)](#) expand the use of narrative analysis to estimate the value-added-tax multipliers for 51 countries, showing that the effect of tax changes on output is highly nonlinear.

Narrative analysis is also used to specialize the time-series model in [Romer and Romer \(2010\)](#) for specific economic models under various environments. For example, [Mertens and Ravn \(2012\)](#) differentiate between surprise and anticipated tax changes to analyze the dynamic effects of tax changes on GDP, finding that anticipated tax cuts lead to a contraction in GDP. [Demirel \(2021\)](#) and [Ghassibe and Zanetti \(2021\)](#) examine the state-dependent effects of exogenous tax changes on GDP, allowing for varying tax multiplier estimations during recessions and expansions. Researchers widely apply narrative analysis to examine the effect of tax changes on GDP in other fields, enabling comparisons with conventional analysis outcomes.

The current study extends its focus beyond short-run relationships to estimate the long-run relationship between GDP and fiscal shocks. Previous studies have primarily concentrated on the short-term effects of fiscal policy. For example, one benchmark model specified by [Romer and Romer \(2010\)](#) is given as

$$\Delta y_t = \gamma_* + \sum_{j=0}^{q-1} \pi_{j*} \Delta \tau_{t-i} + \sum_{j=1}^{p-1} \varphi_{j*} \Delta y_{t-j} + e_t \quad (19)$$

to examine how GDP responds to exogenous tax changes, where y_t is the logarithm of real GDP and $\Delta \tau_t$ is the logarithm of an exogenous tax change. Note that all variables in (19) are differenced. Thus, it characterizes the short-run relationship between Δy_t and $\Delta \tau_t$.

Because y_t and τ_t are both observable, we can estimate their long-run relationship by applying cointegration analysis. To this end, we augment the cointegration error on the right side of (19) as follows:

$$\Delta y_t = \gamma_* + \rho_* u_{t-1} + \sum_{j=0}^{q-1} \pi_{j*} \Delta \tau_{t-i} + \sum_{j=1}^{p-1} \varphi_{j*} \Delta y_{t-j} + e_t, \quad (20)$$

where $u_t := y_t - \beta_* \tau_t - \zeta_* t - \nu_*$. Note that the long-run relationship between y_t and τ_t can be found by estimating the long-run coefficient β_* , and the short-run relationship can be found by estimating the coefficients of π_{j*} and φ_{j*} . To estimate the unknown parameters, we also convert (20) as follows:

$$\Delta y_t = \alpha_* + \rho_* y_{t-1} + \theta_* \tau_{t-1} + \xi_* t + \sum_{j=0}^{q-1} \pi_{j*} \Delta \tau_{t-i} + \sum_{j=1}^{p-1} \varphi_{j*} \Delta y_{t-j} + e_t. \quad (21)$$

For this estimation, we first examine the partial sum processes of the exogenous tax changes used in our empirical analysis. Figure 2 illustrates the partial sum processes due to the exogenous tax changes.¹

¹Data are obtained from <https://eml.berkeley.edu/~cromer/> (Accessed: Feb. 10, 2023).

The solid and dashed lines represent the partial sum processes of tax changes for deficit reduction (τ_{1t}) and long-run growth (τ_{2t}), respectively, and the dotted line represents the partial sum process of their sum (τ_t).²

The exogenous tax changes exhibit characteristics suitable for NARDL analysis. First, tax changes for budget deficits always result in tax increases, so $\Delta\tau_{1t}$ is always positive. Second, most tax changes aimed at long-run economic growth involve tax decreases; out of 31 legislated tax changes for long-run growth, only six of them result in tax increases. Consequently, overall, the partial sum processes for deficit reduction and long-run growth remain in positive and negative regions, respectively. Although the NARDL model assumptions do not perfectly align with the characteristics of the exogenous fiscal shocks, we use the approximation of $\Delta\tau_t^+ := \max[0, \Delta\tau_t]$ for tax changes due to budget deficit and $\Delta\tau_t^- := \min[0, \Delta\tau_t]$ for tax changes due to long-run growth.

Next, we specify the following NARDL model and estimate the long- and short-run parameters:

$$\Delta y_t = \gamma_* + \rho_* u_{t-1} + \sum_{j=0}^{q-1} \left(\pi_{j*}^+ \Delta\tau_{t-i}^+ + \pi_{j*}^- \Delta\tau_{t-i}^- \right) + \sum_{j=1}^{p-1} \varphi_{j*} \Delta y_{t-j} + e_t, \quad (22)$$

where $u_t := y_t - \beta_*^+ \tau_t^+ - \beta_*^- \tau_t^- - \zeta_* t - \nu_*$. This can be rewritten as

$$\Delta y_t = \alpha_* + \rho_* y_{t-1} + \theta_*^+ \tau_{t-1}^+ + \theta_*^- \tau_{t-1}^- + \xi_* t + \sum_{j=0}^{q-1} \left(\pi_{j*}^+ \Delta\tau_{t-i}^+ + \pi_{j*}^- \Delta\tau_{t-i}^- \right) + \sum_{j=1}^{p-1} \varphi_{j*} \Delta y_{t-j} + e_t, \quad (23)$$

which we estimate by OLS. If $\beta_*^+ = \beta_*^-$ (or $\theta_*^+ = \theta_*^-$) and $\pi_{j*}^+ = \pi_{j*}^-$, (22) reduces to (20). Economically, this implies that the relationship between tax changes aimed at deficit reduction and long-run growth in real GDP is roughly symmetric in both the long and short run.

7.2 Empirical Results

This section presents the estimation and inference results using the tax change data outlined in the previous section. We have limited the sample period to 1947Q1–2007Q4 by excluding periods with missing observations.

Before presenting the estimation and inference results, we provide the basic statistical characteristics of the data. The logarithm of the GDP quantity index, multiplied by 100, is represented by y_t , and τ_t , τ_{1t} , and

²We obtain the partial sum processes by first converting the nominal tax changes into consistent values over the period 1947Q1 to 2007Q4. To this end, we first discount the nominal values using the price index implied by the nominal GDP and the quantity index for GDP in the data set, and then apply a log transformation. We find that $\Delta\tau_t = \Delta\tau_{1t} + \Delta\tau_{2t}$, $\Delta\tau_{1t} := \text{sgn}(\Delta T_{1t}) \log(|\Delta T_{1t}|/p_t)$, $\Delta\tau_{2t} := \text{sgn}(\Delta T_{2t}) \log(|\Delta T_{2t}|/p_t)$, and $p_t := NY_t/Y_t$, where ΔT_{1t} and ΔT_{2t} represent the nominal tax changes for budget deficit and long-run growth, respectively, and NY_t and Y_t represent the nominal GDP and quantity GDP index, respectively. If $\Delta T_{1t} = 0$ or $\Delta T_{2t} = 0$, we let $\Delta\tau_{1t} = 0$ or $\Delta\tau_{2t} = 0$, respectively. The partial sum processes in Figure 1 represent τ_t , τ_{1t} , and τ_{2t} .

$\tau_{2,t}$ are defined as in footnote 2. The descriptive statistics of Δy_t , $\Delta \tau_{1t}$, $\Delta \tau_{2t}$, and $\Delta \tau_t$ can be found in Table A.9 in the Online Supplement. Furthermore, our unit-root test on y_t , τ_{1t} , τ_{2t} , and τ_t follows the method of Phillips and Perron (1988), including or excluding the time trend. The test results indicate that we cannot reject the unit-root hypothesis for the series.

We report the estimation results in Table 4. The columns marked “Exo” give the parameter estimates obtained by OLS for the NARDL and ARDL models. That is, the unknown parameters in (23) and (21) are estimated by OLS. Orders for the NARDL model are based on the Akaike information criterion (AIC), with $p = 3$ and $q = 1$ for both the NARDL and the ARDL models. Standard errors are listed in parentheses below the parameter estimates. Except for the coefficient of y_{t-1} , we use the asymptotic critical values from the mixed normal distribution. For the t -test on the coefficient of y_{t-1} , we use the asymptotic critical values provided by Banerjee et al. (1998). Furthermore, we test whether all coefficients of y_{t-1} , τ_{t-1}^+ , and τ_{t-1}^- are equal to zero by applying the F -test of Pesaran et al. (2001). Finally, we test the hypotheses of symmetry between long-run parameters, short-run parameters, or both by using the Wald tests given in Section 5. The results are presented in the two bottom panels. We summarize the results in Table 4 as follows:

- (a) The coefficient of y_{t-1} is significant at the 10% and 5% levels for the NARDL and ARDL models, respectively by the t -test. Although we cannot reject the hypothesis of no cointegration by the F -test for the NARDL model, it is significant at the 10% level for the ARDL model. Our analysis using the 2SNARDL model also suggests a cointegrating relationship between the log real GDP and the log of an exogenous log tax shock.
- (b) The NARDL model estimation indicates that an increase in an exogenous tax shock measured by τ_{t-1}^+ reduces the log real GDP. In contrast, a decrease in an exogenous tax shock measured by τ_{t-1}^- increases the log of real GDP. The ARDL model shows the same relationship between the log of an exogenous tax shock and the log real GDP, aligning with standard economic theory.
- (c) The estimated coefficients of τ_{t-1}^+ and τ_{t-1}^- are almost equal in magnitude, suggesting no long-run asymmetry between the log real GDP and the log of an exogenous tax shock. We confirm this using the Wald tests. Both Wald tests $\mathcal{W}_T^{(1)}$ and $W_T^{(1)}$ provide p -values that make it difficult to reject the symmetry hypothesis.
- (d) Short-run symmetry is confirmed by the Wald tests $\mathcal{W}_T^{(2)}$ and $W_T^{(2)}$, because they do not reject the symmetry hypothesis. Moreover, neither the long-run nor the short-run symmetry hypothesis is challenged by the Wald test $\mathcal{W}_T^{(3)}$ or $W_T^{(3)}$. As such, we conclude that the ARDL model is appropriate for studying the relationship between the log real GDP and the log of an exogenous tax shock.
- (e) We present the estimation results for the log of an endogenous tax shock, calculated in the same way as for the log of an exogenous tax shock. Columns labeled “Endo” give the estimation and inference

results obtained using the log of the endogenous tax shock data. Similarly, the columns labeled “Sum” show the estimation and inference results obtained using the logs of both exogenous and endogenous tax shocks. The estimated signs of τ_{t-1}^+ , τ_{t-1}^- , and τ_{t-1} are inconsistent with the parameter values posited by standard economic theory. When using the logs of both exogenous and endogenous tax shocks jointly, there is little evidence of cointegration. These estimation results indicate that only the log of an exogenous tax shock can be used to estimate the coefficients having signs consistent with standard economic theory. \square

Next, we estimate the NARDL and ARDL models using the 2SNARDL method proposed by [Cho et al. \(2023a\)](#). For the ARDL model, we apply 2SNARDL estimation by imposing the short- and long-run parameter symmetry conditions. The results are presented in [Table 5](#), which is structured similarly to [Table 4](#). This separate investigation is conducted to corroborate the inference results presented in [Table 4](#). We summarize the results in [Table 5](#).

- (a) The NARDL and ARDL models estimated by 2SNARDL show that the coefficient of u_{t-1} for the exogenous tax shock is statistically significant. The significance levels are 10% and 5% for the NARDL and ARDL models, respectively. Moreover, we apply the unit-root test of [Phillips and Perron \(1988\)](#) to the cointegration residuals obtained from both models. The results reject the unit-root hypothesis. The p -values are 10.19% and 2.58% for the NARDL and ARDL models, respectively. This confirms the cointegrating relationship between the log real GDP and the log of an exogenous tax shock.
- (b) For the log of an exogenous tax shock, the NARDL model indicates that the long-run coefficient of the log tax increase is -0.4329, whereas that of the log tax decrease is -0.3202. These signs are consistent with standard economic theory, and are statistically significant at the 1% and 10% levels, respectively. For the ARDL model, the long-run coefficient of the log tax change is -0.2328. This sign is also consistent with standard economic theory, and the estimated coefficient is statistically significant at the 1% level.
- (c) Our findings for the endogenous and aggregate log tax shocks align with the results presented in [Table 4](#). The coefficients of τ_{t-1}^+ , τ_{t-1}^- , and τ_{t-1} for the log of endogenous tax shocks are statistically significant, but their signs are inconsistent with standard economic theory. However, for the log of the aggregate tax shock, none of these coefficients are statistically significant. Moreover, the coefficient of u_{t-1} is insignificant. We believe these inconsistent results are due to the correlation between an endogenous shock and a structural error. \square

The results in [Tables 4](#) and [5](#) suggest that by using the log of exogenous tax shocks, we can properly identify the relationship between the log real GDP and a fiscal shock. The findings indicate limited statistical support for the asymmetry between tax shocks for deficit reduction and those for long-run growth. Moreover,

the OLS and 2SNARDL estimations produce qualitatively similar results.

In the Online Supplement, we provide additional empirical results. Rather than using the tax change logarithm τ_t , we use $\Delta r_t := (\Delta T_{1t} + \Delta T_{2t})/NY_t$, which represents the tax change-to-nominal GDP ratio, to measure the effect of fiscal policy and to specify the models corresponding to (20), (21), (22), and (23). From this, we obtain empirical results similar to those using log tax data and further show that an increase in an exogenous tax shock measured by r_{t-1} reduces the long-run log real GDP by about 3%. This is close to the result of [Romer and Romer \(2010\)](#), estimating that GDP will increase by approximately 3% over three years following a tax cut of 1% of GDP; see Section [A.5](#).

8 Conclusion

OLS has an asymptotically singular matrix when used with the NARDL model. However, despite the absence of established limit theory for OLS, it remains popular in empirical literature.

This study investigates the large-sample behavior of OLS by addressing the problem of an asymptotically singular matrix. Specifically, we find that OLS is consistent for the unknown NARDL parameters and follows a mixed normal distribution asymptotically under some mild regularity conditions. This implies that the standard principles of the t - and Wald tests apply, despite the asymptotically singular matrix problem. To derive the asymptotic distribution, we first represent the OLS as a transformation of other primitive estimators that are not affected by an asymptotically singular matrix, and derive their joint weak limits. The representation is obtained by elaborating on the FWL projection method in [Park and Phillips \(1988, 1989\)](#), and the weak limits of the primitive estimators allow us to derive the joint weak limit of the OLS. They further enable us to demonstrate that the convergence rate of the OLS is identical to that of the estimator implied by 2SNARDL, despite the asymptotically singular matrix problem.

In addition, we examine the large-sample behavior of the Wald tests for the NARDL hypothesis. Beyond the standard Wald tests defined by the OLS, we develop supplementary Wald tests using primitive estimators. The null limit distributions of the standard Wald tests are mixed chi-squared, whereas those of the supplementary Wald tests differ when testing for long-run asymmetry. By applying the residual bootstrap method, Monte Carlo simulations show that the supplementary Wald tests generally perform better than the standard Wald tests.

OLS and 2SNARDL target the same parameter, and each has relative advantages over the other. The OLS contains a finite sample bias that is asymptotically negligible, affecting its finite sample performance. In contrast, 2SNARDL estimates the parameter by removing the bias. However, 2SNARDL first estimates the asymptotic covariance matrix between the differenced regressor and cointegration error. Meanwhile,

OLS is not involved in such a preliminary procedure. From this, if the sample size is sufficiently large, the OLS can be preferred to the 2SNARDL for practical purposes; if the sample size is not large, 2SNARDL can be preferred over OLS when it successfully removes the bias.

Lastly, we illustrate the proper use of the NARDL model by estimating the long- and short-run relationships between GDP and exogenous fiscal shocks due to deficit reduction and long-run growth. For this we use the empirical data from [Romer and Romer \(2010\)](#). Because all tax changes for deficit reduction are tax increases, and most changes for long-run growth are tax decreases, the NARDL model approximates the relationship between GDP and the exogenous fiscal shocks. We estimate the model and examine whether the relationships between tax increases and decreases are symmetric in both the long and short run. We find no evidence of asymmetric relationships between them.

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Wald Test	Null Hypothesis	Symmetry	Null Limit Distribution
$W_T^{(1)} := \hat{\alpha}'_T \hat{\mathbf{R}}'_1 (\hat{\mathbf{W}}_T^{(1)})^{-1} \hat{\mathbf{R}}_1 \hat{\alpha}_T$	$\mathcal{H}_0' : \boldsymbol{\theta}^+ = \boldsymbol{\theta}^-$	Long-run	Mixed Chi-squared
$W_T^{(2)} := \hat{\alpha}'_T \hat{\mathbf{R}}'_2 (\hat{\mathbf{W}}_T^{(2)})^{-1} \hat{\mathbf{R}}_2 \hat{\alpha}_T$	$\mathcal{H}_0'' : \boldsymbol{\pi}^+ = \boldsymbol{\pi}^-$	Short-run	Mixed Chi-squared
$W_T^{(3)} := \hat{\alpha}'_T \hat{\mathbf{R}}'_3 (\hat{\mathbf{W}}_T^{(3)})^{-1} \hat{\mathbf{R}}_3 \hat{\alpha}_T$	$\mathcal{H}_0''' : \boldsymbol{\beta}^+ = \boldsymbol{\beta}^-$ and $\boldsymbol{\pi}^+ = \boldsymbol{\pi}^-$	Long- and Short-run	Mixed Chi-squared
$\mathcal{W}_T^{(1)} := \ddot{v}'_T \ddot{\mathbf{D}}_1 \ddot{\mathbf{R}}'_1 (\ddot{\mathbf{W}}_T^{(1)})^{-1} \ddot{\mathbf{R}}_1 \ddot{\mathbf{D}}_1 \ddot{v}_T$	$\mathbb{H}_0' : \boldsymbol{\beta}^+ = \boldsymbol{\beta}^-$	Long-run	Nonstandard
$\mathcal{W}_T^{(2)} := \ddot{\tau}'_T \ddot{\mathbf{D}} \ddot{\mathbf{R}}'_2 (\ddot{\mathbf{W}}_T^{(2)})^{-1} \ddot{\mathbf{R}}_2 \ddot{\mathbf{D}} \ddot{\tau}_T$	$\mathcal{H}_0'' : \boldsymbol{\pi}^+ = \boldsymbol{\pi}^-$	Short-run	Mixed Chi-squared
$\mathcal{W}_T^{(3)} := \ddot{\delta}'_T \ddot{\mathbf{D}} \ddot{\mathbf{R}}'_3 (\ddot{\mathbf{W}}_T^{(3)})^{-1} \ddot{\mathbf{R}}_3 \ddot{\mathbf{D}} \ddot{\delta}_T$	$\mathbb{H}_0''' : \boldsymbol{\beta}^+ = \boldsymbol{\beta}^-$ and $\boldsymbol{\pi}^+ = \boldsymbol{\pi}^-$	Long- and Short-run	Nonstandard

Table 1: SUMMARY OF THE WALD TESTS. This table summarizes the hypotheses and the null limit distributions of the Wald tests defined in Section 5. $W_T^{(1)}$, $W_T^{(2)}$, and $W_T^{(3)}$ are defined by the OLS estimator $\hat{\alpha}_T$, whereas $\mathcal{W}_T^{(1)}$, $\mathcal{W}_T^{(2)}$, and $\mathcal{W}_T^{(3)}$ are defined by the primitive estimators, viz., \ddot{v}_T , $\ddot{\tau}_T$, and $\ddot{\delta}_T$, respectively. When the null limit distribution of the Wald test is mixed chi-squared, the asymptotic critical values of the test can be selected from the chi-square distribution. However, for the Wald test whose null limit distribution is nonstandard, the residual bootstrap can be applied to the test. Section 6 illustrates the application of the residual bootstrap to the Wald test.

Wald Test	Method	Bootstrap Method					Mixed Chi-squared Distribution				
	$\alpha \setminus T$	100	200	300	400	500	100	200	300	400	500
$\mathcal{W}_T^{(1)}$	10%	11.34	10.78	10.18	10.26	10.32	39.68	40.84	41.20	42.78	41.72
	5%	5.98	5.46	4.90	5.46	5.32	32.04	32.80	33.02	34.62	33.42
	1%	1.00	1.02	0.94	1.38	0.90	19.34	19.62	19.82	20.96	21.40
$\mathcal{W}_T^{(2)}$	10%	9.58	8.96	9.70	9.56	9.96	12.10	10.20	10.52	10.20	10.10
	5%	4.46	4.28	5.14	4.90	4.80	6.30	4.94	5.78	5.00	5.38
	1%	1.04	0.86	1.02	0.84	1.02	1.56	1.06	1.28	0.90	1.06
$\mathcal{W}_T^{(3)}$	10%	11.46	10.50	10.20	9.98	10.62	36.38	36.46	37.28	38.14	37.12
	5%	5.54	5.18	4.94	5.28	5.20	28.10	27.56	28.44	29.44	28.86
	1%	1.02	0.84	0.80	1.28	0.96	16.62	16.18	16.12	17.58	17.50
$W_T^{(1)}$	10%	10.24	10.12	10.62	9.34	9.90	14.44	12.78	12.10	10.90	10.96
	5%	5.38	5.52	5.14	4.34	4.86	8.56	7.22	6.46	5.26	5.56
	1%	1.24	1.14	1.08	0.92	1.08	2.84	1.92	1.32	1.14	1.34
$W_T^{(2)}$	10%	9.82	10.90	9.38	10.32	10.44	11.98	11.94	10.24	10.86	10.82
	5%	4.90	5.56	4.56	5.42	5.68	6.52	6.52	5.20	5.70	6.00
	1%	1.04	0.96	1.00	1.36	1.12	1.74	1.10	1.18	1.38	1.46
$W_T^{(3)}$	10%	9.96	11.32	10.06	9.90	10.84	14.98	13.62	11.72	10.98	11.66
	5%	5.06	5.64	4.82	4.96	5.86	8.42	7.54	6.00	5.74	6.60
	1%	1.14	1.04	1.16	1.10	1.14	2.62	1.82	1.50	1.50	1.42

Table 2: EMPIRICAL REJECTION RATES OF THE WALD TESTS (IN PERCENT). This table shows the empirical rejection rates of the Wald statistics testing $\mathbb{H}'_0 : \beta_* = 0$, $\mathcal{H}''_0 : \pi_*^+ = \pi_*^-$, and $\mathbb{H}'''_0 : \beta_* = 0$ and $\pi_*^+ = \pi_*^-$. The total number of repetitions is 5000, and the bootstrap iteration is 500. DGP: $\Delta y_t = \rho_* u_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^-$, $\Delta x_t = 1/4 + \kappa_* \Delta x_{t-1} + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\kappa_*, \rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-) = (1/2, -1/2, 1/2, 1/2, 1, 1)$. Here, $\mathcal{W}_T^{(1)}$, $\mathcal{W}_T^{(2)}$, and $\mathcal{W}_T^{(3)}$ denote the Wald tests in Section 5, and $W_T^{(1)}$, $W_T^{(2)}$, and $W_T^{(3)}$ are the standard Wald tests.

Wald Test	Method	Bootstrap Method					Mixed Chi-squared Distribution				
	$\alpha \setminus T$	100	200	300	400	500	100	200	300	400	500
$\mathcal{W}_T^{(1)}$	10%	52.00	91.58	99.30	99.92	100.0	73.96	97.34	99.92	99.98	100.0
	5%	39.20	86.62	98.54	99.88	100.0	67.62	96.32	99.82	99.98	100.0
	1%	17.32	70.56	94.76	99.44	99.94	55.08	93.26	99.48	99.96	100.0
$\mathcal{W}_T^{(2)}$	10%	16.48	23.52	30.24	37.72	44.20	19.12	25.62	31.06	38.96	45.46
	5%	9.16	14.64	19.44	26.76	32.58	11.80	16.78	21.04	27.98	33.92
	1%	2.32	4.30	6.52	10.92	14.18	3.94	5.82	7.46	11.64	15.32
$\mathcal{W}_T^{(3)}$	10%	50.70	90.78	99.18	99.92	100.0	69.84	96.36	99.80	99.98	100.0
	5%	36.98	85.84	98.32	99.90	99.98	63.90	95.14	99.66	99.98	100.0
	1%	16.44	69.22	94.32	99.36	99.92	51.42	91.68	99.20	99.94	100.0
$W_T^{(1)}$	10%	47.92	91.16	99.16	99.92	100.0	58.56	93.16	99.24	99.94	100.0
	5%	35.04	85.24	98.22	99.90	100.0	47.72	88.78	98.74	99.92	100.0
	1%	15.22	67.52	94.24	99.12	99.94	28.80	76.20	95.82	99.52	99.98
$W_T^{(2)}$	10%	15.42	22.08	29.92	37.12	45.18	18.28	24.42	31.34	38.48	46.34
	5%	8.74	14.10	19.78	26.18	31.78	11.28	15.62	21.00	27.80	33.48
	1%	2.10	4.76	6.88	10.38	13.88	3.30	5.98	7.80	11.42	14.92
$W_T^{(3)}$	10%	41.94	87.02	98.54	99.92	100.0	52.28	89.68	98.86	99.92	100.0
	5%	30.68	79.86	97.32	99.76	100.0	41.42	84.08	97.84	99.82	100.0
	1%	12.40	61.20	91.60	98.86	99.88	23.66	69.66	93.92	99.16	99.96

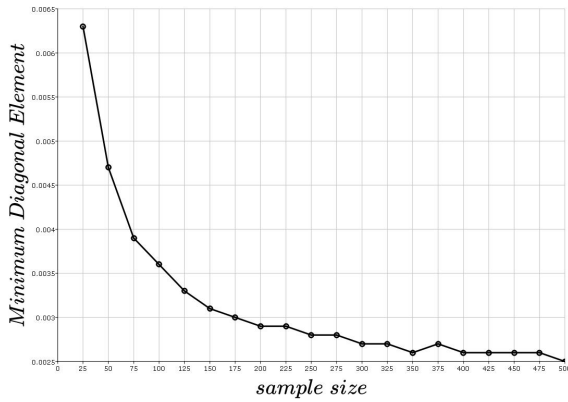
Table 3: EMPIRICAL REJECTION RATES OF THE WALD TESTS (IN PERCENT). This table shows the empirical rejection rates of the Wald statistics testing $\mathbb{H}'_0 : \beta_* = 0$, $\mathcal{H}''_0 : \pi_*^+ = \pi_*^-$, and $\mathbb{H}'''_0 : \beta_* = 0$ and $\pi_*^+ = \pi_*^-$. The total number of repetitions is 5000, and the bootstrap iteration is 500. DGP: $\Delta y_t = \rho_* u_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^-$, $\Delta x_t = 1/4 + \kappa_* \Delta x_{t-1} + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\kappa_*, \rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-) = (1/2, -1/2, 1/8, -1/8, 1/4, -1/4)$. Here, $\mathcal{W}_T^{(1)}$, $\mathcal{W}_T^{(2)}$, and $\mathcal{W}_T^{(3)}$ denote the Wald tests in Section 5, and $W_T^{(1)}$, $W_T^{(2)}$, and $W_T^{(3)}$ are the standard Wald tests.

NARDL Model				ARDL Model			
Variables \ Tax	Exo.	Endo.	Sum.	Variables \ Tax	Exo.	Endo.	Sum.
y_{t-1}	-0.0683*	-0.0817	-0.0497	y_{t-1}	-0.070**	-0.0755	-0.0404
	(0.0191)	(0.0223)	(0.0158)		(0.0185)	(0.0220)	(0.0148)
τ_{t-1}^+	-0.0123 [†]	0.0158**	0.0016	τ_{t-1}	-0.0139**	0.0142*	-0.0053
	(0.0078)	(0.0078)	(0.0093)		(0.0060)	(0.0077)	(0.0074)
τ_{t-1}^-	-0.0123 [†]	0.0149	-0.0093				
	(0.0083)	(0.0176)	(0.0090)				
Trend	0.0549***	0.0631***	0.0324**	Trend	0.0570***	0.0584***	0.0333***
	(0.0177)	(0.0176)	(0.0127)		(0.0151)	(0.0169)	(0.0120)
Constant	0.7588***	0.6974***	0.8357***	Constant	0.7826***	0.7542***	0.8543***
	(0.1874)	(0.1644)	(0.1744)		(0.1539)	(0.1604)	(0.1561)
Δy_{t-1}	0.3129***	0.3118***	0.3135***	Δy_{t-1}	0.3091***	0.3035***	0.3031***
	(0.0633)	(0.0658)	(0.0646)		(0.0630)	(0.0657)	(0.0648)
Δy_{t-2}	0.1265*	0.1446**	0.1190*	Δy_{t-2}	0.1304**	0.1331**	0.1091*
	(0.0646)	(0.0658)	(0.0645)		(0.0643)	(0.0653)	(0.0647)
$\Delta \tau_t^+$	-0.0029	0.0890*	0.03984 [†]	$\Delta \tau_t$	-0.0444 [†]	0.0434 [†]	-0.0122
	(0.0435)	(0.0465)	(0.0341)		(0.0272)	(0.0362)	(0.0226)
$\Delta \tau_t^-$	-0.0780**	-0.0302	-0.0683*				
	(0.0391)	(0.0598)	(0.0347)				
AIC	-6.5459	-6.5372	-6.5332	AIC	-6.5561	-6.5434	-6.5284
BIC	-6.4225	-6.4099	-6.5332	BIC	-6.4602	-6.4475	-6.4378
t -test	-3.5680*	-3.6519*	-3.1308 [†]	t -test	-3.8220**	-3.4319*	-2.7229
F -test	4.5387	4.9164	3.8509	F -test	7.3222*	6.5583*	4.7046
$\mathcal{W}_T^{(1)}$					9.8862	0.0048	9.8910
					(0.4344)	(0.9696)	(0.5000)
$\mathcal{W}_T^{(2)}$					1.4822	3.8085	5.2908
					(0.7472)	(0.1902)	(0.6567)
$\mathcal{W}_T^{(3)}$					30.9528	1.4114	32.3642
					(0.2737)	(0.2659)	(0.2718)
$W_T^{(1)}$					0.0000	0.0039	1.0285
					(0.9982)	(0.9604)	(0.4485)
$W_T^{(2)}$					1.5426	2.5180	4.4950
					(0.2265)	(0.1259)	(0.0398)
$W_T^{(3)}$					1.5527	2.5326	5.2070
					(0.5474)	(0.3706)	(0.1525)

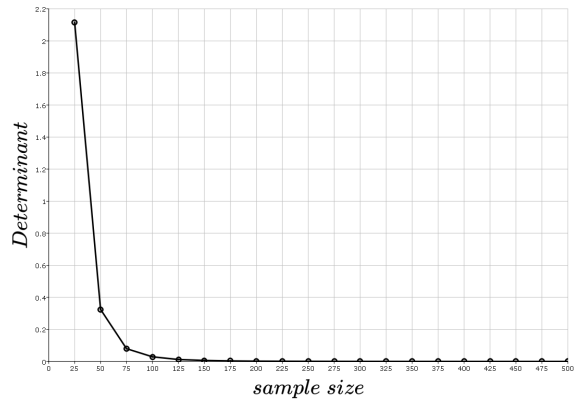
Table 4: OLS ESTIMATION OF THE NARDL AND ARDL MODELS. This table presents the OLS estimation using quarterly data from [Romer and Romer \(2010\)](#). The left and right panels display estimated parameters for (23) and (21), respectively. Figures in parentheses indicate standard errors of the OLS estimates. At the bottom of the top panels, AIC, BIC, t -test, and [Pesaran et al.'s \(2001\)](#) F -test are reported. [†], *, **, and *** indicate significance at 25%, 10%, 5%, and 1% levels, respectively. Wald tests in the last two bottom panels show the Wald tests in Section 5 and the standard Wald tests. Figures in parentheses below the Wald tests show p -values. They are obtained from 100000 bootstrap iterations.

	NARDL Model				ARDL Model			
	Variables \ Tax	Exo.	Endo.	Sum.	Variables \ Tax	Exo.	Endo.	Sum.
Long-Run	Constant	4.2360 [†] (2.5919)	3.7413*** (1.2787)	4.9730** (2.3861)	Constant	6.0785*** (1.7968)	4.8528*** (1.3852)	5.8407** (2.8526)
	τ_{t-1}^+	-0.4329*** (0.1318)	0.2715*** (0.0546)	0.2759 [†] (0.1723)	τ_{t-1}	-0.2328*** (0.0709)	0.2523*** (0.0591)	0.1564 (0.1716)
	τ_{t-1}^-	-0.3202* (0.1722)	0.3276* (0.1757)	0.2598 [†] (0.1826)	Trend	0.8261*** (0.0127)	0.8367*** (0.0098)	0.8287*** (0.0202)
	Trend	0.8340*** (0.0184)	0.8461*** (0.0090)	0.8436*** (0.0169)				
Short-Run	u_{t-1}	-0.0683* (0.0191)	-0.0817* (0.0223)	-0.0497 [†] (0.0158)	u_{t-1}	-0.0708** (0.0185)	-0.0755* (0.0220)	-0.0404 (0.0148)
	Constant	0.6734*** (0.1424)	0.6918*** (0.1458)	0.5683*** (0.1472)	Constant	0.5752*** (0.1391)	0.6590*** (0.1392)	0.6295*** (0.1404)
	Δy_{t-1}	0.3129*** (0.0633)	0.3118*** (0.0658)	0.3135*** (0.0646)	Δy_{t-1}	0.3091*** (0.0630)	0.3035*** (0.0657)	0.3031*** (0.0648)
	Δy_{t-2}	0.1265* (0.0646)	0.1446** (0.0658)	0.1190* (0.0645)	Δy_{t-2}	0.1304** (0.0643)	0.1331** (0.0653)	0.1091* (0.0647)
	$\Delta \tau_t^+$	-0.0029 (0.0435)	0.0890* (0.0465)	0.0398 [†] (0.0341)	$\Delta \tau_t$	-0.0444 [†] (0.0272)	0.0434 [†] (0.0362)	-0.0122 (0.0226)
	$\Delta \tau_t^-$	-0.0780** (0.0391)	-0.0302 (0.0598)	-0.0683* (0.0347)				

Table 5: 2SNARDL ESTIMATION OF THE NARDL AND ARDL MODELS. This table presents the 2SNARDL estimation using the quarterly data from [Romer and Romer \(2010\)](#). The left and right panels display estimated parameters for (22) and (20), respectively. [†], *, **, and *** imply that the tests are significant at 25%, 10%, 5%, and 1%, respectively.



(a) Average of Traces



(b) Average of Determinants $\times 10^{12}$

Figure 1: ASYMPTOTIC SINGULARITY OF THE MATRIX $\mathbf{D}^{-1}(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}_t') \mathbf{D}^{-1}$. Figure 1 (a) shows the scatter diagram between the sample size and the averaged minimum diagonal element of $\mathbf{D}^{-1}(\sum_{t=1}^T \mathbf{z}_t \mathbf{z}_t') \mathbf{D}^{-1}$ obtained by imposing the DGP condition given in Table 3. Figure 1 (b) shows the scatter diagram between the sample size and the averaged determinant $\times 10^{12}$ of the same matrix. For the scatter diagrams, 10000 independent experiments are repeated to compute the averages from the 10000 independent matrices.

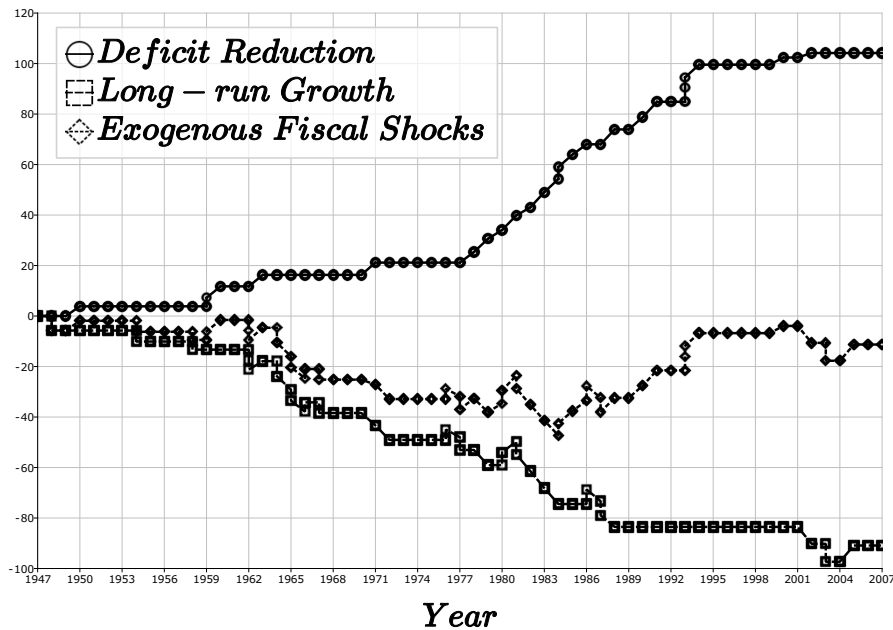


Figure 2: PARTIAL SUM PROCESS FORMED BY EXOGENOUS FISCAL SHOCKS. The solid, dashed, and dotted lines represent deficit reduction, long-run growth, and exogenous fiscal shocks, respectively.

Online Supplement for
‘Estimation and Inference of Nonlinear Autoregressive Distributed Lag Models
with Time Trend by Ordinary Least Squares’

by

Jin Seo Cho

Yonsei University

This Online Supplement is an Appendix that provides proofs of all the results in the paper, including the lemmas, additional Monte Carlo simulations, and supplementary empirical findings.

A Supplements

A.1 Supplementary Lemmas

Before proving the main claims in the text, we first provide some preliminary lemmas to prove the main claims efficiently.

The following two lemmas provide alternative representations of OLS under different environments. They are obtained by elaborating on the Frisch-Waugh-Lovell projection method. We first suppose that $y_t \in \mathbb{R}$ is a dependent variable and $(\mathbf{x}'_t, \mathbf{z}'_t)' \in \mathbb{R}^{(s+k)}$ is an explanatory variable, and the OLS estimator is obtained by regressing y_t against $(\mathbf{x}'_t, \mathbf{z}'_t)'$. Given this, we provide alternative forms of the OLS estimator in the following lemmas:

Lemma A.1 (Complete Form of Frisch-Waugh-Lovell). *Suppose that $\{(y_t, \mathbf{x}'_t, \mathbf{z}'_t)' \in \mathbb{R}^{1+s+k} : t = 1, 2, \dots, T\}$. If the OLS estimators are obtained as follows: for $j = 1, 2, \dots, s$,*

$$(\tilde{\boldsymbol{\beta}}_T, \hat{\boldsymbol{\gamma}}_T) := \arg \min_{\boldsymbol{\beta}, \boldsymbol{\gamma}} \sum_{t=1}^T (y_t - \mathbf{x}_t \boldsymbol{\beta} - \mathbf{z}'_t \boldsymbol{\gamma})^2, \quad \hat{\boldsymbol{\phi}}_{jT} := \arg \min_{\phi_j} \sum_{t=1}^T (x_{jt} - \mathbf{z}'_t \phi_j)^2, \quad \text{and}$$

$$(\hat{\boldsymbol{\xi}}_T, \hat{\boldsymbol{\delta}}_T) := \arg \min_{\boldsymbol{\xi}, \boldsymbol{\delta}} \sum_{t=1}^T (y_t - \hat{\mathbf{v}}'_t \boldsymbol{\xi} - \mathbf{z}'_t \boldsymbol{\delta})^2,$$

where for each t , $\hat{\mathbf{v}}_t := \mathbf{x}_t - \hat{\boldsymbol{\phi}}'_T \mathbf{z}_t$ and $\hat{\boldsymbol{\phi}}_T := (\hat{\boldsymbol{\phi}}_{1T}, \dots, \hat{\boldsymbol{\phi}}_{sT})$, then $\tilde{\boldsymbol{\beta}}_T = \hat{\boldsymbol{\xi}}_T$ and $\hat{\boldsymbol{\gamma}}_T = \hat{\boldsymbol{\delta}}_T - \hat{\boldsymbol{\phi}}_T \hat{\boldsymbol{\xi}}_T$. \square

Therefore, we can obtain the OLS estimator $(\tilde{\beta}_T, \tilde{\gamma}_T)$ by combining the two OLS estimators $\hat{\phi}_T$ and $(\hat{\xi}_T, \hat{\delta}_T)$ obtained from the first- and second-step OLS estimators, respectively.

The following lemma assumes a different environment. We let the OLS estimator be obtained by regressing y_t against $(\mathbf{x}_t, \mathbf{z}'_t, \mathbf{w}'_t)' \in \mathbb{R}^{s+k+d}$ and provide another alternative form of the OLS estimator:

Lemma A.2 (Augmented Frisch-Waugh-Lovell, AFWL). *Suppose that $\{(y_t, \mathbf{x}'_t, \mathbf{z}'_t, \mathbf{w}'_t)' \in \mathbb{R}^{1+s+k+d} : t = 1, 2, \dots, T\}$. If the OLS estimators are obtained as follows: for $j = 1, 2, \dots, s$,*

$$\begin{aligned} (\tilde{\beta}_T, \tilde{\gamma}_T, \hat{\alpha}_T) &:= \arg \min_{\beta, \gamma, \alpha} \sum_{t=1}^T (y_t - \mathbf{x}'_t \beta - \mathbf{z}'_t \gamma - \mathbf{w}'_t \alpha)^2, \quad \hat{\phi}_{jT} := \arg \min_{\phi} \sum_{t=1}^T (x_{jt} - \mathbf{z}'_t \phi_j)^2, \quad \text{and} \\ (\hat{\xi}_T, \hat{\delta}_T, \hat{\theta}_T) &:= \arg \min_{\xi, \delta, \theta} \sum_{t=1}^T (y_t - \hat{\mathbf{v}}'_t \xi - \mathbf{z}'_t \delta - \mathbf{w}'_t \theta)^2, \end{aligned}$$

where for each t , $\hat{\mathbf{v}}_t := \mathbf{x}_t - \hat{\phi}'_T \mathbf{z}_t$ and $\hat{\phi}_T := (\hat{\phi}_{1T}, \dots, \hat{\phi}_{sT})$, then $\tilde{\beta}_T = \hat{\xi}_T$, $\tilde{\gamma}_T = \hat{\delta}_T - \hat{\phi}_T \hat{\xi}_T$, and $\hat{\alpha}_T = \hat{\theta}_T$. \square

Note that \mathbf{w}_t is added as an additional regressor to the regressors given in Lemma A.1 and that the nuisance parameter estimator $\hat{\alpha}_T$ is the same as the nuisance parameter estimator $\hat{\theta}_T$ obtained in the second step.

We now prove Lemmas A.1 and A.2. For notational simplicity, we let

$$\mathbf{Y} := [y_1, y_2, \dots, y_T]', \quad \mathbf{X} := [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_T]', \quad \mathbf{Z} := [\mathbf{z}_1, \mathbf{z}_2, \dots, \mathbf{z}_T]', \quad \hat{\mathbf{V}} := [\hat{v}_1, \hat{v}_2, \dots, \hat{v}_T]',$$

and $\mathbf{W} := [\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_T]'$.

Proof of Lemma A.1. From the definition of $(\tilde{\beta}_T, \tilde{\gamma}_T)$, we first note that

$$\begin{bmatrix} \tilde{\beta}_T \\ \tilde{\gamma}_T \end{bmatrix} = \begin{bmatrix} \mathbf{X}'\mathbf{X} & \mathbf{X}'\mathbf{Z} \\ \mathbf{Z}'\mathbf{X} & \mathbf{Z}'\mathbf{Z} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{X}'\mathbf{Y} \\ \mathbf{Z}'\mathbf{Y} \end{bmatrix} = \begin{bmatrix} (\mathbf{X}'\mathbf{Q}\mathbf{X})^{-1} \mathbf{X}'\mathbf{Q}\mathbf{Y} \\ (\mathbf{Z}'\mathbf{Z})^{-1} \mathbf{Z}'[\mathbf{I} - \mathbf{X}(\mathbf{X}'\mathbf{Q}\mathbf{X})^{-1} \mathbf{X}'\mathbf{Q}]\mathbf{Y} \end{bmatrix}, \quad (\text{A.1})$$

where $\mathbf{Q} := \mathbf{I} - \mathbf{Z}(\mathbf{Z}'\mathbf{Z})^{-1} \mathbf{Z}'$. Next, we note that

$$\hat{\mathbf{V}} = \mathbf{X} - \mathbf{Z}\hat{\phi}_T = \mathbf{X} - \mathbf{Z}(\mathbf{Z}'\mathbf{Z})^{-1} \mathbf{Z}'\mathbf{X} = \mathbf{Q}\mathbf{X}. \quad (\text{A.2})$$

Therefore, $\mathbf{Z}'\hat{\mathbf{V}} = \mathbf{0}$ by noting that $\mathbf{Z}'\mathbf{Q} = \mathbf{0}$. Third, we note that

$$\begin{bmatrix} \hat{\xi}_T \\ \hat{\delta}_T \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{V}}'\hat{\mathbf{V}} & \hat{\mathbf{V}}'\mathbf{Z} \\ \mathbf{Z}'\hat{\mathbf{V}} & \mathbf{Z}'\mathbf{Z} \end{bmatrix}^{-1} \begin{bmatrix} \hat{\mathbf{V}}'\mathbf{Y} \\ \mathbf{Z}'\mathbf{Y} \end{bmatrix} = \begin{bmatrix} (\hat{\mathbf{V}}'\hat{\mathbf{V}})^{-1} \hat{\mathbf{V}}'\mathbf{Y} \\ (\mathbf{Z}'\mathbf{Z})^{-1} \mathbf{Z}'\mathbf{Y} \end{bmatrix}$$

using the fact that $\mathbf{Z}'\widehat{\mathbf{V}} = \mathbf{0}$. Therefore,

$$\widehat{\boldsymbol{\xi}}_T = (\widehat{\mathbf{V}}'\widehat{\mathbf{V}})^{-1}\widehat{\mathbf{V}}'\mathbf{Y} = (\mathbf{X}'\mathbf{Q}\mathbf{X})^{-1}\mathbf{X}'\mathbf{Q}\mathbf{Y} \quad (\text{A.3})$$

using (A.2). This shows that $\widetilde{\boldsymbol{\beta}}_T = \widehat{\boldsymbol{\xi}}_T$. Finally, we note that

$$\widehat{\boldsymbol{\delta}}_T - \widehat{\boldsymbol{\phi}}_T'\widehat{\boldsymbol{\xi}}_T = (\mathbf{Z}'\mathbf{Z})^{-1}\mathbf{Z}'\mathbf{Y} - (\mathbf{Z}'\mathbf{Z})^{-1}\mathbf{Z}'\mathbf{X}(\widehat{\mathbf{V}}'\widehat{\mathbf{V}})^{-1}\widehat{\mathbf{V}}'\mathbf{Y} = (\mathbf{Z}'\mathbf{Z})^{-1}\mathbf{Z}'[\mathbf{I} - \mathbf{X}(\mathbf{X}'\mathbf{Q}\mathbf{X})^{-1}\mathbf{X}'\mathbf{Q}]\mathbf{Y} = \widehat{\boldsymbol{\gamma}}_T,$$

which follows from (A.1), where the second equality follows from (A.3). Thus, $\widehat{\boldsymbol{\delta}}_T - \widehat{\boldsymbol{\phi}}_T'\widehat{\boldsymbol{\xi}}_T = \widehat{\boldsymbol{\gamma}}_T$. This completes the proof. \blacksquare

Proof of Lemma A.2. To prove the claim, we represent the OLS estimators in different forms. If we let

$$(\widetilde{\boldsymbol{\beta}}_T(\boldsymbol{\alpha}), \widehat{\boldsymbol{\gamma}}_T(\boldsymbol{\alpha})) := \arg \min_{\boldsymbol{\beta}, \boldsymbol{\gamma}} \sum_{t=1}^T (y_t - \mathbf{x}_t'\boldsymbol{\beta} - \mathbf{z}_t'\boldsymbol{\gamma} - \mathbf{w}_t'\boldsymbol{\alpha})^2,$$

then

$$\widehat{\boldsymbol{\alpha}}_T = \arg \min_{\boldsymbol{\alpha}} \sum_{t=1}^T (y_t - \mathbf{x}_t'\widetilde{\boldsymbol{\beta}}_T(\boldsymbol{\alpha}) - \mathbf{z}_t'\widehat{\boldsymbol{\gamma}}_T(\boldsymbol{\alpha}) - \mathbf{w}_t'\boldsymbol{\alpha})^2,$$

and $(\widetilde{\boldsymbol{\beta}}_T(\widehat{\boldsymbol{\alpha}}_T), \widehat{\boldsymbol{\gamma}}_T(\widehat{\boldsymbol{\alpha}}_T)) = (\widetilde{\boldsymbol{\beta}}_T, \widehat{\boldsymbol{\gamma}}_T)$. Likewise, if we let

$$(\widehat{\boldsymbol{\xi}}_T(\boldsymbol{\theta}), \widehat{\boldsymbol{\delta}}_T(\boldsymbol{\theta})) := \arg \min_{\boldsymbol{\xi}, \boldsymbol{\delta}} \sum_{t=1}^T (y_t - \widehat{\mathbf{v}}_t'\boldsymbol{\xi} - \mathbf{z}_t'\boldsymbol{\delta} - \mathbf{w}_t'\boldsymbol{\theta})^2,$$

then

$$\widehat{\boldsymbol{\theta}}_T = \arg \min_{\boldsymbol{\theta}} \sum_{t=1}^T (y_t - \widehat{\mathbf{v}}_t'\widehat{\boldsymbol{\xi}}_T(\boldsymbol{\theta}) - \mathbf{z}_t'\widehat{\boldsymbol{\delta}}_T(\boldsymbol{\theta}) - \mathbf{w}_t'\boldsymbol{\theta})^2,$$

and $(\widehat{\boldsymbol{\xi}}_T(\widehat{\boldsymbol{\theta}}_T), \widehat{\boldsymbol{\delta}}_T(\widehat{\boldsymbol{\theta}}_T)) = (\widehat{\boldsymbol{\xi}}_T, \widehat{\boldsymbol{\delta}}_T)$.

Here, for each $\boldsymbol{\alpha}$, if we let $y_t(\boldsymbol{\alpha}) := y_t - \mathbf{w}_t'\boldsymbol{\alpha}$,

$$(\widetilde{\boldsymbol{\beta}}_T(\cdot), \widehat{\boldsymbol{\gamma}}_T(\cdot)) := \arg \min_{\boldsymbol{\beta}, \boldsymbol{\gamma}} \sum_{t=1}^T (y_t(\cdot) - \mathbf{x}_t'\boldsymbol{\beta} - \mathbf{z}_t'\boldsymbol{\gamma})^2, \quad \text{and}$$

$$(\widehat{\boldsymbol{\xi}}_T(\cdot), \widehat{\boldsymbol{\delta}}_T(\cdot)) := \arg \min_{\boldsymbol{\xi}, \boldsymbol{\delta}} \sum_{t=1}^T (y_t(\cdot) - \widehat{\mathbf{v}}_t'\boldsymbol{\xi} - \mathbf{z}_t'\boldsymbol{\delta})^2,$$

so that Lemma A.1 implies that $\tilde{\beta}_T(\cdot) = \hat{\xi}_T(\cdot)$ and $\tilde{\gamma}_T(\cdot) = \hat{\delta}_T(\cdot) - \hat{\phi}_T \hat{\xi}_T(\cdot)$. Therefore,

$$\begin{aligned} \sum_{t=1}^T \left(y_t(\cdot) - \hat{v}_t' \hat{\xi}_T(\cdot) - z_t' \hat{\delta}_T(\cdot) \right)^2 &= \sum_{t=1}^T \left(y_t(\cdot) - (\mathbf{x}_t - \hat{\phi}_T' z_t)' \hat{\xi}_T(\cdot) - z_t' \hat{\delta}_T(\cdot) \right)^2 \\ &= \sum_{t=1}^T \left(y_t(\cdot) - \mathbf{x}_t' \hat{\xi}_T(\cdot) - z_t' (\hat{\delta}_T(\cdot) - \hat{\phi}_T \hat{\xi}_T(\cdot)) \right)^2 = \sum_{t=1}^T \left(y_t(\cdot) - \mathbf{x}_t' \tilde{\beta}_T(\cdot) - z_t' \tilde{\gamma}_T(\cdot) \right)^2, \end{aligned}$$

implying that

$$\arg \min_{\alpha} \sum_{t=1}^T \left(y_t(\alpha) - \hat{v}_t' \hat{\xi}_T(\alpha) - z_t' \hat{\delta}_T(\alpha) \right)^2 = \arg \min_{\theta} \sum_{t=1}^T \left(y_t(\theta) - \mathbf{x}_t' \tilde{\beta}_T(\theta) - z_t' \tilde{\gamma}_T(\theta) \right)^2,$$

viz., $\hat{\alpha}_T = \hat{\theta}_T$. Thus, it follows that $\tilde{\beta}_T(\hat{\alpha}_T) = \hat{\xi}_T(\hat{\theta}_T)$ and $\tilde{\gamma}_T(\hat{\alpha}_T) = \hat{\delta}_T(\hat{\theta}_T) - \hat{\phi}_T \hat{\xi}_T(\hat{\theta}_T)$. That is, $\tilde{\beta}_T = \hat{\xi}_T$ and $\tilde{\gamma}_T = \hat{\delta}_T - \hat{\phi}_T \hat{\xi}_T$. This completes the proof. \blacksquare

The following lemma shows that \tilde{v}_T and $\tilde{\omega}_T$ defined in Section 3 suffer from an asymptotically singular matrix problem.

Lemma A.3. *Given Assumption 1,*

- (i) $T^{-1} \sum_{t=1}^T \tilde{u}_{t-1}^2 \xrightarrow{\mathbb{P}} \sigma_u^2 := \mathbb{E}[u_t^2]$;
- (ii) $T^{-1/2} \left(\sum_{t=1}^T \tilde{u}_{t-1} \mathbf{r}_{t-1} \right) \tilde{\mathbf{D}}_1^{-1} \Rightarrow \tilde{\mathbf{M}}_{1u} := \mathbf{0}_{1 \times (2k+2)}$, where $\tilde{\mathbf{D}}_1 := \text{diag}[T^{3/2} \mathbf{I}_{2k}, T^{3/2}, T^{1/2}]$;
- (iii)

$$\tilde{\mathbf{D}}_1^{-1} \left(\sum_{t=1}^T \mathbf{r}_{t-1} \mathbf{r}_{t-1}' \right) \tilde{\mathbf{D}}_1^{-1} \Rightarrow \tilde{\mathcal{M}}_{11} := \begin{bmatrix} \frac{1}{3} \boldsymbol{\mu}_* \boldsymbol{\mu}_*' & \frac{1}{3} \boldsymbol{\mu}_* & \frac{1}{2} \boldsymbol{\mu}_* \\ \frac{1}{3} \boldsymbol{\mu}_*' & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{2} \boldsymbol{\mu}_*' & \frac{1}{2} & 1 \end{bmatrix},$$

which is singular;

- (iv) $T^{-1/2} \left(\sum_{t=1}^T \tilde{u}_{t-1} \mathbf{z}_{2t} \right) \tilde{\mathbf{D}}_2^{-1} \xrightarrow{\mathbb{P}} \tilde{\mathbf{M}}_{2u} := \mathbb{E}[u_{t-1} \mathbf{z}_{2t}]$, where $\tilde{\mathbf{D}}_2 := \text{diag}[T^{1/2} \mathbf{I}_{p+2kq-1}]$;

(v)

$$\tilde{\mathbf{D}}_2^{-1} \left(\sum_{t=1}^T \mathbf{z}_{2t} \mathbf{r}_{t-1}' \right) \tilde{\mathbf{D}}_1^{-1} \Rightarrow \tilde{\mathcal{M}}_{21} := \begin{bmatrix} \frac{1}{2} \delta_* \boldsymbol{\nu}_{p-1} \boldsymbol{\mu}_*' & \frac{1}{2} \delta_* \boldsymbol{\nu}_{p-1} & \delta_* \boldsymbol{\nu}_{p-1} \\ \frac{1}{2} \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* \boldsymbol{\mu}_*' & \frac{1}{2} \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* & \boldsymbol{\nu}_q \otimes \boldsymbol{\mu}_* \end{bmatrix};$$

- (vi) $\tilde{\mathbf{D}}_2^{-1} \left(\sum_{t=1}^T \mathbf{z}_{2t} \mathbf{z}_{2t}' \right) \tilde{\mathbf{D}}_2^{-1} \xrightarrow{\mathbb{P}} \tilde{\mathbf{M}}_{22} := \mathbf{M}_{22}$; and

- (vii) if we let $\tilde{\mathbf{D}} := \text{diag}[T^{1/2}, \tilde{\mathbf{D}}_1, \tilde{\mathbf{D}}_2]$, $\tilde{\mathbf{D}}^{-1} \left(\sum_{t=1}^T \tilde{\mathbf{z}}_t \tilde{\mathbf{z}}_t' \right) \tilde{\mathbf{D}}^{-1} \Rightarrow \tilde{\mathcal{M}}$, where

$$\tilde{\mathbf{D}}^{-1} \left(\sum_{t=1}^T \tilde{\mathbf{z}}_t \tilde{\mathbf{z}}_t' \right) \tilde{\mathbf{D}}^{-1} \Rightarrow \tilde{\mathcal{M}} := \begin{bmatrix} \sigma_u^2 & \tilde{\mathbf{M}}_{u1} & \tilde{\mathbf{M}}_{u2} \\ \tilde{\mathbf{M}}_{1u} & \tilde{\mathcal{M}}_{11} & \tilde{\mathcal{M}}_{12} \\ \tilde{\mathbf{M}}_{2u} & \tilde{\mathcal{M}}_{21} & \tilde{\mathbf{M}}_{22} \end{bmatrix},$$

which is singular, where $\widetilde{\mathbf{D}} := \text{diag}[T^{1/2}, \widetilde{\mathbf{D}}_1, \widetilde{\mathbf{D}}_2]$, $\widetilde{\mathcal{M}}_{12} := \widetilde{\mathcal{M}}'_{21}$, $\widetilde{\mathbf{M}}_{u1} := \widetilde{\mathbf{M}}'_{1u}$, and $\widetilde{\mathbf{M}}_{u2} := \widetilde{\mathbf{M}}'_{2u}$. \square

Both $\widetilde{\mathbf{v}}_T$ and $\widetilde{\boldsymbol{\omega}}_T$ suffer from the asymptotically singular matrix problem by Lemma A.3 (iii and vii). Specifically, every column from the second to $(1+k)$ -th columns of $\widetilde{\mathcal{M}}$ is proportional to the $(2+2k)$ -th column. Likewise, every column from the first to k -th columns in $\widetilde{\mathcal{M}}_{11}$ is proportional to the $(1+2k)$ -th column of $\widetilde{\mathcal{M}}_{11}$.

We now prove Lemma A.3.

Proof of Lemma A.3. (i) This follows from Lemma B.6 (iv) given in Section A.2.

(ii) This follows from Lemmas B.3 (v), B.4 (v), and B.5 (iv) given in Section A.2.

(iii) This follows from Lemmas B.3 (i, ii), B.4 (i, ii), and B.5 (i) given in Section A.2.

(iv) This follows from Lemma B.2 (vii) given in Section A.2.

(v) This follows from Lemma B.2 (ii, iii, and iv) given in Section A.2.

(vi) This follows from Lemma B.2 (i) given in Section A.2.

(vii) The given weak convergence follows from Lemma A.3 (i, ii, iii, iv, v, and vi) given in Section A.2, and the singularity follows from the structure of $\widetilde{\mathcal{M}}$. \blacksquare

A.2 Preliminary Lemmas

We next provide preliminary lemmas to prove the main claims efficiently.

Lemma B.1. Given Assumption 1, $\mathbf{B}_T(\cdot) := T^{-1/2} \sum_{t=1}^{[\cdot]T} \mathbf{w}_t \Rightarrow \mathcal{B}(\cdot)$. \square

Lemma B.2. Given Assumption 1,

- (i) $T^{-1} \sum_{t=1}^T \mathbf{z}_{2t} \mathbf{z}'_{2t} \xrightarrow{\mathbb{P}} \mathbb{E}[\mathbf{z}_{2t} \mathbf{z}'_{2t}]$;
- (ii) $T^{-1} \sum_{t=1}^T \mathbf{z}_{2t} \xrightarrow{\mathbb{P}} [\delta_* \boldsymbol{\nu}'_{p-1}, \boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_*]'$;
- (iii) $T^{-2} \sum_{t=1}^T (t-1) \mathbf{z}_{2t} \xrightarrow{\mathbb{P}} [\frac{1}{2} \delta_* \boldsymbol{\nu}'_{p-1}, \frac{1}{2} \boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_*]'$;
- (iv) $T^{-3} \sum_{t=1}^T \ddot{\mathbf{x}}_{t-1} \mathbf{z}'_{2t} \xrightarrow{\mathbb{P}} [\frac{1}{2} \delta_* \boldsymbol{\mu}_* \boldsymbol{\nu}'_{p-1}, \frac{1}{2} \boldsymbol{\mu}_* \boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_*]'$;
- (v) $T^{-3/2} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \mathbf{z}'_{2t} \Rightarrow [\delta_* \int \widetilde{\mathcal{B}}_s \boldsymbol{\nu}'_{p-1}, \int \widetilde{\mathcal{B}}_s \boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_*]'$;
- (vi) $T^{-2} \sum_{t=1}^T y_{t-1} \mathbf{z}'_{2t} \xrightarrow{\mathbb{P}} [\frac{1}{2} \delta_*^2 \boldsymbol{\nu}'_{p-1}, \frac{1}{2} \delta_* \boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_*]'$;
- (vii) $T^{-1} \sum_{t=1}^T \ddot{u}_{t-1} \mathbf{z}_{2t} \xrightarrow{\mathbb{P}} \mathbb{E}[u_{t-1} \mathbf{z}_{2t}]$. \square

Lemma B.3. Given Assumption 1,

- (i) $T^{-2} \sum_{t=1}^T t \rightarrow \frac{1}{2}$;
- (ii) $T^{-2} \sum_{t=1}^T \ddot{\mathbf{x}}_t \xrightarrow{\mathbb{P}} \frac{1}{2} \boldsymbol{\mu}_*$;
- (iii) $T^{-3/2} \sum_{t=1}^T \ddot{\mathbf{m}}_t \Rightarrow \int \widetilde{\mathcal{B}}_s$;
- (iv) $T^{-2} \sum_{t=1}^T y_t \xrightarrow{\mathbb{P}} \frac{1}{2} \delta_*$;

$$(v) \sum_{t=1}^T \ddot{u}_{t-1} \equiv 0. \quad \square$$

Lemma B.4. *Given Assumption 1,*

$$\begin{aligned} (i) \quad T^{-3} \sum_{t=1}^T t^2 &\rightarrow \frac{1}{3}; & (iv) \quad T^{-3} \sum_{t=1}^T ty_t &\xrightarrow{\mathbb{P}} \frac{1}{3} \delta_*; \\ (ii) \quad T^{-3} \sum_{t=1}^T t \ddot{x}_t &\xrightarrow{\mathbb{P}} \frac{1}{3} \boldsymbol{\mu}_*; & (v) \quad \sum_{t=1}^T (t-1) \ddot{u}_{t-1} &\equiv 0. \quad \square \\ (iii) \quad \sum_{t=1}^T (t-1) \ddot{\mathbf{m}}_{t-1} &\equiv \mathbf{0}; \end{aligned}$$

Lemma B.5. *Given Assumption 1,*

$$\begin{aligned} (i) \quad T^{-3} \sum_{t=1}^T \ddot{x}_t \ddot{x}'_t &\xrightarrow{\mathbb{P}} \frac{1}{3} \boldsymbol{\mu}_* \boldsymbol{\mu}'_*; & (iii) \quad T^{-3} \sum_{t=1}^T \ddot{x}_t y_t &\xrightarrow{\mathbb{P}} \frac{1}{3} \delta_* \boldsymbol{\mu}_*; \\ (ii) \quad T^{-2} \sum_{t=1}^T \ddot{x}_{t-1} \ddot{\mathbf{m}}'_{t-1} &\Rightarrow \int \mathcal{B}_s \bar{\mathcal{B}}'_s; & (iv) \quad \sum_{t=1}^T \ddot{x}_{t-1} \ddot{u}_{t-1} &\equiv \mathbf{0}. \quad \square \end{aligned}$$

Remark. $\int \mathcal{B}_s \bar{\mathcal{B}}'_s = \int \bar{\mathcal{B}}_s \bar{\mathcal{B}}'_s = \int \mathcal{B}_s \mathcal{B}'_s - 3 \int r \mathcal{B}_s \int r \mathcal{B}'_s$ from the definition of $\bar{\mathcal{B}}_s(v) := \mathcal{B}_s(v) - 3v \int r \mathcal{B}_s$. □

Lemma B.6. *Given Assumption 1,*

$$\begin{aligned} (i) \quad T^{-2} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \ddot{\mathbf{m}}'_{t-1} &\Rightarrow \int \mathcal{B}_s \bar{\mathcal{B}}'_s; & (iii) \quad T^{-3} \sum_{t=1}^T y_t^2 &\xrightarrow{\mathbb{P}} \frac{1}{3} \delta_*^2; \\ (ii) \quad \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \tilde{u}_{t-1} &\equiv \mathbf{0}; & (iv) \quad \hat{\sigma}_{u,T}^2 &:= T^{-1} \sum_{t=1}^T \tilde{u}_t^2 \xrightarrow{\mathbb{P}} \sigma_u^2 := \mathbb{E}[u_t^2]. \quad \square \end{aligned}$$

Lemma B.7. *Let $\boldsymbol{\varrho}_{m*} := \lim_{T \rightarrow \infty} T^{-1} \sum_{t=1}^T \sum_{\tau=1}^{t-1} \mathbb{E}[s_\tau u_t]$. Given Assumption 1,*

$$\begin{aligned} (i) \quad \sqrt{T}(\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) &\Rightarrow 3 \int r \mathcal{B}_s; & (iv) \quad T^{-1} \sum_{t=1}^T \mathbf{m}_{t-1} e_t &\Rightarrow \int \mathcal{B}_s d\mathcal{B}_e; \\ (ii) \quad \text{for every } t, \mathbf{r}'_t \tilde{\mathbf{v}}_T &= \ddot{\mathbf{r}}'_t \ddot{\mathbf{v}}_T; & (v) \quad \hat{\sigma}_{e,T}^2 &\xrightarrow{\mathbb{P}} \sigma_e^2 := \mathbb{E}[e_t^2]. \quad \square \\ (iii) \quad T^{-1} \sum_{t=1}^T \mathbf{m}_{t-1} u_t &\Rightarrow \int \mathcal{B}_s d\mathcal{B}_u + \boldsymbol{\varrho}_{m*}; \end{aligned}$$

We now prove the preliminary Lemmas B.1 to B.7.

Proof of Lemma B.1. This trivially follows theorem 7.30 of [White \(2001\)](#). ■

Proof of Lemma B.2. (i) It holds by the ergodic theorem.

(ii) It holds by the ergodic theorem and the fact that $\mathbb{E}[z_{2t}] = [\delta_* \boldsymbol{\nu}'_{p-1}, \boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_*]'$ because $\delta_* \boldsymbol{\nu}_{p-1} = \mathbb{E}[\Delta \mathbf{y}_{t-}], \boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_* = \mathbb{E}[(\Delta \mathbf{x}_t^+, \dots, \Delta \mathbf{x}_{t-q+1}^+)]$, and $\boldsymbol{\nu}'_q \otimes \boldsymbol{\mu}'_* = \mathbb{E}[(\Delta \mathbf{x}_t^-, \dots, \Delta \mathbf{x}_{t-q+1}^-)]$.

(iii) We note that $T^{-2} \sum_{t=1}^T (t-1) z_{2t} = T^{-1} \sum_{t=1}^T ((t-1)/T) z_{2t}$, and we let $\mathbf{q}_t := ((t-1)/T) z_{2t}$ for notational simplicity, which is a heterogeneous process. Therefore, $T^{-1} \sum_{t=1}^T (\mathbf{q}_t - \mathbb{E}[\mathbf{q}_t]) \xrightarrow{\mathbb{P}} \mathbf{0}$. In

addition, $T^{-1} \sum_{t=1}^T \mathbb{E}[\mathbf{q}_t] = T^{-2} \sum_{t=1}^T (t-1) \mathbb{E}[\mathbf{z}_{2t}] \rightarrow \frac{1}{2} \mathbb{E}[\mathbf{z}_{2t}]$, implying that $T^{-1} \sum_{t=1}^T \mathbf{q}_t \xrightarrow{\mathbb{P}} \frac{1}{2} \mathbb{E}[\mathbf{z}_{2t}]$ by White (2001, theorem 3.47), given the DGP condition in Assumption 1. We further note that $\mathbb{E}[\mathbf{z}_{2t}] = [\delta_* \mathbf{l}'_{p-1}, \mathbf{l}'_q \otimes \boldsymbol{\mu}'_*]'$, leading to the desired result.

(iv) We first note that $\ddot{\mathbf{x}}_{t-1} = \boldsymbol{\mu}_*(t-1) + \mathbf{m}_{t-1}$. Therefore, $\sum_{t=1}^T \ddot{\mathbf{x}}_{t-1} \mathbf{z}'_{2t} = \sum_{t=1}^T \boldsymbol{\mu}_*(t-1) \mathbf{z}'_{2t} + \sum_{t=1}^T \mathbf{m}_{t-1} \mathbf{z}'_{2t}$. The proof of Lemma B.2 (iii) already shows that $T^{-2} \sum_{t=1}^T (t-1) \mathbf{z}_{2t} \xrightarrow{\mathbb{P}} \frac{1}{2} \mathbb{E}[\mathbf{z}_{2t}]$. Furthermore, $\sum_{t=1}^T \mathbf{m}_{t-1} \mathbf{z}'_{2t} = O_{\mathbb{P}}(T^{3/2})$ as shown in the proof of Lemma B.2 (v). Therefore, it follows that $T^{-2} \sum_{t=1}^T \ddot{\mathbf{x}}_{t-1} \mathbf{z}'_{2t} \xrightarrow{\mathbb{P}} \frac{1}{2} \boldsymbol{\mu}_* \mathbb{E}[\mathbf{z}'_{2t}]$, as desired.

(v) Note that $\ddot{\mathbf{m}}_{t-1} = \mathbf{m}_{t-1} - (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*)(t-1)$. Therefore, $\sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \mathbf{z}'_{2t} = \sum_{t=1}^T \mathbf{m}_{t-1} \mathbf{z}'_{2t} - (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) \sum_{t=1}^T (t-1) \mathbf{z}'_{2t}$. We here note that $\sum_{t=1}^T \mathbf{m}_{t-1} \mathbf{z}'_{2t} = \sum_{t=1}^T \mathbf{m}_{t-1} \mathbb{E}[\mathbf{z}'_{2t}] + \sum_{t=1}^T \mathbf{m}_{t-1} (\mathbf{z}'_{2t} - \mathbb{E}[\mathbf{z}'_{2t}])$. The proof of Lemma A.3 (iv) implies that $T^{-3/2} \sum_{t=1}^T \mathbf{m}_{t-1} \Rightarrow \int \mathcal{B}_s$, and $\sum_{t=1}^T \mathbf{m}_{t-1} (\mathbf{z}'_{2t} - \mathbb{E}[\mathbf{z}'_{2t}]) = o_{\mathbb{P}}(T^{3/2})$ by noting that $\mathbf{m}_{t-1} = O_{\mathbb{P}}(T^{1/2})$ and $\sum_{t=1}^T (\mathbf{z}'_{2t} - \mathbb{E}[\mathbf{z}'_{2t}]) = O_{\mathbb{P}}(T^{1/2})$. Therefore, $T^{-3/2} \sum_{t=1}^T \mathbf{m}_{t-1} \mathbf{z}'_{2t} \Rightarrow \int \mathcal{B}_s \mathbb{E}[\mathbf{z}'_{2t}]$. Next, $T^{-3/2} (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) \sum_{t=1}^T (t-1) \mathbf{z}'_{2t} = \sqrt{T} (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) T^{-2} \sum_{t=1}^T (t-1) \mathbf{z}'_{2t}$, and Lemma B.7 (i) implies that $\sqrt{T} (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) \Rightarrow 3 \int r \mathcal{B}_s$. In addition to this, Lemma B.2 (iii) shows that $T^{-2} \sum_{t=1}^T (t-1) \mathbf{z}'_{2t} \xrightarrow{\mathbb{P}} \frac{1}{2} \mathbb{E}[\mathbf{z}'_{2t}]$. Therefore, $T^{-3/2} (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) \sum_{t=1}^T (t-1) \mathbf{z}'_{2t} \Rightarrow \frac{3}{2} \int r \mathcal{B}_s \mathbb{E}[\mathbf{z}'_{2t}]$. Hence, if we combine all these, $T^{-3/2} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \mathbf{z}'_{2t} \Rightarrow (\int \mathcal{B}_s - \frac{3}{2} \int r \mathcal{B}_s) \mathbb{E}[\mathbf{z}'_{2t}] = \int \widetilde{\mathcal{B}}_s \mathbb{E}[\mathbf{z}'_{2t}]$.

(vi) Note that $y_{t-1} = \delta_*(t-1) + \sum_{j=1}^{t-1} d_j$. Therefore, $\sum_{t=1}^T y_{t-1} \mathbf{z}'_{2t} = \sum_{t=1}^T \delta_*(t-1) \mathbf{z}'_{2t} + \sum_{t=1}^T (\sum_{j=1}^{t-1} d_j) \mathbf{z}'_{2t}$. The proof of Lemma B.2 (iii) already showed that $T^{-2} \sum_{t=1}^T (t-1) \mathbf{z}_{2t} \xrightarrow{\mathbb{P}} \frac{1}{2} \mathbb{E}[\mathbf{z}_{2t}]$. Furthermore, we note that $\sum_{t=1}^T (\sum_{j=1}^{t-1} d_j) \mathbf{z}'_{2t} = O_{\mathbb{P}}(T^{3/2})$. Therefore, $T^{-2} \sum_{t=1}^T y_{t-1} \mathbf{z}'_{2t} \xrightarrow{\mathbb{P}} \frac{1}{2} \delta_* \mathbb{E}[\mathbf{z}_{2t}]$, as desired.

(vii) In the proof of Lemma B.6 (iv), we show that $\ddot{u}_t = u_t + O_{\mathbb{P}}(T^{-1/2})$. Therefore, it follows that $T^{-1} \sum_{t=1}^T \ddot{u}_{t-1} \mathbf{z}_{2t} = T^{-1} \sum_{t=1}^T u_{t-1} \mathbf{z}_{2t} + o_{\mathbb{P}}(1) \xrightarrow{\mathbb{P}} \mathbb{E}[u_{t-1} \mathbf{z}_{2t}]$ by the ergodic theorem. This completes the proof. \blacksquare

Proof of Lemma B.3. (i) $\sum_{t=1}^T t = T(T+1)/2$, leading to the desired result.

(ii) Note that $\ddot{\mathbf{x}}_t = \boldsymbol{\mu}_* t + \mathbf{m}_t$, so that $\sum_{t=1}^T \ddot{\mathbf{x}}_t = \boldsymbol{\mu}_* \sum_{t=1}^T t + \sum_{t=1}^T \mathbf{m}_t$. Here, $T^{-2} \sum_{t=1}^T t \rightarrow \frac{1}{2}$ by Lemma B.3 (i), and Lemma B.1 implies that $T^{-3/2} \sum_{t=1}^T \mathbf{m}_t = T^{-1} \sum_{t=1}^T \frac{1}{\sqrt{T}} \mathbf{m}_t = \int \mathbf{B}_s(r) dr \Rightarrow \int \mathcal{B}_s$. Therefore, $T^{-3/2} \sum_{t=1}^T \ddot{\mathbf{x}}_t = \boldsymbol{\mu}_* T^{-3/2} \sum_{t=1}^T t + o_{\mathbb{P}}(1) \xrightarrow{\mathbb{P}} \frac{1}{2} \boldsymbol{\mu}_*$.

(iii) Note that $\ddot{\mathbf{m}}_t = \mathbf{m}_t - (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*)t$. Thus, $T^{-3/2} \sum_{t=1}^T \ddot{\mathbf{m}}_t = T^{-3/2} \sum_{t=1}^T \mathbf{m}_t - \sqrt{T} (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) T^{-2} \sum_{t=1}^T t$. Lemma B.7 (i) implies that $\sqrt{T} (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) \Rightarrow 3 \int r \mathcal{B}_s$. Lemma B.3 (i) implies that $T^{-2} \sum_{t=1}^T t \rightarrow \frac{1}{2}$. In addition to these, $T^{-3/2} \sum_{t=1}^T \mathbf{m}_t = T^{-1} \sum_{t=1}^T \frac{1}{\sqrt{T}} \mathbf{m}_t = \int \mathbf{B}_s(r) dr \Rightarrow \int \mathcal{B}_s$ by Lemma B.1. Thus, $T^{-3/2} \sum_{t=1}^T \ddot{\mathbf{m}}_t \Rightarrow \int \mathcal{B}_s(r) - 3 \int r dr \int v \mathcal{B}_s(v) dv = \int \widetilde{\mathcal{B}}_s$ by the definition of $\widetilde{\mathcal{B}}_s(\cdot)$, viz., $\widetilde{\mathcal{B}}_s(\cdot) := \mathcal{B}_s(\cdot) - \frac{3}{2}(\cdot) \int v \mathcal{B}_s(v) dv$.

(iv) From (5), $T^{-2} \sum_{t=1}^T y_t = \delta_* T^{-2} \sum_{t=1}^T t + T^{-2} \sum_{t=1}^T \sum_{j=1}^t d_j = \frac{1}{2} \delta_* + o_{\mathbb{P}}(1)$.

(v) We note that $\ddot{u}_{t-1} = \tilde{u}_{t-1} := y_{t-1} - r'_{t-1}\tilde{v}_T$, so that $\sum_{t=1}^T \ddot{u}_{t-1}r_{t-1} \equiv \mathbf{0}$. We here note that $r_{t-1} := [\tilde{x}'_{t-1}, (t-1), 1]'$. This completes the proof. \blacksquare

Proof of Lemma B.4. (i) $\sum_{t=1}^T t^2 = T(T+1)(2T+1)/6$, leading to the desired result.

(ii) $T^{-3} \sum_{t=1}^T t\ddot{x}_t = \mu_* T^{-3} \sum_{t=1}^T t^2 + T^{-3} \sum_{t=1}^T t\mathbf{m}_t$. Here, it follows that $T^{-3} \sum_{t=1}^T t^2 \rightarrow \frac{1}{3}$ and $T^{-5/2} \sum_{t=1}^T t\mathbf{m}_t = T^{-1} \sum_{t=1}^T \binom{t}{T} \frac{1}{\sqrt{T}} \mathbf{m}_t = \int r \mathbf{B}_{sT}(r) dr \Rightarrow \int r \mathcal{B}_s$. Therefore, $T^{-3} \sum_{t=1}^T t\ddot{x}_t = \frac{1}{3}\mu_* + o_{\mathbb{P}}(1)$.

(iii) Note that $\ddot{\mathbf{m}}_t = \ddot{x}_t - t\ddot{\mu}_T$ and $\ddot{\mu}_T = (\sum_{t=1}^{T-1} t^2)^{-1} \sum_{t=1}^{T-1} t\ddot{x}_t$. Therefore, $\sum_{t=1}^T (t-1)\ddot{\mathbf{m}}_{t-1} \equiv \mathbf{0}$.

(iv) From (5), $T^{-3} \sum_{t=1}^T ty_t = \delta_* T^{-3} \sum_{t=1}^T t^2 + T^{-3} \sum_{t=1}^T t \sum_{j=1}^t d_j = \frac{1}{3}\delta_* + o_{\mathbb{P}}(1)$.

(v) The proof of Lemma B.3 (v) already shows the given claim. \blacksquare

Proof of Lemma B.5. (i) Using the fact that $\ddot{x}_t = \mu_* t + \mathbf{m}_t$, $\sum_{t=1}^T \ddot{x}_t \ddot{x}'_t = \sum_{t=1}^T (\mu_* t + \mathbf{m}_t)(\mu_* t + \mathbf{m}_t)' = \sum_{t=1}^T \mu_* \mu_*' t^2 + \sum_{t=1}^T \mu_* \mathbf{m}_t' t + \sum_{t=1}^T \mathbf{m}_t \mu_*' t + \sum_{t=1}^T \mathbf{m}_t \mathbf{m}_t'$. Here, $T^{-3} \sum_{t=1}^T \mu_* \mu_*' t^2 \rightarrow \frac{1}{3}\mu_* \mu_*'$ by Lemma B.4 (i), and $T^{-5/2} \sum_{t=1}^T \mu_* \mathbf{m}_t' t \Rightarrow \mu_* \int r \mathcal{B}_s$ as shown in the proof of Lemma B.4 (ii). Furthermore, $T^{-2} \sum_{t=1}^T \mathbf{m}_t \mathbf{m}_t' = T^{-1} \sum_{t=1}^T \frac{1}{\sqrt{T}} \mathbf{m}_t \frac{1}{\sqrt{T}} \mathbf{m}_t' = \int \mathbf{B}_{sT}(r) \mathbf{B}_{sT}(r)' dr \Rightarrow \int \mathcal{B}_s \mathcal{B}_s'$. Thus, $T^{-3} \sum_{t=1}^T \ddot{x}_t \ddot{x}'_t \xrightarrow{\mathbb{P}} \frac{1}{3}\mu_* \mu_*'$.

(ii) We first note that $\sum_{t=1}^T \ddot{x}_{t-1} \ddot{\mathbf{m}}'_{t-1} = \sum_{t=1}^T (\mu_* (t-1) + \mathbf{m}_{t-1}) \ddot{\mathbf{m}}'_{t-1} = \mu_* \sum_{t=1}^T (t-1) \ddot{\mathbf{m}}'_{t-1} + \sum_{t=1}^T \mathbf{m}_{t-1} \ddot{\mathbf{m}}'_{t-1} = \sum_{t=1}^T \mathbf{m}_{t-1} \ddot{\mathbf{m}}'_{t-1}$ by Lemma B.4 (iii). We further note that $\sum_{t=1}^T \mathbf{m}_{t-1} \ddot{\mathbf{m}}'_{t-1} = \sum_{t=1}^T \mathbf{m}_{t-1} (\mathbf{m}_{t-1} - (\ddot{\mu}_T - \mu_*) (t-1))'$ using the fact that $\ddot{\mathbf{m}}_t = \mathbf{m}_t - (\ddot{\mu}_T - \mu_*) t$. Here, we note that $T^{-2} \sum_{t=1}^T \mathbf{m}_t \mathbf{m}_t' \Rightarrow \int \mathcal{B}_s \mathcal{B}_s'$ as shown in the proof of Lemma B.5 (i), and $T^{-2} \sum_{t=1}^T t \mathbf{m}_t (\ddot{\mu}_T - \mu_*)' = T^{-5/2} \sum_{t=1}^T t \mathbf{m}_t \sqrt{T} (\ddot{\mu}_T - \mu_*)' \Rightarrow 3 \int r \mathcal{B}_s \int r \mathcal{B}_s$ by Lemma B.7 (ii) and the fact that $T^{-5/2} \sum_{t=1}^T t \mathbf{m}_t = T^{-1} \sum_{t=1}^T \frac{t}{T} \frac{1}{\sqrt{T}} \mathbf{m}_t = \int r \mathbf{B}_s(r) dr \Rightarrow \int r \mathcal{B}_s$ as shown in the proof of Lemma B.4 (ii). Therefore, $T^{-2} \sum_{t=1}^T \ddot{x}_{t-1} \ddot{\mathbf{m}}'_{t-1} \Rightarrow \int \mathcal{B}_s (\mathcal{B}_s - 3r \int s \mathcal{B}_s)' = \int \mathcal{B}_s \bar{\mathcal{B}}_s'$. We further note that $\int \mathcal{B}_s \bar{\mathcal{B}}_s' = \int \bar{\mathcal{B}}_s \bar{\mathcal{B}}_s'$ by the definition of $\bar{\mathcal{B}}_s$ and the fact that $\int r^2 = \frac{1}{3}$.

(iii) Using the fact that $\ddot{x}_t = \mu_* t + \mathbf{m}_t$ and $y_t = \delta_* t + \sum_{j=1}^t d_j$, $\sum_{t=1}^T \ddot{x}_t y_t = \mu_* \delta_* \sum_{t=1}^T t^2 + \delta_* \sum_{t=1}^T t \mathbf{m}_t + \mu_* \sum_{t=1}^T t \sum_{j=1}^t d_j + \sum_{t=1}^T \mathbf{m}_t \sum_{j=1}^t d_j$. Here, $T^{-3} \sum_{t=1}^T t^2 \rightarrow \frac{1}{3}$ by Lemma B.4 (i), and $T^{-5/2} \sum_{t=1}^T t \mathbf{m}_t \Rightarrow \int r \mathcal{B}_s$ as shown in the proof of Lemma B.4 (ii). Furthermore, we note that $\sum_{t=1}^T t \sum_{j=1}^t d_j = O_{\mathbb{P}}(T^{5/2})$ and $\sum_{t=1}^T \mathbf{m}_t \sum_{j=1}^t d_j = O_{\mathbb{P}}(T^2)$. Therefore, $T^{-3} \sum_{t=1}^T \ddot{x}_t y_t \xrightarrow{\mathbb{P}} \frac{1}{3}\delta_* \mu_*$.

(iv) The proof of Lemma B.3 (v) already shows the given claim. \blacksquare

Proof of Lemma B.6. (i) We first note that $\sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \ddot{\mathbf{m}}'_{t-1} = \sum_{t=1}^T (\mathbf{m}_{t-1} - (\ddot{\mu}_T - \mu_*) (t-1)) \ddot{\mathbf{m}}'_{t-1} = \sum_{t=1}^T \mathbf{m}_{t-1} \ddot{\mathbf{m}}'_{t-1} - (\ddot{\mu}_T - \mu_*) \sum_{t=1}^T (t-1) \ddot{\mathbf{m}}'_{t-1} = \sum_{t=1}^T \mathbf{m}_{t-1} \ddot{\mathbf{m}}'_{t-1}$ by Lemma B.4 (iii). We next note that $\sum_{t=1}^T \mathbf{m}_{t-1} \ddot{\mathbf{m}}'_{t-1} = \sum_{t=1}^T \mathbf{m}_{t-1} (\mathbf{m}_{t-1} - (\ddot{\mu}_T - \mu_*) (t-1))'$ using the fact that $\ddot{\mathbf{m}}_t = \mathbf{m}_t - (\ddot{\mu}_T - \mu_*) t$. Here, $T^{-2} \sum_{t=1}^T \mathbf{m}_t \mathbf{m}_t' \Rightarrow \int \mathcal{B}_s \mathcal{B}_s'$ as shown in the proof of Lemma B.5 (i), and $T^{-2} \sum_{t=1}^T t \mathbf{m}_t (\ddot{\mu}_T -$

$\mu_*') \Rightarrow 3 \int r \mathcal{B}_s \int r \mathcal{B}_s$ as shown in the proof of Lemma B.5 (ii). Therefore, $T^{-2} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \dot{\mathbf{m}}'_{t-1} \Rightarrow \int \mathcal{B}_s (\mathcal{B}_s - 3r \int s \mathcal{B}_s)' = \int \mathcal{B}_s \bar{\mathcal{B}}'_s$.

(ii) As Lemma B.7 (iii) shows, for each t , $\mathbf{r}'_t \tilde{\mathbf{v}}_T = \dot{\mathbf{r}}'_t \ddot{\mathbf{v}}_T$, so that $\tilde{u}_t := y_t - \mathbf{r}'_t \tilde{\mathbf{v}}_T = \ddot{u}_{t-1} := y_t - \dot{\mathbf{r}}'_t \ddot{\mathbf{v}}_T$. We further note that $\ddot{\mathbf{v}}_T := (\sum_{t=1}^T \dot{\mathbf{r}}_{t-1} \dot{\mathbf{r}}'_{t-1})^{-1} \sum_{t=1}^T \dot{\mathbf{r}}_{t-1} y_{t-1}$, so that $\sum_{t=1}^T \dot{\mathbf{r}}_{t-1} \tilde{u}_{t-1} = \mathbf{0}$. We now note that $\dot{\mathbf{r}}_{t-1} := [\dot{\mathbf{m}}'_{t-1}, (t-1), 1]'$, leading to that $\sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} \tilde{u}_{t-1} = \mathbf{0}$.

(iii) From (5), $y_t = \delta_* t + \sum_{j=1}^t d_j$. We here note that $\sum_{t=1}^T y_t^2 = \sum_{t=1}^T (\delta_* t + \sum_{j=1}^t d_j)^2 = \sum_{t=1}^T \delta_*^2 t^2 + 2 \sum_{t=1}^T \delta_* t \sum_{j=1}^t d_j + \sum_{t=1}^T (\sum_{j=1}^t d_j)^2$. Furthermore, $T^{-3} \sum_{t=1}^T t^2 \rightarrow \frac{1}{3}$ by Lemma B.4 (i), $\sum_{t=1}^T \delta_* t \sum_{j=1}^t d_j = O_{\mathbb{P}}(T^{5/2})$, and $\sum_{t=1}^T (\sum_{j=1}^t d_j)^2 = O_{\mathbb{P}}(T^2)$, implying that $T^{-3} \sum_{t=1}^T y_t^2 \xrightarrow{\mathbb{P}} \frac{1}{3} \delta_*^2$.

(iv) Note that $\tilde{u}_t := y_t - \mathbf{r}'_t \tilde{\mathbf{v}}_T$, and $\mathbf{r}'_t \tilde{\mathbf{v}}_T = \ddot{\mathbf{x}}'_t \tilde{\mathbf{v}}_T + t \tilde{\zeta}_T + \tilde{\nu}_T$ with $\ddot{\mathbf{x}}_t = \ddot{\mathbf{m}}_t + \ddot{\mu}_T t$. Furthermore, $y_t = \beta'_* (\ddot{\mathbf{m}}_t + \ddot{\mu}_T t) + \zeta_* t + \nu_* + u_t$ using (6). Hence, $\tilde{u}_t = u_t - (\beta_T - \beta_*)' \ddot{\mathbf{m}}_t - (\vartheta_T - \vartheta_{T*}) t - (\ddot{\nu}_T - \nu_*)$. We now note that Lemma 3, $\ddot{\mathbf{m}}_t = O_{\mathbb{P}}(T^{1/2})$, and $t = O(T)$ imply that $\tilde{u}_t = u_t + O_{\mathbb{P}}(T^{-1/2})$. Therefore, $T^{-1} \sum_{t=1}^T \tilde{u}_t^2 = T^{-1} \sum_{t=1}^T u_t^2 + o_{\mathbb{P}}(1)$, and $T^{-1} \sum_{t=1}^T u_t^2 \xrightarrow{\mathbb{P}} \mathbb{E}[u_t^2]$ by the ergodic theorem, implying that $T^{-1} \sum_{t=1}^T \tilde{u}_t^2 \xrightarrow{\mathbb{P}} \sigma_u^2 := \mathbb{E}[u_t^2]$. \blacksquare

Proof of Lemma B.7. (i) Note that $\ddot{\mu}_T = (\sum_{t=1}^{T-1} t^2)^{-1} \sum_{t=1}^{T-1} t \ddot{\mathbf{x}}_t$ and $\ddot{\mathbf{x}}_t = \mu_* t + \mathbf{m}_t$. Therefore, $\ddot{\mu}_T - \mu_* = (\sum_{t=1}^{T-1} t^2)^{-1} \sum_{t=1}^{T-1} t \mathbf{m}_t$, so that $\sqrt{T}(\ddot{\mu}_T - \mu_*) = (T^{-3} \sum_{t=1}^{T-1} t^2)^{-1} T^{-5/2} \sum_{t=1}^{T-1} t \mathbf{m}_t$. Lemma B.4 (i) implies that $T^{-3} \sum_{t=1}^{T-1} t^2 \rightarrow \frac{1}{3}$. Furthermore, $T^{-5/2} \sum_{t=1}^{T-1} t \mathbf{m}_t = T^{-1} \sum_{t=1}^{T-1} \frac{t}{\sqrt{T}} \mathbf{m}_t = \int r \mathbf{B}_{sT}(r) dr \Rightarrow \int r \mathcal{B}_s$. Hence, $\sqrt{T}(\ddot{\mu}_T - \mu_*) \Rightarrow 3 \int r \mathcal{B}_s$.

(ii) Note that $\mathbf{r}'_t \tilde{\mathbf{v}}_T = \ddot{\mathbf{x}}'_t \tilde{\mathbf{v}}_T + t \tilde{\zeta}_T + \tilde{\nu}_T$ with $\ddot{\mathbf{x}}_t = \ddot{\mathbf{m}}_t + \ddot{\mu}_T t$. Therefore, $\mathbf{r}'_t \tilde{\mathbf{v}}_T = \dot{\mathbf{m}}'_t \tilde{\mathbf{v}}_T + t(\dot{\mu}'_T \tilde{\mathbf{v}}_T + \tilde{\zeta}_T) + \tilde{\nu}_T = \dot{\mathbf{m}}'_t \ddot{\mathbf{v}}_T + t \ddot{\vartheta}_T + \ddot{\nu}_T = \dot{\mathbf{r}}'_t \ddot{\mathbf{v}}_T$, where the second last equality holds by Proposition 2, and the last equality follows from the definition of $\dot{\mathbf{r}}_t$.

(iii) Note that $T^{-1} \sum_{t=1}^T \mathbf{m}_{t-1} u_t = T^{-1} \sum_{t=1}^T T^{-1/2} \mathbf{m}_{t-1} \sqrt{T}(B_{uT}(t/T) - B_{uT}((t-1)/T)) = \int \mathbf{B}_{sT}(r) dB_{uT}(r)$. We here note that $\int \mathbf{B}_{sT}(r) dB_{uT}(r) \Rightarrow \int \mathcal{B}_s d\mathcal{B}_u + \varrho_{m*}$ by applying theorem 4 of de Jong and Davidson (2000).

(iv) We first note that $T^{-1} \sum_{t=1}^T \mathbf{m}_{t-1} e_t = T^{-1} \sum_{t=1}^T T^{-1/2} \mathbf{m}_{t-1} \sqrt{T}(B_{eT}(t/T) - B_{eT}((t-1)/T)) = \int \mathbf{B}_{sT}(r) dB_{eT}(r)$. Note that $\int \mathbf{B}_{sT}(r) dB_{eT}(r) \Rightarrow \int \mathcal{B}_s d\mathcal{B}_e$ by applying theorem 4 of de Jong and Davidson (2000) and noting that $\mathbb{E}[s_{\tau} e_t] = \mathbf{0}$ for each $\tau < t$.

(v) Note that if we let $\ddot{e}_t := \Delta y_t - \ddot{\mathbf{z}}_t \ddot{\tau}_T$, it follows that $\hat{\sigma}_{e,T}^2 = T^{-1} \sum_{t=1}^T \ddot{e}_t^2$ and that $\ddot{e}_t = -\ddot{\mathbf{z}}'_t (\ddot{\tau}_T - \tau_{T*}) + e_t$ from the fact that $\Delta y_t = \ddot{\mathbf{z}}'_t \tau_{T*} + e_t$, implying that

$$\sum_{t=1}^T \ddot{e}_t^2 = (\ddot{\tau}_T - \tau_{T*})' \ddot{\mathbf{D}} \left(\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{\mathbf{z}}_t \ddot{\mathbf{z}}'_t \ddot{\mathbf{D}}^{-1} \right) \ddot{\mathbf{D}} (\ddot{\tau}_T - \tau_{T*}) - 2 \left(\sum_{t=1}^T e_t \ddot{\mathbf{z}}_t \right) \ddot{\mathbf{D}}^{-1} \ddot{\mathbf{D}} (\ddot{\tau}_T - \tau_{T*}) + \sum_{t=1}^T e_t^2.$$

We examine the asymptotic behavior of each element on the right side. First, Lemmas 3 (vi) and 4 (i) imply that $\ddot{\mathbf{D}} (\ddot{\tau}_T - \tau_{T*}) = O_{\mathbb{P}}(1)$ and $\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{\mathbf{z}}_t \ddot{\mathbf{z}}'_t \ddot{\mathbf{D}}^{-1} = O_{\mathbb{P}}(1)$. Second, from the definitions of $\ddot{\mathbf{z}}_t$ and $\ddot{\mathbf{D}}$,

$\sum_{t=1}^T e_t \ddot{z}_t \ddot{\mathbf{D}}^{-1} = [T^{-1/2} \sum_{t=1}^T e_t \ddot{u}_{t-1}, T^{-1} \sum_{t=1}^T e_t \ddot{\mathbf{m}}'_{t-1}, T^{-3/2} \sum_{t=1}^T e_t (t-1), T^{-1/2} \sum_{t=1}^T e_t, T^{-1/2} \sum_{t=1}^T e_t z'_{2t}]'$. We verify that each element on the right side is $O_{\mathbb{P}}(1)$. We first note that $T^{-3/2} \sum_{t=1}^T e_t (t-1) = O_{\mathbb{P}}(1)$, $T^{-1/2} \sum_{t=1}^T e_t = O_{\mathbb{P}}(1)$, and $T^{-1/2} \sum_{t=1}^T e_t z_{2t} = O_{\mathbb{P}}(1)$ by the martingale difference CLT based upon the fact that $\{e_t, \mathcal{F}_t\}$ is an MDA. In addition, $T^{-1} \sum_{t=1}^T e_t \ddot{\mathbf{m}}_{t-1} = T^{-1} \sum_{t=1}^T e_t \mathbf{m}_{t-1} - (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) T^{-1} \sum_{t=1}^T e_t (t-1)$ by noting that $\ddot{\mathbf{m}}_{t-1} = \mathbf{m}_{t-1} - (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*)(t-1)$ as given in the proof of Lemma B.6 (i). Here, Lemmas B.7 (i and iv) imply that $(\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) = O_{\mathbb{P}}(T^{-1/2})$ and $T^{-1} \sum_{t=1}^T e_t \mathbf{m}_{t-1} = O_{\mathbb{P}}(1)$, respectively, so that $T^{-1} \sum_{t=1}^T e_t \ddot{\mathbf{m}}_{t-1} = O_{\mathbb{P}}(1)$. Finally, $T^{-1/2} \sum_{t=1}^T e_t \ddot{u}_{t-1} = T^{-1/2} \sum_{t=1}^T e_t u_{t-1} + o_{\mathbb{P}}(1)$ using the fact that $\ddot{u}_{t-1} = u_{t-1} + O_{\mathbb{P}}(T^{-1/2})$ as given in the proof of Lemma B.6 (iv). All these facts imply that $\sum_{t=1}^T e_t \ddot{z}_t \ddot{\mathbf{D}}^{-1} = O_{\mathbb{P}}(1)$. By these two facts, it follows that $\sum_{t=1}^T \ddot{e}_t^2 = \sum_{t=1}^T e_t^2 + O_{\mathbb{P}}(1)$, implying that $\hat{\sigma}_{e,T}^2 := T^{-1} \sum_{t=1}^T \ddot{e}_t^2 = T^{-1} \sum_{t=1}^T e_t^2 + O_{\mathbb{P}}(T^{-1})$. The desired result follows from the ergodic theorem, and this completes the proof. ■

A.3 Proofs

Proof of Lemma 1. (i) This follows from Lemmas B.3 (i, ii, iv), B.4 (i, ii, iv), B.5 (i, iii), B.6 (iii), and the remarks below Lemmas B.3, B.4, and B.5.

(ii) This follows from Lemma B.2 (i).

(iii) This follows from Lemmas B.2 (ii, iii, iv, vi) and the remark below Lemma B.2.

(iv) This follows from Lemmas 1 (i, ii, iii) and the structure of \mathbf{M} . ■

Proof of Lemma 2. (i) This follows from Lemmas B.3 (v), B.4 (v), and B.6 (ii).

(ii) This follows from Lemmas B.3 (i, ii, iii), B.4 (i, ii, iii), and B.6 (i).

(iii) This follows from Lemma B.2 (vii).

(iv) This follows from Lemmas B.2 (ii, iii, iv, and vi).

(v) This follows from Lemma B.2 (i).

(vi) This follows from Lemma A.3 (i) and Lemmas 2 (i, ii, iii, iv, v). ■

Proof of Lemma 3. (i) We note that $\ddot{\mathbf{D}}_1(\ddot{v}_T - \bar{v}_{T*}) = (\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}'_{t-1} \ddot{\mathbf{D}}_1^{-1})^{-1} \ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} u_{t-1}$ from (13), and Lemma 2 (vii) implies that $\ddot{\mathbf{D}}_1^{-1} (\sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} \ddot{\mathbf{r}}'_{t-1}) \ddot{\mathbf{D}}_1^{-1} \Rightarrow \mathcal{M}_{11}$. We therefore focus on the limit distribution of $\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} u_{t-1}$. Note that

$$\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1} u_{t-1} = \left[T^{-1} \sum_{t=1}^T \ddot{\mathbf{m}}'_{t-1} u_{t-1}, T^{-3/2} \sum_{t=1}^T (t-1) u_{t-1}, T^{-1/2} \sum_{t=1}^T u_{t-1} \right]'$$

We now examine the asymptotic behavior of each element on the right side. First, we note that $\ddot{\mathbf{m}}_{t-1} = \mathbf{m}_{t-1} - (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*)(t-1)$. Therefore, $T^{-1} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} u_{t-1} = T^{-1} \sum_{t=1}^T \mathbf{m}_{t-2} u_{t-1} + T^{-1} \sum_{t=1}^T \mathbf{s}_{t-1} u_{t-1} -$

$(\ddot{\mu}_T - \mu_*)T^{-1} \sum_{t=1}^T (t-1)u_{t-1}$. We here note that $T^{-1} \sum_{t=1}^T \mathbf{m}_{t-2}u_{t-1} \Rightarrow \int \mathcal{B}_s d\mathcal{B}_u + \boldsymbol{\varrho}_{m^*}$ by Lemma B.7 (iii), and $\sqrt{T}(\ddot{\mu}_T - \mu_*) \Rightarrow 3 \int r\mathcal{B}_s$ by Lemma B.7 (i). In addition to this, $T^{-3/2} \sum_{t=1}^T (t-1)u_{t-1} = T^{-1} \sum_{t=1}^T \frac{(t-1)}{T} \sqrt{T}(B_{uT}((t-1)/T) - B_{uT}((t-2)/T)) = \int rdB_{uT}(r) \Rightarrow \int rd\mathcal{B}_u$. Hence, it follows that $T^{-1} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1}u_{t-1} \Rightarrow \mathcal{S}_1 := \int \mathcal{B}_s d\mathcal{B}_u + \boldsymbol{\varrho}_{m^*} - 3 \int r\mathcal{B}_s \int rd\mathcal{B}_u$. Next, it is already showed that $T^{-3/2} \sum_{t=1}^T (t-1)u_{t-1} \Rightarrow \mathcal{S}_2 := \int rd\mathcal{B}_u$. Third, note that $T^{-1/2} \sum_{t=1}^T u_{t-1} = T^{-1} \sum_{t=1}^T \sqrt{T}(B_{uT}((t-1)/T) - B_{uT}((t-2)/T)) = \int rdB_{uT}(r) \Rightarrow \mathcal{S}_3 := \int d\mathcal{B}_u$. We now combine the first to third facts to obtain that $\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{\mathbf{r}}_{t-1}u_{t-1} \Rightarrow \mathcal{S}$, leading to that $\ddot{\mathbf{D}}_1(\ddot{v}_T - \bar{v}_{T^*}) \Rightarrow \mathcal{L} := \mathcal{M}_{11}^{-1} \mathcal{S}$, as desired.

(ii) We first note that $\tilde{v}_T - v_* = \mathbf{P}_T \ddot{v}_T - \mathbf{P} \bar{v}_{T^*}$. Therefore, $\tilde{v}_T - v_* = (\mathbf{P}_T - \mathbf{P})(\ddot{v}_T - \bar{v}_{T^*}) + \mathbf{P}(\ddot{v}_T - \bar{v}_{T^*}) + (\mathbf{P}_T - \mathbf{P})(\bar{v}_{T^*} - \bar{v}_*) + \mathbf{P}(\bar{v}_{T^*} - \bar{v}_*) + (\mathbf{P}_T - \mathbf{P})\bar{v}_*$. From the definition of \mathbf{P}_T and Lemma 3 (i), we note that $(\mathbf{P}_T - \mathbf{P}) = O_{\mathbb{P}}(T^{-1/2})$, $(\ddot{v}_T - \bar{v}_{T^*}) = O_{\mathbb{P}}(\ddot{\mathbf{D}}^{-1})$, and $(\mathbf{P}_T - \mathbf{P})(\bar{v}_{T^*} - \bar{v}_*) = \mathbf{0}$. Furthermore, $\mathbf{P}(\bar{v}_{T^*} - \bar{v}_*) = [\mathbf{0}', \mathbf{0}', (\vartheta_{T^*} - \vartheta_*)', \mathbf{0}']'$ such that $(\vartheta_{T^*} - \vartheta_*) = \beta'_*(\ddot{\mu}_T - \mu_*)$, and $(\mathbf{P}_T - \mathbf{P})\bar{v}_* = [\mathbf{0}, \mathbf{0}, -\beta'_*(\ddot{\mu}_T - \mu_*), \mathbf{0}]'$, so that $\mathbf{P}(\bar{v}_{T^*} - \bar{v}_*) + (\mathbf{P}_T - \mathbf{P})\bar{v}_* = \mathbf{0}$. Hence, it now follows that $\tilde{v}_T - v_* = (\mathbf{P}_T - \mathbf{P})(\ddot{v}_T - \bar{v}_{T^*}) + \mathbf{P}(\ddot{v}_T - \bar{v}_{T^*}) = \mathbf{P}(\ddot{v}_T - \bar{v}_{T^*}) + O_{\mathbb{P}}(T^{-3/2})$, so that

$$\ddot{\mathbf{D}}_1(\tilde{v}_T - v_*) = \begin{bmatrix} T(\ddot{\beta}_T - \beta_*)' \\ -\mu'_* T(\ddot{\beta}_T - \beta_*) \\ \sqrt{T}(\ddot{v}_T - v_*) \end{bmatrix} + o_{\mathbb{P}}(1) \Rightarrow \begin{bmatrix} \mathcal{L}'_1 \\ -\mu'_* \mathcal{L}_1 \\ \mathcal{L}_3 \end{bmatrix}$$

by Lemma 3 (i). ■

Proof of Lemma 4. (i) We first note that $\ddot{\mathbf{D}}(\ddot{\tau}_T - \tau_{T^*}) = (\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t \ddot{z}'_t \ddot{\mathbf{D}}^{-1})^{-1} \ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t e_t$ from (14), and Lemma 2 (vi) implies that $\ddot{\mathbf{D}}^{-1}(\sum_{t=1}^T \ddot{z}_t \ddot{z}'_t) \ddot{\mathbf{D}}^{-1} \Rightarrow \mathcal{M}$. We therefore focus on the limit distribution of $\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t e_t$. We note that $\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t e_t = \ddot{\mathbf{D}}^{-1} \sum_{t=1}^T [\ddot{u}_{t-1} e_r, \ddot{\mathbf{m}}'_{t-1} e_t, (t-1)e_t, e_t, \mathbf{z}'_{2t} e_t]'$.

We now investigate the asymptotic behavior of each element on the right side. First, we already showed in the proof of Lemma B.6 (iv) that $\ddot{u}_t = u_t + O_{\mathbb{P}}(T^{-1/2})$. Therefore, $T^{-1/2} \sum_{t=1}^T \ddot{u}_{t-1} e_t = T^{-1/2} \sum_{t=1}^T u_{t-1} e_t + o_{\mathbb{P}}(1)$. In addition, $T^{-1/2} \sum_{t=1}^T u_{t-1} e_t = T^{-1} \sum_{t=1}^T \sqrt{T}(B_{ueT}(t/T) - B_{ueT}((t-1)/T)) = \int dB_{ueT}(r) \Rightarrow \mathcal{J}_1 := \int d\mathcal{B}_{ue}$. Second, we note that $\ddot{\mathbf{m}}_{t-1} = \mathbf{m}_{t-1} - (\ddot{\mu}_T - \mu_*)(t-1)$. Therefore, $T^{-1} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} e_t = T^{-1} \sum_{t=1}^T \mathbf{m}_{t-1} e_t - (\ddot{\mu}_T - \mu_*)T^{-1} \sum_{t=1}^T (t-1)e_t$. We here note that $T^{-1} \sum_{t=1}^T \mathbf{m}_{t-1} e_t \Rightarrow \int \mathcal{B}_s d\mathcal{B}_e$ by Lemma B.7 (iv) and $\sqrt{T}(\ddot{\mu}_T - \mu_*) \Rightarrow 3 \int r\mathcal{B}_s$ by Lemma B.7 (i). In addition to this, $T^{-3/2} \sum_{t=1}^T (t-1)e_t = T^{-1} \sum_{t=1}^T \frac{(t-1)}{T} \sqrt{T}(B_{eT}((t-1)/T) - B_{eT}((t-2)/T)) = \int rdB_{eT}(r) \Rightarrow \int rd\mathcal{B}_e$. Hence, it follows that $T^{-1} \sum_{t=1}^T \ddot{\mathbf{m}}_{t-1} e_t \Rightarrow \mathcal{J}_2 := \int \mathcal{B}_s d\mathcal{B}_e - 3 \int r\mathcal{B}_s \int rd\mathcal{B}_e = \int \bar{\mathcal{B}}_s d\mathcal{B}_e$. Third, it is already showed that $T^{-3/2} \sum_{t=1}^T (t-1)e_{t-1} \Rightarrow \mathcal{J}_3 := \int rd\mathcal{B}_e$. Fourth, we note that $T^{-1/2} \sum_{t=1}^T e_t = T^{-1} \sum_{t=1}^T \sqrt{T}(B_{eT}(t/T) - B_{eT}((t-1)/T)) = \int dB_{eT}(r) \Rightarrow \mathcal{J}_4 := \int d\mathcal{B}_e$. Fifth, note that $T^{-1/2} \sum_{t=1}^T \mathbf{z}_{2t} e_t = T^{-1} \sum_{t=1}^T \sqrt{T}(\mathbf{B}_{zeT}(t/T) - \mathbf{B}_{zeT}((t-1)/T)) = \int d\mathbf{B}_{zeT}(r) \Rightarrow \mathcal{J}_5 := \int d\mathcal{B}_{ze}$. We next combine the first to fifth facts to obtain that $\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t e_t \Rightarrow \mathcal{J}$

by noting that

$$\mathcal{F} = \left[\mathcal{F}_1 \quad \mathcal{F}'_2 \quad \mathcal{F}_3 \quad \mathcal{F}_4 \quad \mathcal{F}'_5 \right]' := \left[\int d\mathcal{B}_{ue} \quad \int \bar{\mathcal{B}}'_s d\mathcal{B}_e \quad \int rd\mathcal{B}_e \quad \int d\mathcal{B}_e \quad \int d\mathcal{B}'_{ze} \right]',$$

leading to that $\ddot{\mathbf{D}}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_{T*}) \Rightarrow \mathcal{M}^{-1} \mathcal{F}$, as desired.

(ii) From the definitions of $\boldsymbol{\tau}_{T*} := [\rho_*, \boldsymbol{\tau}'_{1T}, \boldsymbol{\kappa}'_*]'$ and $\boldsymbol{\tau}_{1T} := [(\boldsymbol{\eta}_* + \rho_*(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*))', \varsigma_* + \boldsymbol{\eta}'_*(\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) + \rho_*(\ddot{\vartheta}_T - \vartheta_{T*}), \gamma_* + \rho_*(\ddot{\nu}_T - \nu_*)]'$, we obtain that $\ddot{\mathbf{D}}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_{T*}) = \ddot{\mathbf{D}}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_*) + [0, -\rho_* T(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*)', -\rho_* T^{3/2}(\ddot{\vartheta}_T - \vartheta_{T*}), -\rho_* T^{1/2}(\ddot{\nu}_T - \nu_*), \mathbf{0}']' \Rightarrow \mathcal{D}$ by Lemma 4 (i) and noting that $\boldsymbol{\eta}_* = \mathbf{0}$. In addition, Lemma 3 implies that $T(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*) \Rightarrow \mathcal{L}'_1$, and $T^{1/2}(\ddot{\nu}_T - \nu_*) \Rightarrow \mathcal{L}_3$. Furthermore, the proof of Lemma 3 (i) shows that $T^{3/2}(\ddot{\vartheta}_T - \vartheta_{T*}) \Rightarrow \mathcal{L}_2$. Therefore, $\ddot{\mathbf{D}}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_*) \Rightarrow \mathcal{D} - \rho_* [0, \mathcal{L}'_1, \mathcal{L}_2, \mathcal{L}_3, \mathbf{0}']' = \mathcal{D} - \rho_* [0, \mathcal{L}', \mathbf{0}']'$. This completes the proof. \blacksquare

Proof of Theorem 1. (i) We note that $(\hat{\boldsymbol{\alpha}}_T - \boldsymbol{\alpha}_*) = (\mathbf{T}_T - \mathbf{T})\boldsymbol{\tau}_* + \mathbf{T}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_*) + (\mathbf{T}_T - \mathbf{T})(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_*) = (\mathbf{T}_T - \mathbf{T})\boldsymbol{\tau}_* + \mathbf{T}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_*) + o_{\mathbb{P}}(\mathbf{T}_T - \mathbf{T})$ using (10) and (11). We further note that

$$\begin{aligned} & (\mathbf{T}_T - \mathbf{T})\boldsymbol{\tau}_* + \mathbf{T}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_*) \\ &= \begin{bmatrix} (\ddot{\rho}_T - \rho_*) \\ -\boldsymbol{\beta}_*(\ddot{\rho}_T - \rho_*) + (\ddot{\boldsymbol{\eta}}_T - \boldsymbol{\eta}_*) - \rho_*(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*) \\ (\ddot{\zeta}_T - \varsigma_*) - \boldsymbol{\mu}'_*(\ddot{\boldsymbol{\eta}}_T - \boldsymbol{\eta}_*) - \zeta_*(\ddot{\rho}_T - \rho_*) - \rho_*(\ddot{\zeta}_T - \zeta_*) - \boldsymbol{\eta}'_*(\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*) \\ (\ddot{\gamma}_T - \gamma_*) - \rho_*(\ddot{\nu}_T - \nu_*) - \nu_*(\ddot{\rho}_T - \rho_*) \\ (\ddot{\boldsymbol{\kappa}}_T - \boldsymbol{\kappa}_*) \end{bmatrix} \end{aligned}$$

and the fact that $\tilde{\boldsymbol{\beta}}_T = \ddot{\boldsymbol{\beta}}_T$, $\tilde{\zeta}_T = -\ddot{\boldsymbol{\mu}}'_T \ddot{\boldsymbol{\beta}}_T + \ddot{\vartheta}_T$ and $\zeta_* = -\boldsymbol{\mu}'_* \boldsymbol{\beta}_* + \vartheta_*$, so that $(\tilde{\zeta}_T - \zeta_*) = (\ddot{\vartheta}_T - \vartheta_{T*}) - \boldsymbol{\mu}'_*(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*) - (\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*)'(\tilde{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*)$, where $(\ddot{\vartheta}_T - \vartheta_{T*}) = O_{\mathbb{P}}(T^{-3/2})$ and $(\ddot{\boldsymbol{\mu}}_T - \boldsymbol{\mu}_*)'(\tilde{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*) = O_{\mathbb{P}}(T^{-3/2})$ by Lemmas 4 (i), B.7 (i), and 3 (ii). Therefore, it now follows that

$$\begin{aligned} & (\mathbf{T}_T - \mathbf{T})\boldsymbol{\tau}_* + \mathbf{T}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_*) \\ &= (\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_{T*}) - (\ddot{\rho}_T - \rho_*) \begin{bmatrix} 0 \\ \boldsymbol{\beta}_* \\ \zeta_* \\ \nu_* \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{0} \\ -\boldsymbol{\mu}'_* \{(\ddot{\boldsymbol{\eta}}_T - \boldsymbol{\eta}_*) - \rho_*(\ddot{\boldsymbol{\beta}}_T - \boldsymbol{\beta}_*)\} + O_{\mathbb{P}}(T^{-3/2}) \\ 0 \\ \mathbf{0} \end{bmatrix}. \quad (\text{A.4}) \end{aligned}$$

We here use the fact that $\boldsymbol{\eta}_* = \mathbf{0}$. We further note that $\sqrt{T}(\ddot{\boldsymbol{\tau}}_T - \boldsymbol{\tau}_{T*}) \Rightarrow [\mathcal{D}_1, \mathbf{0}'_{2k \times 1}, 0, \mathcal{D}_4, \mathcal{D}_5]'$ by

Lemma 4 (i) and $-\sqrt{T}(\ddot{\rho}_T - \rho_*) [0, \beta'_*, \zeta_*, \nu_*, \mathbf{0}'] \Rightarrow -\mathcal{D}_1 [0, \beta'_*, \zeta_*, \nu_*, \mathbf{0}']$. In addition, we note that $-\mu'_* \sqrt{T} \{(\ddot{\eta}_T - \eta_*) - \rho_*(\ddot{\beta}_T - \beta_*)\} + O_{\mathbb{P}}(T^{-1}) = o_{\mathbb{P}}(1)$ because $\sqrt{T} \{(\ddot{\eta}_T - \eta_*) - \rho_*(\ddot{\beta}_T - \beta_*)\} = O_{\mathbb{P}}(T^{-1/2})$ by Lemma 4 (i). Therefore, it follows that

$$\sqrt{T}(\widehat{\alpha}_T - \alpha_*) \Rightarrow [\mathcal{D}_1, -\beta'_* \mathcal{D}_1, -\zeta_* \mathcal{D}_1, \mathcal{D}_4 - \nu_* \mathcal{D}_1, \mathcal{D}'_5]'. \quad (\text{A.5})$$

We finally note that the derived weak limit is identical to $\mathbf{c}_* \mathcal{D}_1 + [0, \mathbf{0}', 0, 0, \mathcal{D}'_5]'$.

(ii, iii, and iv) For an efficient proof, we prove (ii, iii, and iv) together by supposing that $\beta_* = \mathbf{0}$ and $\zeta_* = 0$, although it is not permitted by $\rho_* < 0$. If so, it algebraically follows from (A.4) that

$$\begin{aligned} (\widehat{\alpha}_T - \alpha_*) &= (\mathbf{T}_T - \mathbf{T})\tau_* + \mathbf{T}(\ddot{\tau}_T - \tau_*) + o_{\mathbb{P}}(\mathbf{T}_T - \mathbf{T}) \\ &= (\ddot{\tau}_T - \tau_{T*}) + \begin{bmatrix} 0 \\ \mathbf{0} \\ -\mu'_* \{(\ddot{\eta}_T - \eta_*) - \rho_*(\ddot{\beta}_T - \beta_*)\} + O_{\mathbb{P}}(T^{-3/2}) \\ -\nu_*(\ddot{\rho}_T - \rho_*) \\ \mathbf{0} \end{bmatrix} + o_{\mathbb{P}}(\mathbf{T}_T - \mathbf{T}). \end{aligned}$$

Here, $\widehat{\mathbf{D}}(\ddot{\tau}_T - \tau_{T*}) \Rightarrow [\mathcal{D}_1, \mathcal{D}'_2, 0, \mathcal{D}_4, \mathcal{D}'_5]'$ and $T\{(\ddot{\eta}_T - \eta_*) - \rho_*(\ddot{\beta}_T - \beta_*)\} \Rightarrow \mathcal{D}_2$ by Lemma 4 (i), so that

$$\widehat{\mathbf{D}}(\widehat{\alpha}_T - \alpha_*) \Rightarrow [\mathcal{D}_1, \mathcal{D}'_2, -\mu'_* \mathcal{D}_2, \mathcal{D}_4 - \nu_* \mathcal{D}_1, \mathcal{D}'_5]', \quad (\text{A.6})$$

where $\widehat{\mathbf{D}} := \text{diag}[\sqrt{T}, T\mathbf{I}_{2k+1}, \sqrt{T}, \widehat{\mathbf{D}}_2]$. From the weak limits in (A.5) and (A.6), (ii, iii, and iv) follow by applying the weak limits corresponding to the conditions in (ii, iii, and iv). For example, if the conditions in (ii) are imposed, the weak limit of $\widehat{\theta}_T^+$ is determined by (A.6) as \mathcal{D}_2^+ , but the others are determined by (A.5), so that the weak limit in (ii) is delivered. As another example, if the conditions in (iv) are imposed, the weak limit of $\widehat{\xi}_T$ is determined by (A.6) as $\mu'_* \mathcal{D}_2$, but the others are determined by (A.5), so that the weak limit in (iv) is delivered. In this manner, the weak limits in (ii, iii, and iv) are obtained. ■

Proof of Theorem 2. (i) We show the null limit distribution of each test using Lemma 4.

(i.a) Note that $(\widehat{\theta}_T^+ - \widehat{\theta}_T^-) = (\theta_*^+ - \theta_*^-) - (\ddot{\rho}_T - \rho_*)(\beta_*^+ - \beta_*^-) + (\ddot{\eta}_T^+ - \eta_{T*}^+) - (\ddot{\eta}_T^- - \eta_{T*}^-) + o_{\mathbb{P}}(T^{-1})$, so that it follows that $(\widehat{\theta}_T^+ - \widehat{\theta}_T^-) = (\ddot{\eta}_T^+ - \eta_{T*}^+) - (\ddot{\eta}_T^- - \eta_{T*}^-) + o_{\mathbb{P}}(T^{-1})$ under \mathcal{H}_0' . Therefore, $\widehat{\mathbf{R}}_1 \widehat{\alpha}_T =$

$\mathbf{R}_1(\ddot{\tau}_T - \tau_{T*}) + o_{\mathbb{P}}(T^{-1})$, and it follows from Lemmas 4 (i) and B.7 (v) that

$$\begin{aligned} W_T^{(1)} &= (\ddot{\tau}_T - \tau_{T*})' \ddot{\mathbf{D}} \mathbf{R}'_1 \left(\hat{\sigma}_{e,T}^2 \mathbf{R}_1 \left(\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t \ddot{z}'_t \ddot{\mathbf{D}}^{-1} \right)^{-1} \mathbf{R}'_1 \right)^{-1} \mathbf{R}_1 \ddot{\mathbf{D}} (\ddot{\tau}_T - \tau_{T*}) + o_{\mathbb{P}}(1) \\ &\Rightarrow \mathcal{D}' \mathbf{R}'_1 (\sigma_e^2 \mathbf{R}_1 \mathcal{M}^{-1} \mathbf{R}'_1)^{-1} \mathbf{R}_1 \mathcal{D}. \end{aligned}$$

(i.b) We note that $(\hat{\pi}_T^+, \hat{\pi}_T^-) = (\ddot{\pi}_T^+, \ddot{\pi}_T^-)$. Therefore, it follows from Lemmas 4 (i) and B.7 (v) that

$$\begin{aligned} W_T^{(2)} &= (\ddot{\tau}_T - \tau_{T*})' \ddot{\mathbf{D}} \hat{\mathbf{R}}'_2 \left(\hat{\sigma}_{e,T}^2 \hat{\mathbf{R}}_2 \left(\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t \ddot{z}'_t \ddot{\mathbf{D}}^{-1} \right)^{-1} \hat{\mathbf{R}}'_2 \right)^{-1} \hat{\mathbf{R}}_2 \ddot{\mathbf{D}} (\ddot{\tau}_T - \tau_{T*}) + o_{\mathbb{P}}(1) \\ &\Rightarrow \mathcal{D}' \hat{\mathbf{R}}'_2 (\sigma_e^2 \hat{\mathbf{R}}_2 \mathcal{M}^{-1} \hat{\mathbf{R}}'_2)^{-1} \hat{\mathbf{R}}_2 \mathcal{D}. \end{aligned}$$

(i.c) From the notice given in the proofs of (i.a) and (i.b), it follows from Lemmas 4 (i) and B.7 (v) that

$$\begin{aligned} W_T^{(3)} &= (\ddot{\tau}_T - \tau_{T*})' \ddot{\mathbf{D}} \mathbf{R}'_3 \left(\hat{\sigma}_{e,T}^2 \mathbf{R}_3 \left(\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t \ddot{z}'_t \ddot{\mathbf{D}}^{-1} \right)^{-1} \mathbf{R}'_3 \right)^{-1} \mathbf{R}_3 \ddot{\mathbf{D}} (\ddot{\tau}_T - \tau_{T*}) + o_{\mathbb{P}}(1) \\ &\Rightarrow \mathcal{D}' \mathbf{R}'_3 (\sigma_e^2 \mathbf{R}_3 \mathcal{M}^{-1} \mathbf{R}'_3)^{-1} \mathbf{R}_3 \mathcal{D}. \end{aligned}$$

(ii) We show the power behavior of each test using Lemma 4.

(ii.a) We show that $W_T^{(1)} = O_{\mathbb{P}}(T)$. Note that $(\hat{\theta}_T^+ - \hat{\theta}_T^-) = (\theta_*^+ - \theta_*^-) - (\dot{\rho}_T - \rho_*) (\beta_*^+ - \beta_*^-) + o_{\mathbb{P}}(T^{-1/2})$ under \mathcal{H}'_1 and $(\dot{\rho}_T - \rho_*) = O_{\mathbb{P}}(T^{-1/2})$, so that $(\hat{\theta}_T^+ - \hat{\theta}_T^-) - (\theta_*^+ - \theta_*^-) = O_{\mathbb{P}}(T^{-1/2})$. Therefore, $(\hat{\theta}_T^+ - \hat{\theta}_T^-) = O_{\mathbb{P}}(T^{1/2})$, and this implies that $W_T^{(1)} = O_{\mathbb{P}}(T)$.

(ii.b) We show that $W_T^{(2)} = O_{\mathbb{P}}(T)$. Note that Lemma 4 (i) implies that $\ddot{\pi}_T^+ - \ddot{\pi}_T^- = \pi_*^+ - \pi_*^- + O_{\mathbb{P}}(T^{-1/2})$. Therefore, $\ddot{\pi}_T^+ - \ddot{\pi}_T^- = O_{\mathbb{P}}(T^{1/2})$, implying that $W_T^{(2)} = O_{\mathbb{P}}(T)$.

(ii.c) From the proofs of (ii.a) and (ii.b), $(\hat{\theta}_T^+ - \hat{\theta}_T^-) = O_{\mathbb{P}}(T^{1/2})$ and $(\ddot{\pi}_T^+ - \ddot{\pi}_T^-) = O_{\mathbb{P}}(T^{1/2})$. Therefore, it trivially follows that $W_T^{(3)} = O_{\mathbb{P}}(T)$.

(iii) We show the null limit distribution of each test using Lemmas 3 and 4.

(iii.a) First, Lemma B.6 (iv) implies that $\hat{\sigma}_{u,T}^2 \xrightarrow{\mathbb{P}} \sigma_u^2$, and $\ddot{\mathbf{D}}_1^{-1} \sum_{t=1}^T \ddot{r}_{t-1} \ddot{r}'_{t-1} \ddot{\mathbf{D}}_1^{-1} \Rightarrow \mathcal{M}_{11}$ from Lemma 2 (vii). Therefore, $\ddot{\mathbf{W}}_T^{(1)} \Rightarrow \sigma_u^2 \ddot{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \ddot{\mathbf{R}}_1'$. Second, \mathbb{H}'_0 implies that $\ddot{\mathbf{R}}_1 \ddot{\mathbf{D}}_1 \ddot{\nu}_T = T(\hat{\beta}_T^+ - \beta_*^+) - T(\hat{\beta}_T^- - \beta_*^-) \Rightarrow (\mathcal{L}_1^+ - \mathcal{L}_1^-)$. If we combine these two facts, it follows that $\mathcal{W}_T^{(1)} \Rightarrow (\mathcal{L}_1^+ - \mathcal{L}_1^-)' (\sigma_u^2 \ddot{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \ddot{\mathbf{R}}_1')^{-1} (\mathcal{L}_1^+ - \mathcal{L}_1^-)$ that is identical to the given weak limit by the definitions of $\ddot{\mathbf{R}}_1$ and \mathcal{L} .

(iii.b) First, Lemma B.7 (v) implies that $\hat{\sigma}_{e,T}^2 \xrightarrow{\mathbb{P}} \sigma_e^2$, and $\ddot{\mathbf{D}}^{-1} \sum_{t=1}^T \ddot{z}_t \ddot{z}'_t \ddot{\mathbf{D}}^{-1} \Rightarrow \mathcal{M}$ from Lemma 2

(vi). Therefore, $\ddot{\mathbf{W}}_T^{(2)} \Rightarrow \sigma_e^2 \widehat{\mathbf{R}}_2 \mathcal{M}^{-1} \widehat{\mathbf{R}}_2'$. Second, $\widehat{\mathbf{R}}_2 \ddot{\mathbf{D}} \ddot{\tau}_T = \sqrt{T}(\ddot{\pi}_T^+ - \ddot{\pi}_T^-) \Rightarrow \mathcal{D}_5^+ - \mathcal{D}_5^- = \widehat{\mathbf{R}}_2 \mathcal{D}$. If we combine these two facts, it follows that $\mathcal{W}_T^{(2)} \Rightarrow \mathcal{D}' \widehat{\mathbf{R}}_2' (\sigma_e^2 \widehat{\mathbf{R}}_2 \mathcal{M}^{-1} \widehat{\mathbf{R}}_2')^{-1} \widehat{\mathbf{R}}_2 \mathcal{D}$.

(iii.c) We note that from the definition of $\mathcal{W}_T^{(3)}$, it follows that $\mathcal{W}_T^{(3)} = \mathcal{W}_T^{(1)} + \mathcal{W}_T^{(2)}$, and it follows from (i.a and i.b) that $\mathcal{W}_T^{(3)} \Rightarrow \mathcal{L}' \widehat{\mathbf{R}}_1' (\sigma_u^2 \widehat{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \widehat{\mathbf{R}}_1')^{-1} \widehat{\mathbf{R}}_1 \mathcal{L} + \mathcal{D}' \widehat{\mathbf{R}}_2' (\sigma_e^2 \widehat{\mathbf{R}}_2 \mathcal{M}^{-1} \widehat{\mathbf{R}}_2')^{-1} \widehat{\mathbf{R}}_2 \mathcal{D}$ under \mathbb{H}_0''' .

(iv) We next show the power behavior of each test.

(iv.a) To show the claim, we show that $\mathcal{W}_T^{(1)} = O_{\mathbb{P}}(T^2)$ under \mathbb{H}_1' . Given that $\ddot{\mathbf{W}}_T^{(1)} \Rightarrow \sigma_u^2 \widehat{\mathbf{R}}_1 \mathcal{M}_{11}^{-1} \widehat{\mathbf{R}}_1'$, we focus on the limit behavior of $\widehat{\mathbf{R}}_1 \ddot{\mathbf{D}}_1 \ddot{v}_T$. Note that $\widehat{\mathbf{R}}_1 \ddot{\mathbf{D}}_1 (\ddot{v}_T - \bar{v}_{T*}) \Rightarrow (\mathcal{L}_1^+ - \mathcal{L}_1^-)$ by Lemma 3 (i) and $\widehat{\mathbf{R}}_1 \ddot{\mathbf{D}}_1 \bar{v}_{T*} = T\beta_* = O(T)$. Therefore, $\widehat{\mathbf{R}}_1 \ddot{\mathbf{D}}_1 \ddot{v}_T = O_{\mathbb{P}}(T)$, implying that $\mathcal{W}_T^{(1)} = O_{\mathbb{P}}(T^2)$, leading to the desired result.

(iv.b) We show that $\mathcal{W}_T^{(2)} = O_{\mathbb{P}}(T)$ under \mathcal{H}'' . Given that $\ddot{\mathbf{W}}_T^{(2)} \Rightarrow \sigma_e^2 \widehat{\mathbf{R}}_2 \mathcal{M}^{-1} \widehat{\mathbf{R}}_2'$, we focus on the limit behavior of $\widehat{\mathbf{R}}_2 \ddot{\mathbf{D}} \ddot{\tau}_T$. We note that $\widehat{\mathbf{R}}_2 \ddot{\mathbf{D}} (\ddot{\tau}_T - \tau_{T*}) = \sqrt{T}[(\ddot{\pi}_T^+ - \ddot{\pi}_T^-) - (\pi_*^+ - \pi_*^-)] \Rightarrow \widehat{\mathbf{R}}_2 \mathcal{D}$ by Lemma 4 (i) and $\widehat{\mathbf{R}}_2 \ddot{\mathbf{D}} \tau_{T*} = \sqrt{T}(\pi_*^+ - \pi_*^-) = O(T^{1/2})$. Therefore, $\widehat{\mathbf{R}}_2 \ddot{\mathbf{D}} \ddot{\tau}_T = O_{\mathbb{P}}(T^{1/2})$, implying that $\mathcal{W}_T^{(2)} = O_{\mathbb{P}}(T)$.

(iv.c) We show that $\mathcal{W}_T^{(3)} = O_{\mathbb{P}}(T^2)$ under \mathbb{H}_1''' . Note that $\mathcal{W}_T^{(3)} = \mathcal{W}_T^{(1)} + \mathcal{W}_T^{(2)}$, and $\mathcal{W}_T^{(1)}$ and $\mathcal{W}_T^{(2)}$ are $O_{\mathbb{P}}(T^2)$ and $O_{\mathbb{P}}(T)$ by (ii.a) and (ii.b), respectively. Therefore, $\mathcal{W}_T^{(3)} = O_{\mathbb{P}}(T^2)$ under \mathbb{H}_{11}''' and $\mathcal{W}_T^{(3)} = O_{\mathbb{P}}(T)$ under $\mathbb{H}_{01}''' \cap \mathbb{H}_{12}'''$. This completes the proof. \blacksquare

A.4 Additional Monte Carlo Simulations

In this section, we compare the finite sample performance of OLS with 2SNARDL and also provide additional simulation evidence for the main claims.

A.4.1 Comparison of OLS with 2SNARDL

In this section, we compare the finite sample performance of OLS with 2SNARDL by simulation.

For the simulation, we assume the following simulation environment. We first suppose that

$$\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t,$$

$$u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1), \quad \text{and} \quad \Delta x_t = \omega_* + \varrho_* \Delta x_{t-1} + v_t,$$

where $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ and $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 0)$. We further assume two DGP conditions by letting (i) $(\omega_*, \varrho_*) = (1/2, 0)$ or (ii) $(\omega_*, \varrho_*) = (1/4, 1/2)$. That is, we let $\{\Delta x_t\}$ be an independent or autocorrelated series. For each DGP, we plug the equation for u_t into

the equation for Δy_t to obtain

$$\Delta y_t = \alpha_* + \rho_* y_{t-1} + \theta_*^+ x_{t-1}^+ + \theta_*^- x_{t-1}^- + \xi_*(t-1) + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$$

and estimate the coefficients in this equation by OLS and 2SNARDL. For the 2SNARDL, we first estimate ρ_* , β_*^+ , and β_*^- by following [Cho et al. \(2023a\)](#) and next indirectly estimate θ_*^+ and θ_*^- by noting that $\theta_*^+ = -\rho_* \beta_*^+$ and $\theta_*^- = -\rho_* \beta_*^-$.

Using the OLS and 2SNARDL estimates, we report their finite sample biases and root mean square errors (RMSEs). For example, the finite sample bias and RMSE of $\hat{\theta}_T^+$ are computed as follows:

$$\text{Bias} = \frac{1}{m} \sum_{i=1}^m (\hat{\theta}_{T,j}^+ - \theta_*^+) \quad \text{and} \quad \text{RMSE} = \sqrt{\frac{1}{m} \sum_{i=1}^m (\hat{\theta}_{T,j}^+ - \theta_*^+)^2},$$

where j indicates the experimental index, and m denotes the total number of experiments. For the simulation, we let $m = 50000$.

Table [A.1](#) reports the finite sample biases of the OLS and 2SNARDL estimators when $\{\Delta x_t\}$ is an independent series. As we see from the table, the performance of the OLS estimator is comparable to the 2SNARDL estimator. As T increases, the finite sample bias converges to zero for both estimators, which implies that the asymptotic bias is negligible. Nonetheless, each parameter estimator has nuanced results. Specifically, when T is small, say $T = 100$, the finite sample biases of the OLS estimator are greater than those of the 2SNARDL estimator for the long-run parameters. If the sample size is as large as 2000, this relationship is reversed. For the short-run parameter, the OLS estimator for ρ_* always exhibits bigger biases than 2SNARDL, but this relationship is reversed for π_*^+ and π_*^- . For the case of φ_* , both estimators exhibit similar finite sample biases.

Table [A.2](#) reports the finite sample RMSEs of the OLS and 2SNARDL estimators when $\{\Delta x_t\}$ is an independent series. From the table, as T increases, the finite sample RMSE converges to zero for both estimators, which implies that both estimators are consistent for the unknown parameters. We further observe that both estimators exhibit similar RMSEs for each sample size. It is difficult to say one estimator is superior to another in terms of finite sample RMSE. This aspect implies that the 2SNARDL estimator for θ_*^+ and θ_*^- has the same convergence rate as for the OLS estimator, although the 2SNARDL estimators for β_*^+ and β_*^- are super-consistent. The main reason of this is in the fact that the 2SNARDL estimator for ρ_* has \sqrt{T} convergence rate, so that the convergence rate of the 2SNARDL estimator for θ_*^+ and θ_*^- is determined by the 2SNARDL estimator for ρ_* .

Tables [A.3](#) and [A.4](#) report the finite sample biases and RMSEs of the OLS and 2SNARDL estimators,

respectively, when $\{\Delta x_t\}$ is an autocorrelated series. Although there exist minor differences between the tables, their qualitative properties are identical to those of Tables A.1 and A.2, respectively. This aspect implies that the simulation results are the same irrespective of whether Δx_t is serially correlated or not.

From this experiment, we observe that both OLS and 2SNARDL estimators are consistent estimators. As T increases, the finite sample biases and RMSEs decrease. Although the performances of the two estimators in terms of finite sample bias depend on multiple factors such as the sample size and the roles of the parameters, the overall performance of the OLS estimator is not so different from 2SNARDL in terms of their finite sample RMSEs.

A.4.2 Additional Simulation Evidence

In this section, we provide additional simulation evidence for the main claims. The main goal of this section is to verify the properties in Theorem 1.

Theorem 1 demonstrates that the convergence rate of the OLS estimator depends on the DGP conditions. Specifically, four different DGP conditions are considered in Theorem 1 as follows:

- Theorem 1 (i): for each $j = 1, 2, \dots, k$, $\beta_{j*}^\pm \neq 0$ and $\zeta_* \neq 0$;
- Theorem 1 (ii): $\beta_*^+ = \mathbf{0}$, but for each $j = 1, 2, \dots, k$, $\beta_{j*}^- \neq 0$, and $\zeta_* \neq 0$;
- Theorem 1 (iii): $\beta_*^- = \mathbf{0}$, but for each $j = 1, 2, \dots, k$, $\beta_{j*}^+ \neq 0$, and $\zeta_* \neq 0$; and
- Theorem 1 (iv): for each $j = 1, 2, \dots, k$, $\beta_{j*}^\pm \neq 0$ but $\zeta_* = 0$,

and Theorem 1 shows that the convergence rate of the OLS estimator is different under each condition. We verify this property by simulation.

DGP Condition under Theorem 1 (i) For simulation, we first generate data according to the DGP condition in Theorem 1 (i). Specifically, we generate data observations according to the DGP condition in Section A.4.1 by letting $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 1)$ and $(\omega_*, \varrho_*) = (1/2, 0)$. Using the data set generated by this DGP condition, we compute OLS estimators by repeating independent experiments 50000 times.

We corroborate Theorem 1 (i) in two ways. First, we compute the finite sample bias and RMSE of the OLS estimator. For this, we compute the bias and RMSE by multiplying the convergence rate in Theorem 1 (i) to the OLS estimator. For example, as $\hat{\theta}_T^+$ has convergence rate \sqrt{T} , we compute the bias and RMSE as

$$\text{Bias} = \frac{1}{m} \sum_{j=1}^m \sqrt{T}(\hat{\theta}_{T,j}^+ - \theta_*^+) \quad \text{and} \quad \text{RMSE} = \sqrt{\frac{1}{m} \sum_{j=1}^m T(\hat{\theta}_{T,j}^+ - \theta_*^+)^2},$$

where m denotes the total number of experiments, viz., 50000. If the convergence rate in Theorem 1 (i)

is correct for the OLS estimator, the finite sample bias and RMSE have to converge to zero and a positive constant as the sample size increases. Otherwise, the finite sample RMSE would converge to zero or diverge to positive infinity. We contain the finite sample bias and RMSE in Table A.5 and observe these two features for the long- and short-run parameters by letting the sample size increase from 100 to 2000, corroborating the convergence rate in Theorem 1 (i).

Second, we compute the standard t -test using the OLS estimator to compare its finite sample null distribution with the standard mixed-normal distribution. Theorem 1 (i) implies that the null limit distribution of the t -test is the standard mixed-normal. Figure A.1 (a) shows the QQ-plots between the t -tests defined by the long- and short-run OLS estimators and the standard normal distribution. The QQ-plots are obtained by letting $T = 3000$ and repeating independent experiments 50000 times. They are distributed around the 45-degree line, and this corroborates the distributional property given in Theorem 1 (i).

DGP Condition under Theorem 1 (ii) We next verify Theorem 1 (ii) in the same way. We generate data according to the DGP condition in Section A.4.1 by letting $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 0, -3/2, 1)$ and $(\omega_*, \varrho_*) = (1/2, 0)$. This parameter condition obeys the condition in Theorem 1 (ii).

We verify Theorem 1 (ii) in the same manner to the earlier case. The only difference is in the convergence rate of the OLS estimator. Theorem 1 (ii) implies that the convergence rate of $\hat{\theta}_T^+$ is T , but the other convergence rates are the same as before. Therefore, we modify the finite sample bias and RMSE of $\hat{\theta}_T^+$ into the following:

$$\text{Bias} = \frac{1}{m} \sum_{j=1}^m T(\hat{\theta}_{T,j}^+ - \theta_*^+) \quad \text{and} \quad \text{RMSE} = \sqrt{\frac{1}{m} \sum_{j=1}^m T^2(\hat{\theta}_{T,j}^+ - \theta_*^+)^2},$$

while maintaining the previous formula for the others. We contain the finite sample biases and RMSEs in Table A.6 and observe that they converge to zero and a positive constant as the sample size increases. This corroborates that the convergence rate given in Theorem 1 (ii) is correct.

Second, we compare the finite sample null distribution of the standard t -test with the standard mixed-normal distribution. Figure A.1 (b) shows the QQ-plots between the t -tests and the standard normal distribution. The QQ-plots are distributed around the 45-degree line, corroborating the distributional property given in Theorem 1 (ii).

DGP Condition under Theorem 1 (iii) We next verify Theorem 1 (iii) in the same way. We generate data according to the DGP condition in Section A.4.1 by letting $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, 0, 1)$ and $(\omega_*, \varrho_*) = (1/2, 0)$. This parameter condition obeys the condition in Theorem 1 (iii).

We verify Theorem 1 (iii) in a manner similar to Theorem 1 (i). Theorem 1 (iii) implies that the convergence rate of $\widehat{\theta}_T^-$ is T , and the other convergence rates are \sqrt{T} . Therefore, we modify the finite sample bias and RMSE of $\widehat{\theta}_T^-$ into the following:

$$\text{Bias} = \frac{1}{m} \sum_{j=1}^m T(\widehat{\theta}_{T,j}^- - \theta_*^-) \quad \text{and} \quad \text{RMSE} = \sqrt{\frac{1}{m} \sum_{j=1}^m T^2(\widehat{\theta}_{T,j}^- - \theta_*^-)^2},$$

while maintaining the same formula for the others as in Theorem 1 (i). We contain the finite sample biases and RMSEs in Table A.7 and corroborate that the convergence rate given in Theorem 1 (iii) is correct.

Second, we draw the QQ-plots between the finite sample null distribution of the standard t -tests and the standard mixed-normal distribution. Figure A.1 (c) shows the QQ-plots and corroborates the distributional property given in Theorem 1 (iii).

DGP Condition under Theorem 1 (iv) We finally verify Theorem 1 (iv). We generate data according to the DGP condition in Section A.4.1 by letting $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 0)$ and $(\omega_*, \varrho_*) = (1/2, 0)$ to obey the condition in Theorem 1 (iv).

Given that the convergence rate of the OLS estimator is \sqrt{T} , we compute the finite sample bias and RMSE as for Theorem 1 (i) and contain them in Table A.8. We observe that they converge to zero and positive constants, respectively, as T grows. Further, the QQ-plots between the t -tests and the standard mixed-normal are distributed according to the 45-degree line. These two features corroborate Theorem 1 (iv).

A.5 Empirical Supplements

In this section, we provide additional empirical supplements.

A.5.1 Preliminary Empirical Analysis

This section provides two preliminary empirical analyses. First, Table A.9 provides the descriptive statistics of the variables examined in Sections 7.2 and A.5.2. The sample period is from 1947Q1 to 2007:Q4.

Second, Table A.10 provides the testing results using Phillips and Perron's (1988) unit-root test applied to the partial sum processes for Tables 4 and A.11. As we apply the unit-root testing by including both constant and trend, or including only constant, two testing results are provided for each variable. Except for r_t defined as the tax-to-nominal GDP ratio as given in Section A.5.2, the test results show that nonstationary data analysis has to be conducted for the other variables.

A.5.2 Tax Changes Measured by Tax-to-GDP Ratio

This section extends the work of [Romer and Romer \(2010\)](#) to investigate the long- and short-run relationships between fiscal shocks and real GDP. Rather than using the tax change logarithm τ_t , we use $\Delta r_t := (\Delta T_{1t} + \Delta T_{2t})/NY_t$, which represents the tax change-to-nominal GDP ratio, to measure the effect of fiscal policy and to specify the models corresponding to (20), (21), (22), and (23). As with Tables 4 and 5, we estimate the models using OLS and 2SNARDL. The estimation and inference results are presented in Tables A.11 and A.12, respectively. We summarize the results as follows:

- (a) For the exogenous tax change, the coefficient of y_{t-1} in Table A.11 is statistically significant at the 25% level for the NARDL and ARDL models, by the t -test. The F -test does not reject the hypothesis of no cointegration. However, the coefficient of u_{t-1} in the t -test of Table A.12 is statistically significant at the 25% and 10% levels for the NARDL and ARDL models, respectively. We give more weight to the inference results in Table A.12 than to those in Table A.11, because the long-run parameters can be estimated super-consistently by 2SNARDL. In addition, neither $\mathcal{W}_T^{(1)}$ nor $W_T^{(1)}$ rejects the symmetry hypothesis in the long-run parameters, indicating that the ARDL model can estimate a cointegrating relationship between y_t and r_t more efficiently.
- (b) The ARDL model estimation indicates that an increase in an exogenous tax shock measured by r_{t-1} reduces the long-run log real GDP by about 3%. This is close to the result of [Romer and Romer \(2010\)](#), estimating that GDP will increase by approximately 3% over three years following a tax cut of 1% of GDP.
- (c) The Wald tests $\mathcal{W}_T^{(2)}$ and $W_T^{(2)}$ do not reject the hypothesis of symmetric short-run parameters. Furthermore, neither $\mathcal{W}_T^{(3)}$ nor $W_T^{(3)}$ rejects the hypothesis of long- and short-run symmetry. This confirms that ARDL is appropriate for the long- and short-run relationships between y_t and r_t .
- (d) For endogenous and aggregate tax changes, there is negligible evidence of cointegration between real GDP and the tax change. None of the t - or F -tests in Table A.11 rejects the hypothesis of no cointegration. Furthermore, none of the coefficients of u_{t-1} in Table A.12 is statistically significant. Specifically, for the aggregate tax change, the unit-root test does not affirm that r_t is nonstationary; see Section A.5.1. Therefore, we conclude that the long- and short-run relationships can be properly estimated only by the exogenous tax change. \square

In summary, our empirical results obtained using the specification in [Romer and Romer \(2010\)](#) provide qualitatively the same results as those in Section 7. In particular, the long-run relationship between y_t and r_t captured by the cointegration coefficient is close to their estimate.

Estimation	Parameter \ T	100	500	1000	1500	2000
OLS	θ_*^+	0.0690	0.0152	0.0071	0.0051	0.0039
	θ_*^-	-0.0687	-0.0152	-0.0071	-0.0051	-0.0039
	ρ_*	-0.0557	-0.0105	-0.0048	-0.0035	-0.0026
	φ_*	0.0128	0.0024	0.0010	0.0007	0.0006
	π_*^+	-0.0019	-0.0002	0.0000	-0.0001	-0.0002
	π_*^-	0.0035	0.0005	-0.0005	0.0002	0.0000
2SNARDL	θ_*^+	-0.0573	-0.0200	-0.0099	-0.0070	-0.0054
	θ_*^-	0.0575	0.0200	0.0098	0.0070	0.0054
	ρ_*	-0.0447	-0.0049	-0.0012	-0.0008	-0.0004
	φ_*	0.0162	-0.0002	-0.0009	-0.0007	-0.0006
	π_*^+	0.0144	0.0091	0.0053	0.0037	0.0028
	π_*^-	-0.0135	-0.0088	-0.0058	-0.0036	-0.0030

Table A.1: FINITE SAMPLE BIASES OF OLS AND 2SNADL ESTIMATORS. This table shows the finite sample biases of the OLS and 2SNARDL estimators. The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/2 + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 0)$.

Estimation	Parameter \ T	100	500	1000	1500	2000
OLS	θ_*^+	0.1518	0.0533	0.0360	0.0290	0.0258
	θ_*^-	0.2059	0.0583	0.0376	0.0300	0.0265
	ρ_*	0.1020	0.0353	0.0239	0.0193	0.0172
	φ_*	0.0870	0.0364	0.0256	0.0208	0.0185
	π_*^+	0.1647	0.0685	0.0479	0.0390	0.0348
	π_*^-	0.3081	0.1240	0.0867	0.0706	0.0628
2SNARDL	θ_*^+	0.1506	0.0549	0.0367	0.0295	0.0261
	θ_*^-	0.2330	0.0617	0.0388	0.0308	0.0270
	ρ_*	0.0999	0.0349	0.0238	0.0193	0.0172
	φ_*	0.0892	0.0368	0.0259	0.0209	0.0186
	π_*^+	0.1670	0.0688	0.0480	0.0391	0.0348
	π_*^-	0.3122	0.1235	0.0865	0.0705	0.0628

Table A.2: FINITE SAMPLE ROOT MEAN SQUARE ERRORS OF OLS AND 2SNADL ESTIMATORS. This table shows the finite sample root mean square errors of the OLS and 2SNARDL estimators. The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/2 + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 0)$.

Estimation	Parameter \ T	100	500	1000	1500	2000
OLS	θ_*^+	0.0733	0.0147	0.0073	0.0050	0.0042
	θ_*^-	-0.0709	-0.0147	-0.0074	-0.0050	-0.0042
	ρ_*	-0.0565	-0.0101	-0.0049	-0.0034	-0.0028
	φ_*	0.0060	0.0004	0.0002	0.0002	0.0002
	π_*^+	-0.0207	-0.0041	-0.0017	-0.0014	-0.0014
	π_*^-	0.0041	0.0005	0.0001	0.0007	0.0006
2SNARDL	θ_*^+	-0.0626	-0.0162	-0.0081	-0.0056	-0.0046
	θ_*^-	0.0668	0.0202	0.0104	0.0071	0.0060
	ρ_*	-0.0536	-0.0071	-0.0029	-0.0019	-0.0015
	φ_*	0.0187	0.0002	-0.0003	-0.0003	-0.0002
	π_*^+	0.0060	0.0056	0.0037	0.0024	0.0018
	π_*^-	-0.0110	-0.0074	-0.0044	-0.0024	-0.0021

Table A.3: FINITE SAMPLE BIASES OF OLS AND 2SNADL ESTIMATORS. This table shows the finite sample biases of the OLS and 2SNARDL estimators. The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/4 + 1/2 \Delta x_{t-1} + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 0)$.

Estimation	Parameter \ T	100	500	1000	1500	2000
OLS	θ_*^+	0.1446	0.0503	0.0343	0.0277	0.0251
	θ_*^-	0.1936	0.0537	0.0355	0.0283	0.0256
	ρ_*	0.1000	0.0337	0.0229	0.0185	0.0168
	φ_*	0.0830	0.0345	0.0244	0.0200	0.0182
	π_*^+	0.1750	0.0707	0.0494	0.0401	0.0367
	π_*^-	0.3281	0.1253	0.0873	0.0708	0.0645
2SNARDL	θ_*^+	0.1406	0.0507	0.0345	0.0278	0.0252
	θ_*^-	0.2190	0.0561	0.0364	0.0288	0.0260
	ρ_*	0.1002	0.0332	0.0227	0.0184	0.0167
	φ_*	0.0854	0.0347	0.0246	0.0201	0.0182
	π_*^+	0.1755	0.0705	0.0494	0.0401	0.0367
	π_*^-	0.3304	0.1248	0.0871	0.0707	0.0644

Table A.4: FINITE SAMPLE ROOT MEAN SQUARE ERRORS OF OLS AND 2SNADL ESTIMATORS. This table shows the finite sample root mean square errors of the OLS and 2SNARDL estimators. The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/4 + 1/2 \Delta x_{t-1} + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 0)$.

Estimation	Parameter	Con. Rate \ T	100	500	1000	1500	2000
BIAS	θ_*^+	\sqrt{T}	0.6620	0.3218	0.2360	0.1927	0.1694
	θ_*^-	\sqrt{T}	-0.6644	-0.3208	-0.2358	-0.1925	-0.1717
	ρ_*	\sqrt{T}	-0.5290	-0.2218	-0.1608	-0.1305	-0.1133
	φ_*	\sqrt{T}	0.0998	0.0478	0.0371	0.0358	0.0284
	π_*^+	\sqrt{T}	-0.0025	-0.0159	-0.0125	0.0074	0.0045
	π_*^-	\sqrt{T}	-0.0101	-0.0040	0.0099	-0.0087	0.0082
RMSE	θ_*^+	\sqrt{T}	1.4871	1.1821	1.1389	1.1252	1.1195
	θ_*^-	\sqrt{T}	2.0415	1.2909	1.1944	1.1619	1.1475
	ρ_*	\sqrt{T}	0.9861	0.7842	0.7564	0.7480	0.7444
	φ_*	\sqrt{T}	0.8439	0.8086	0.8096	0.8051	0.8071
	π_*^+	\sqrt{T}	1.6542	1.5294	1.5141	1.5099	1.5103
	π_*^-	\sqrt{T}	3.0823	2.7777	2.7341	2.7314	2.7288

Table A.5: FINITE SAMPLE BIAS AND RMSE OF OLS ESTIMATOR. This table shows the finite sample bias and RMSE of the OLS estimator under the DGP condition of Theorem 1 (i). The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/2 + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 1)$.

Estimation	Parameter	Con. Rate \ T	100	500	1000	1500	2000
BIAS	θ_*^+	T	0.3992	0.1210	0.0944	0.0524	0.0279
	θ_*^-	\sqrt{T}	-0.5741	-0.3598	-0.2601	-0.2052	-0.1868
	ρ_*	\sqrt{T}	-0.4243	-0.2525	-0.1765	-0.1388	-0.1261
	φ_*	\sqrt{T}	0.1732	0.0997	0.0667	0.0579	0.0509
	π_*^+	\sqrt{T}	0.0050	-0.0005	0.0014	0.0004	-0.0119
	π_*^-	\sqrt{T}	0.0007	-0.0048	-0.0046	-0.0204	-0.0011
RMSE	θ_*^+	T	8.1992	7.7456	7.5341	7.4918	7.4571
	θ_*^-	\sqrt{T}	1.6527	1.3495	1.2543	1.2176	1.2066
	ρ_*	\sqrt{T}	0.9416	0.8319	0.8014	0.7881	0.7864
	φ_*	\sqrt{T}	0.8891	0.8642	0.8514	0.8458	0.8480
	π_*^+	\sqrt{T}	1.5746	1.5267	1.5126	1.5258	1.5086
	π_*^-	\sqrt{T}	2.8861	2.7729	2.7416	2.7369	2.7271

Table A.6: FINITE SAMPLE BIAS AND RMSE OF OLS ESTIMATOR. This table shows the finite sample bias and RMSE of the OLS estimator under the DGP condition of Theorem 1 (ii). The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/2 + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 0, -3/2, 1)$.

Estimation	Parameter	Con. Rate \ T	100	500	1000	1500	2000
BIAS	θ_*^+	\sqrt{T}	0.5713	0.2648	0.1867	0.1564	0.1339
	θ_*^-	T	-0.5093	-0.0685	-0.1303	-0.0330	-0.0829
	ρ_*	\sqrt{T}	-0.4594	-0.1827	-0.1256	-0.1052	-0.0904
	φ_*	\sqrt{T}	0.0750	0.0339	0.0188	0.0217	0.0176
	π_*^+	\sqrt{T}	-0.0229	-0.0083	-0.0085	-0.0036	-0.0005
	π_*^-	\sqrt{T}	0.0118	0.0079	-0.0168	0.0089	-0.0082
RMSE	θ_*^+	\sqrt{T}	1.4031	1.0743	1.0309	1.0214	1.0147
	θ_*^-	T	16.300	13.829	13.557	13.417	13.414
	ρ_*	\sqrt{T}	0.9015	0.7060	0.6809	0.6758	0.6731
	φ_*	\sqrt{T}	0.8270	0.7800	0.7828	0.7765	0.7783
	π_*^+	\sqrt{T}	1.6381	1.5289	1.5194	1.5082	1.5083
	π_*^-	\sqrt{T}	3.0672	2.7835	2.7405	2.7345	2.7232

Table A.7: FINITE SAMPLE BIAS AND RMSE OF OLS ESTIMATOR. This table shows the finite sample bias and RMSE of the OLS estimator under the DGP condition of Theorem 1 (iii). The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/2 + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, 0, 1)$.

Estimation	Parameter	Con. Rate \ T	100	500	1000	1500	2000
BIAS	θ_*^+	\sqrt{T}	0.6768	0.3285	0.2547	0.1969	0.1702
	θ_*^-	\sqrt{T}	-0.6737	-0.3247	-0.2561	-0.1951	-0.1724
	ρ_*	\sqrt{T}	-0.5513	-0.2288	-0.1751	-0.1325	-0.1143
	φ_*	\sqrt{T}	0.1251	0.0525	0.0430	0.0280	0.0258
	π_*^+	\sqrt{T}	-0.0214	-0.0032	-0.0088	-0.0020	-0.0146
	π_*^-	\sqrt{T}	0.0024	0.0173	-0.0112	0.0022	0.0142
RMSE	θ_*^+	\sqrt{T}	1.5038	1.1912	1.1460	1.1318	1.1174
	θ_*^-	\sqrt{T}	2.0446	1.2982	1.2131	1.1678	1.1444
	ρ_*	\sqrt{T}	1.0148	0.7887	0.7605	0.7527	0.7437
	φ_*	\sqrt{T}	0.8654	0.8137	0.8136	0.8055	0.8091
	π_*^+	\sqrt{T}	1.6534	1.5324	1.5218	1.5174	1.5112
	π_*^-	\sqrt{T}	3.0824	2.7782	2.7496	2.7250	2.7190

Table A.8: FINITE SAMPLE BIAS AND RMSE OF OLS ESTIMATOR. This table shows the finite sample bias and RMSE of the OLS estimator under the DGP condition of Theorem 1 (iv). The total number of repetitions is 50000. DGP: $\Delta y_t = \rho_* u_{t-1} + \varphi_* \Delta y_{t-1} + \pi_*^+ \Delta x_t^+ + \pi_*^- \Delta x_t^- + e_t$, $u_t = y_t - \beta_*^+ x_t^+ - \beta_*^- x_t^- - \zeta_*(t-1)$, $\Delta x_t = 1/2 + v_t$, and $(e_t, v_t)' \sim \text{IID } N(\mathbf{0}_2, \mathbf{I}_2)$ with $(\rho_*, \pi_*^+, \pi_*^-, \beta_*^+, \beta_*^-, \zeta_*) = (-1/2, 1/2, -1/2, 3/2, -3/2, 0)$.

	Δy_t	Exo.			Endo.			Sum.		
		$\Delta \tau_{1t}$	$\Delta \tau_{2t}$	$\Delta \tau_t$	$\Delta \tau_{1t}$	$\Delta \tau_{2t}$	$\Delta \tau_t$	$\Delta \tau_{1t}$	$\Delta \tau_{2t}$	$\Delta \tau_t$
Mean	0.8256	0.4240	-0.4704	-0.0464	0.3773	-0.1841	0.1932	0.7564	-0.6228	0.1336
Median	0.7876	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Maximum	4.0198	6.4312	0.0000	6.4312	6.7617	0.0000	6.7617	6.7617	0.0000	6.7617
Minimum	-2.7525	0.0000	-7.0965	-7.0965	0.0000	-7.1122	-7.1122	0.0000	-7.1122	-7.1122
Std. Dev.	0.9780	1.3755	1.5073	2.1364	1.3317	1.0117	1.7136	1.7775	1.7316	2.6653
Skewness	-0.0501	3.0654	-3.0598	-0.2762	3.4094	-5.4276	0.4394	2.0432	-2.5281	-0.1450
Kurtosis	4.3614	10.8514	10.8759	6.3787	13.2115	31.1514	10.4245	5.4941	7.7131	4.1776
Obs.	243	243	243	243	243	243	243	243	243	243

	Δy_t	Exo. ratio			Endo. ratio			Sum. ratio		
		Δr_{1t}	Δr_{2t}	Δr_t	Δr_{1t}	Δr_{2t}	Δr_t	Δr_{1t}	Δr_{2t}	Δr_t
Mean	0.8256	0.0246	-0.0517	-0.0271	0.0471	-0.0260	0.0211	0.0679	-0.0738	-0.0059
Median	0.7876	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Maximum	4.0198	0.6977	0.0000	0.6977	1.9542	0.0000	1.9542	1.9542	0.0000	1.9542
Minimum	-2.7525	0.0000	-1.8706	-1.8706	0.0000	-2.8214	-2.8214	0.0000	-2.8214	-2.8214
Std. Dev.	0.9780	0.0963	0.2171	0.2428	0.2245	0.2028	0.3066	0.2351	0.2876	0.3847
Skewness	-0.0501	4.6231	-5.3926	-3.7013	6.0062	-11.5395	-1.0526	5.1164	-5.9045	-1.3783
Kurtosis	4.3614	25.4621	35.2975	25.0905	41.7414	152.4675	44.1557	33.0743	45.6366	21.6860
Obs.	243	243	243	243	243	243	243	243	243	243

Table A.9: DESCRIPTIVE STATISTICS. This table shows the descriptive statistics used in Sections 7.2 and A.5.2.

PP test	y_t	Exo.			Endo.			Sum.		
		τ_{1t}	τ_{2t}	τ_t	τ_{1t}	τ_{2t}	τ_t	τ_{1t}	τ_{2t}	τ_t
PP test w/o trend	-1.4767	0.7551	-0.7188	-1.6243	-2.4701	-0.3499	-2.2743	-1.3064	-0.4173	-2.0303
<i>p</i> -value	0.5439	0.9931	0.8387	0.4686	0.1241	0.9140	0.1812	0.6270	0.9028	0.2738
PP test w/ trend	-2.3488	-1.8278	-1.3653	-1.3483	-0.7094	-2.2995	-0.8156	-0.9285	-2.0326	-2.7414
<i>p</i> -value	0.4056	0.6883	0.8686	0.8732	0.9707	0.4322	0.9618	0.9500	0.5801	0.2210

PP test	y_t	Exo. ratio			Endo. ratio			Sum. ratio		
		r_{1t}	r_{2t}	r_t	r_{1t}	r_{2t}	r_t	r_{1t}	r_{2t}	r_t
PP test w/o trend	-1.4767	0.7288	-0.7859	-1.7004	-2.5409	-0.9379	-3.0710	-1.7735	-1.8303	-2.9448
<i>p</i> -value	0.5439	0.9926	0.8210	0.4299	0.1071	0.7749	0.0301	0.3932	0.3652	0.0418
PP test w/ trend	-2.3488	-1.8466	-2.3558	-2.2056	-1.5667	-2.0336	-2.6499	-1.3375	-2.3690	-3.4114
<i>p</i> -value	0.4056	0.6790	0.4019	0.4840	0.8033	0.5796	0.2587	0.8761	0.3949	0.0521

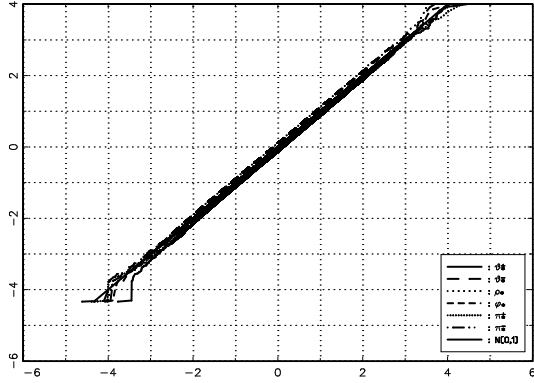
Table A.10: PHILLIPS AND PERRON'S (1988) UNIT-ROOT TESTS APPLIED TO THE QUARTERLY DATA IN ROMER AND ROMER (2010). Two Phillips and Perron's test statistics are computed using the data in Table A.9 by including the time trend and/or the constant. The lag lengths are selected by BIC.

NARDL Model				ARDL Model			
Variables \ Tax	Exo. ratio	Endo. ratio	Sum. ratio	Variables \ Tax	Exo. ratio	Endo. ratio	Sum. ratio
y_{t-1}	-0.0609 [†] (0.0184)	-0.0633 (0.0251)	-0.0460 (0.0177)	y_{t-1}	-0.0552 [†] (0.0163)	-0.0658 (0.0247)	-0.0400 (0.0160)
r_{t-1}^+	-0.1992 [†] (0.1349)	0.0850 (0.0954)	0.0037 (0.0789)	r_{t-1}	-0.1125 [†] (0.0743)	0.1003 (0.0925)	-0.0351 (0.0618)
r_{t-1}^-	-0.0970 [†] (0.0801)	0.0401 (0.1345)	-0.0566 (0.0645)				
Trend	0.0499*** (0.0173)	0.0488** (0.0200)	0.0324** (0.0136)	Trend	0.0419*** (0.0127)	0.0520*** (0.0194)	0.0317*** (0.0135)
Constant	0.2683 (0.2363)	0.3673 [†] (0.2380)	0.3685* (0.2047)	Constant	0.4054** (0.1787)	0.4700*** (0.1663)	0.5261*** (0.1543)
Δy_{t-1}	0.3095*** (0.0639)	0.3144*** (0.0672)	0.3049*** (0.0657)	Δy_{t-1}	0.3042*** (0.0636)	0.3115*** (0.0660)	0.2921*** (0.0650)
Δy_{t-2}	0.1223* (0.0652)	0.1265* (0.0660)	0.1139* (0.0651)	Δy_{t-2}	0.1168* (0.0644)	0.1242* (0.0657)	0.1073* (0.0648)
Δr_t^+	0.1638 (0.6215)	0.2465 (0.2788)	0.1778 (0.2621)	Δr_t	0.1725 (0.6180)	0.2553 (0.2776)	0.1467 (0.2609)
Δr_t^-	-0.2706 (0.2734)	-0.1477 (0.3051)	-0.2350 (0.2087)				
AIC	2.6831	2.6925	2.6895	AIC	2.6739	2.6780	2.6814
BIC	2.8133	2.8226	2.8196	BIC	2.7751	2.7792	2.7826
t -test	-3.3087 [†]	-2.5198	-2.5917	t -test	-3.3867 [†]	-2.6602	-2.4960
F -test	3.9276	3.5933	3.4873	F -test	5.7417	5.2684	4.8210
$\mathcal{W}_T^{(1)}$					52.7574 (0.1294)	2.1358 (0.7290)	48.9740 (0.2581)
$\mathcal{W}_T^{(2)}$					0.0722 (0.8015)	0.8121 (0.4021)	0.4782 (0.4981)
$\mathcal{W}_T^{(3)}$					52.8296 (0.1340)	2.9480 (0.7595)	49.4522 (0.2610)
$W_T^{(1)}$					0.5384 (0.5697)	0.3344 (0.6463)	0.8601 (0.5035)
$W_T^{(2)}$					0.4079 (0.5278)	0.9926 (0.3177)	1.5118 (0.2279)
$W_T^{(3)}$					1.0869 (0.6618)	1.2200 (0.6150)	2.1652 (0.4681)

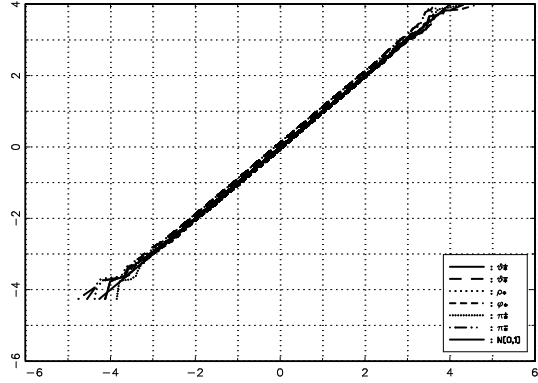
Table A.11: OLS ESTIMATION OF THE NARDL AND ARDL MODELS. This table presents the OLS estimation using quarterly data from [Romer and Romer \(2010\)](#). The left and right panels display estimated parameters for (23) and (21) using r_t instead of τ_t , respectively. Figures in parentheses indicate standard errors of the OLS estimates. At the bottom of the top panels, AIC, BIC, t -test, and [Pesaran et al.'s \(2001\)](#) F -test are reported. [†], *, **, and *** indicate significance at 25%, 10%, 5%, and 1% levels, respectively. Wald tests in the last two bottom panels show the Wald tests in Section 5 and the standard Wald tests. Figures in parentheses below the Wald tests show p -values. They are obtained from 100000 bootstrap iterations.

	NARDL Model				ARDL Model			
	Variables \ Tax	Exo. ratio	Endo. ratio	Sum. ratio	Variables \ Tax	Exo. ratio	Endo. ratio	Sum. ratio
Long-Run	Constant	-2.5602 (2.4603)	-2.5888** (1.1990)	-2.9531 (2.5202)	Constant	-0.3468 (2.3897)	-2.2311* (1.2927)	-1.0492 (2.8199)
	r_{t-1}^+	-6.7407*** (2.0794)	4.2616*** (0.5100)	4.5455*** (1.2686)	r_{t-1}	-3.0752** (1.2428)	3.3960*** (0.5463)	2.2608* (1.2356)
	r_{t-1}^-	-2.8360* (1.5211)	5.1176*** (0.9583)	2.7623** (1.2373)				
	Trend	0.8364*** (0.0166)	0.8391*** (0.0081)	0.8435*** (0.0170)	Trend	0.8242*** (0.0161)	0.8370*** (0.0087)	0.8295*** (0.0190)
Short-Run	u_{t-1}	-0.0609 [†] (0.0184)	-0.0633 (0.0251)	-0.0460 (0.0177)	u_{t-1}	-0.0558* (0.0162)	-0.0627 (0.0248)	-0.0378 (0.0160)
	Constant	0.6763*** (0.1484)	0.6693*** (0.1510)	0.6719*** (0.1534)	Constant	0.5730*** (0.1470)	0.6828*** (0.1468)	0.6517*** (0.1464)
	Δy_{t-1}	0.3095*** (0.0639)	0.3144*** (0.0672)	0.3049*** (0.0657)	Δy_{t-1}	0.3038*** (0.0635)	0.3127*** (0.0669)	0.3007*** (0.0656)
	Δy_{t-2}	0.1223* (0.0652)	0.1265* (0.0660)	0.1139* (0.0651)	Δy_{t-2}	0.1149* (0.0644)	0.1220* (0.0658)	0.1070 [†] (0.0648)
	Δr_t^+	0.1638 (0.6215)	0.2465 (0.2788)	0.1778 (0.2621)	Δr_t	-0.2094 (0.2435)	0.0801 (0.2087)	-0.0737 (0.1596)
	Δr_t^-	-0.2706 (0.2734)	-0.1477 (0.3051)	-0.2350 (0.2087)				

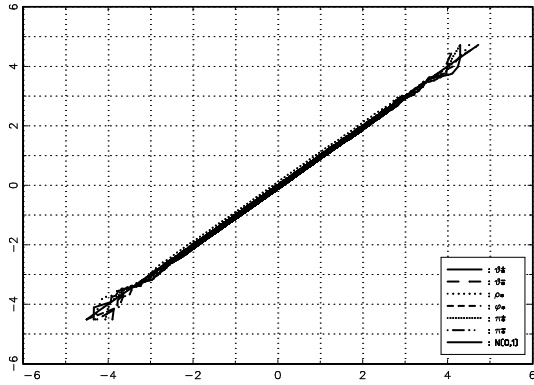
Table A.12: 2SNARDL ESTIMATION OF THE NARDL AND ARDL MODELS. This table presents the 2SNARDL estimation using the quarterly data from [Romer and Romer \(2010\)](#). The left and right panels display estimated parameters for (22) and (20), respectively. [†], *, **, and *** imply that the tests are significant at 25%, 10%, 5%, and 1%, respectively.



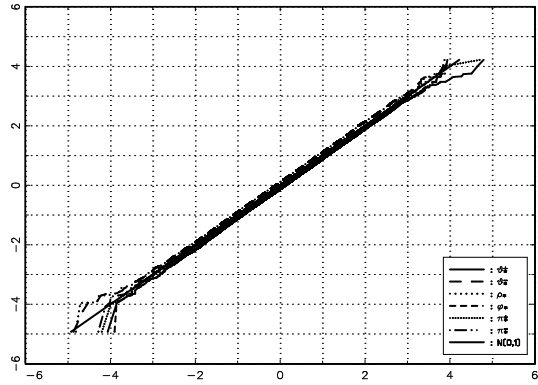
(a) DGP under Theorem 1 (i)



(b) DGP under Theorem 1 (ii)



(c) DGP under Theorem 1 (iii)



(d) DGP under Theorem 1 (iv)

Figure A.1: QQ-PLOTS OF THE t -TESTS UNDER THE NULL AND DGP CONDITIONS IN THEOREM 1. This figure shows the QQ-plots of the t -tests defined by $\hat{\theta}_T^+$, $\hat{\theta}_T^-$, $\hat{\rho}_T$, $\hat{\varphi}_T$, $\hat{\pi}_T^+$, and $\hat{\pi}_T^-$ under the null hypothesis and the DGP conditions in Theorem 1. To draw the QQ-plots, we let $T = 3000$ and computed the standard t -test using the OLS estimator. Total number of independent experiments is 50000.