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Semiparametric Estimation of Partially Varying-Coefficient Dynamic Panel Data Models

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This paper studies a new class of semiparametric dynamic panel data models, in which some of coefficients are allowed to depend on other informative variables and some of the regressors can be endogenous. To estimate both parametric and nonparametric coefficients, a three-stage estimation method is proposed. A nonparametric generalized method of moments (GMM) is adopted to estimate all coefficients firstly and an average method is used to obtain the root-N consistent estimator of parametric coefficients. At the last stage, the estimator of varying coefficients is obtained by the partial residuals. The consistency and asymptotic normality of both estimators are derived. Monte Carlo simulations are conducted to verify the theoretical results and to demonstrate that the proposed estimators perform well in a finite sample.

Keywords Dynamic panel data; Nonparametric GMM; Varying coefficients.

JEL Classification C23; C14; C13.

1. INTRODUCTION

Dynamic panel data models have received a lot of attentions among both theoretical and empirical economists since the seminal work of Balestra and Nerlove (1966). Based on the early work by Anderson and Hsiao (1981, 1982), there exists a rich literature on using the generalized method of moments (GMM) to estimate the dynamic panel data model and on discussing the efficiency of the estimation. For example, Holtz-Eakin et al. (1988) considered the estimation of vector autoregressions with panel data, Arellano and Bond

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(1991), Arellano and Bover (1995), Ahn and Schmidt (1995), Hahn (1997, 1999), and others discussed how to utilize additional instruments to improve the efficiency of GMM estimation. Dynamic panel data models have been widely applied to various empirical studies as well. For example, Baltagi and Levin (1986) estimated the dynamic demand for addictive commodities, Islam (1995) used dynamic panel data approach to study growth empirics, and Park et al. (2007) employed dynamic panel data to analyze the demand between city pairs for some airlines. More references can be found in Arellano (2003), Hsiao (2003), and Baltagi (2005).

It is well known, however, that the aforementioned parametric dynamic panel data models might not be flexible enough to catch nonlinear structure so that they might suffer from the model misspecification. To deal with this misspecification issue, various nonparametric or semiparametric static panel data models have been proposed. For example, Horowitz and Markatou (1996), Li et al. (2002), and Su and Ullah (2006) studied semiparametric estimation of a partially linear panel data model without endogenous regressors, Hoover et al. (1998) considered a smoothing spline and a local polynomial estimation for time-varying coefficient panel data models, Lin and Ying (2001) and Lin and Carroll (2001, 2006) examined the semiparametric estimation of a panel data model with random effects, and Henderson et al. (2008) considered a partially linear panel data model with fixed effects and proposed a consistent estimator based on iterative backfitting procedures and an initial estimator. Finally, Qian and Wang (2012) proposed a marginal integration method to estimate the nonparametric part in a semiparametric panel data with unobserved individual effects.

In recent years, motivated by the increase in the empirical economic growth literature, many studies have paid an attention to the dynamic panel data models. For example, Li and Stengos (1996), Li and Ullah (1998), and Baltagi and Li (2002) considered semiparametric estimation of partially linear dynamic panel data models using instrumental variable methods. Park et al. (2007) focused on constructing a semiparametric efficient estimator in a dynamic panel data model. They considered a linear dynamic panel data model assuming that the error terms are generating from a normal distribution but specifying other parametric distributions nonparametrically. An efficient estimator was established based on a stochastic expansion. However, they ignored the endogenous problem in a dynamic panel data model by assuming all the error terms and the random effects are independent of regressors.

Recently, Cai and Li (2008) proposed a nonparametric GMM estimation of varying-coefficient dynamic panel data models to deal with the potential endogeneity issue. Varying-coefficient models are well known in the statistic literature and also have a lot of applications in economics and finance (Hastie and Tibshirani, 1993; Cai et al., 2000, 2006; Cai and Hong, 2009; Cai et al., 2009, 2012; among others); see Cai (2010) for more details in applications in economics and finance. One of the main advantages of the varying-coefficient models is that it allows coefficients to depend on some informative variables and then balances the dimension reduction and model flexibility.

In this article, we consider a new class of partially varying-coefficient dynamic models. It allows for linearity in some regressors and nonlinearity in other regressors. In other words, some coefficients are constant and others are varying over some variables. The new class model is flexible enough to include many existing models as special cases. By extending the model in Cai and Li (2008) to a partially varying-coefficient model, we reduce the model dimension without influencing the degree of the model flexibility, and furthermore, the root-N consistent estimation of parametric coefficients can be achieved. We propose a three-stage estimation procedure to estimate both the constant and varying coefficients. At the first stage, all coefficients are treated as varying coefficients and then the nonparametric GMM proposed by Cai and Li (2008) is adopted. At the second stage, the constant coefficients are estimated by the average method and the root-N consistency and asymptotic normality of the estimators are derived. Finally, the estimators at the second stage are plugged into the original model to obatin the partial residuals and then the estimators of varying coefficients are obtained by employing the nonparametric GMM again. The partially varying-coefficient panel data model can be applied to various empirical applications. For example, Lin et al. (2006) and Zhou and Li (2011) employed a special case of the partially varying-coefficient models to investigate the so called Kuznet's hypothesis which claims an inverted-U relation between inequality and economic development.

Compared with the existing literature, our paper has the following merits. Firstly, in the existing literature, it is common to adopt the Robinson's (1988) framework to estimate a semiparametric panel data model with endogeneity. When endogenous variables appear in the model, a two-stage estimation is required, where a high dimensional nonparametric estimation, in which the dimension depends on the number of excluded instruments and included exogenous variables, is usually employed at the first stage, and then an instrumental variable regression is adopted using first-stage nonparametric estimators as generated regressors. However, the nonparametric GMM adopted in this paper only requires an one-step relatively low dimensional estimation. The dimension of the estimation depends on the number of smoothing variables rather than the included and excluded exogenous variables. Since the nonparametric GMM is adopted at the first stage, some popular semiparametric estimation methods, such as Robinson's (1988) method and profile least squares method, cannot be applied here to estimate the parametric part. Instead, we propose the average method by taking average of all local estimates to obtain the root-N consistent estimation of parametric coefficients. Finally, varying coefficients can be estimated by applying the low dimensional nonparametric GMM by using the partial residuals.

The rest of the paper is organized as follows. Section 2 introduces the model and estimation procedures. We present the asymptotic results of the proposed estimators in Section 3. Section 4 reports the Monte Carlo simulations to verify the theoretical results and to demonstrate the finite sample performance of the proposed estimators. Finally, Section 5 concludes. All technical proofs are relegated to the Appendices.

2. THE MODEL AND ESTIMATION PROCEDURES

This paper considers a new class of partially varying-coefficient(dynamic) panel data models as follows:

$$Y_{it} = \boldsymbol{X}'_{it,1}\gamma + \boldsymbol{X}'_{it,2}\boldsymbol{\beta}(U_{it}) + \epsilon_{it}, \quad 1 \le i \le N, \; 1 \le t \le T, \tag{1}$$

where Y_{it} is a scalar dependent variable, U_{it} is a scalar smoothing variable,[1] $\boldsymbol{X}_{it,1}$ and $\boldsymbol{X}_{it,2}$ are regressors with $d_1 \times 1$ and $d_2 \times 1$ dimensions, respectively, $\boldsymbol{\gamma}$ denotes $d_1 \times 1$ constant coefficients and $\boldsymbol{\beta}(\cdot)$ denotes $d_2 \times 1$ varying coefficients, and the random error ϵ_{it} allows to be correlated over period t but independent over i. We consider a typical panel data model such that N is large but T is relatively short. Moreover, let $\boldsymbol{X}_{it} = (\boldsymbol{X}'_{it,1}, \boldsymbol{X}'_{it,2})'$ with dimension $d \times 1$ where $d = d_1 + d_2$. In particular, in model (1) $\boldsymbol{X}_{it}$ may contain lagged variables of Y_{it} and endogenous variables correlated with the error term so that the classical dynamic panel model can be regarded as a special case. Also, the above setup is quite flexible to capture a complex dynamic structure in real applications in economics. For example, Li and Stengos (1996), Li and Ullah (1998), and Baltagi and Li (2002) considered a special case by assuming that $\boldsymbol{X}_{it,2}$ only contains a constant term and the above model reduces to the model as in Das (2005) when $\boldsymbol{X}_{it,2}$ is a discrete value random variable. Cai and Li (2008) studied a varying-coefficient model without the parametric part. The papers by Fan and Huang (2005) and Lin et al. (2006) studied model (1) without endogeneity.

In model (1), an ordinary least squares estimation cannot be applied since the orthogonality condition fails, i.e., $E[\epsilon_{it} \mid \boldsymbol{X}_{it}, U_{it}] \neq 0$. Hence, we assume that there exists $\boldsymbol{W}_{it}$, a $q \times 1$ vector of instruments,[2] to satisfy $E[\epsilon_{it} \mid \boldsymbol{V}_{it}] = 0$, where $\boldsymbol{V}_{it} = (\boldsymbol{W}'_{it}, U_{it})'$. By choosing an appropriate vector function $Q(\boldsymbol{V}_{it})$, we have the following conditional moment conditions,

$$E[Q(\boldsymbol{V}_{it})\epsilon_{it} \mid \boldsymbol{V}_{it}] = 0. \tag{2}$$

Instead of using a nonparametric projection of some endogenous components in $\boldsymbol{X}_{it}$ on $Q(\boldsymbol{V}_{it})$, the nonparametric GMM (Cai and Li, 2008) is applied to estimate all varying coefficients at the first stage. At this step, all coefficients are treated to be varying so that $\boldsymbol{\gamma} = \boldsymbol{\gamma}(U_{it})$ and $\boldsymbol{\beta} = \boldsymbol{\beta}(U_{it})$ although $\boldsymbol{\gamma}$ is constant. By assuming that $\boldsymbol{\beta}(\cdot)$ and $\boldsymbol{\gamma}(\cdot)$ are

[1]For simplicity, we only consider the univariate case for the smoothing variable. The estimation procedure and asymptotic results still hold for the multivariate case with much complicated notation.

[2]Instruments should be highly correlated to the endogenous variables and uncorrelated to the structural errors. Cai, Li, et al. (2012) and Cai, Su, et al. (2012) studied the instrumental variable estimation using weak instruments in a panel data model. Berkowitz et al. (2008, 2012) investigated the impact on estimation and testing when instruments are slightly correlated with random errors.

continuous, we apply a local constant approximation to $\boldsymbol{\gamma}(U_{it})$ and $\boldsymbol{\beta}(U_{it})$. Then, model (1) is approximated by the following model in a small neighborhood of u_0:

$$Y_{it} \approx \boldsymbol{X}_{it}'\boldsymbol{\theta} + \epsilon_{it}, \quad 1 \le i \le N, \ 1 \le t \le T, \tag{3}$$

where $\boldsymbol{\theta} = \boldsymbol{\theta}(u_0) = (\boldsymbol{\gamma}'(u_0), \boldsymbol{\beta}'(u_0))'$ is a $d \times 1$ vector of parameters. By following Cai and Li (2008), the sample version of the locally weighted moment conditions becomes $\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{Q}(\boldsymbol{V}_{it})(Y_{it} - \boldsymbol{X}_{it}'\boldsymbol{\theta})K_{h_1}(U_{it} - u_0) = 0$,[3] and the nonparametric GMM estimator is given by

$$\hat{\boldsymbol{\theta}} = \hat{\boldsymbol{\theta}}(u_0) = (\boldsymbol{\Omega}_N'\boldsymbol{\Omega}_N)^{-1}\boldsymbol{\Omega}_N'\boldsymbol{\Phi}_N, \tag{4}$$

where $\boldsymbol{\Omega}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{Q}_{it}\boldsymbol{X}_{it}'K_{h_1}(U_{it} - u_0)$ and $\boldsymbol{\Phi}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{Q}_{it}K_{h_1}(U_{it} - u_0)Y_{it}$. We simply choose instruments $\boldsymbol{Q}_{it}$ to be $\boldsymbol{V}_{it}$ by following the discussion in Cai and Li (2008). Note that we require $q \ge d$ to satisfy the identification condition, and also that $K_{h_1}(\cdot) = h_1^{-1}K(\cdot/h_1)$, where $K(\cdot)$ is a kernel function with a bandwidth $h_1 = h_{1N} > 0$ which controls the degree of smoothing used in the nonparametric GMM estimation.

At the second stage, in order to take advantage of the full sample information to estimate the constant parameter $\boldsymbol{\gamma}$, we employ the average method to achieve the root-N consistent estimator of $\boldsymbol{\gamma}$:

$$\hat{\boldsymbol{\gamma}} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} \hat{\boldsymbol{\gamma}}(U_{it}). \tag{5}$$

The $\hat{\boldsymbol{\gamma}}(U_{it})$ is the first d_1 components in $\hat{\boldsymbol{\theta}}$.

The last step is to estimate the nonparametric part, the functional coefficients $\boldsymbol{\beta}(U_{it})$, by plugging a root-N consistent estimator $\hat{\boldsymbol{\gamma}}$ into model (1). To this end, we define the partial residual $Y_{it}^* = Y_{it} - \boldsymbol{X}_{it,1}'\hat{\boldsymbol{\gamma}}$. Hence, model (1) can be approximated by

$$Y_{it}^* \approx \boldsymbol{P}_{it}'\boldsymbol{\delta} + \epsilon_{it}, \quad 1 \le i \le N, \ 1 \le t \le T, \tag{6}$$

where $\boldsymbol{\delta} = \boldsymbol{\delta}(u_0) = (\boldsymbol{\beta}'(u_0), \dot{\boldsymbol{\beta}}'(u_0))'$, $\dot{\boldsymbol{\beta}}(\cdot)$ denotes the first order derivatives of $\boldsymbol{\beta}(\cdot)$ with respect to U_{it}, and $\boldsymbol{P}_{it} = \binom{X_{it,2}}{X_{it,2} \otimes (U_{it} - u_0)}$ is a $(2d_2) \times 1$ vector. Hence, the nonparametric GMM estimator of the varying coefficients are given by

$$\hat{\boldsymbol{\delta}} = \hat{\boldsymbol{\delta}}(u_0) = (\boldsymbol{S}_N'\boldsymbol{S}_N)^{-1}\boldsymbol{S}_N'\boldsymbol{T}_N, \tag{7}$$

[3]To obtain a unique $\boldsymbol{\theta}$ satisfying the above moment condition, we follow Cai and Li (2008) by pre-multiplying it by $\boldsymbol{\Omega}_N'$.

where $\boldsymbol{S}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{Q}_{it}\boldsymbol{P}'_{it}K_{h_2}(U_{it}-u_0)$ and $\boldsymbol{T}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{Q}_{it}K_{h_2}(U_{it}-u_0)Y_{it}^*$ with $K_{h_2}(\cdot) = h_2^{-1}K(\cdot/h_2)$ and the bandwidth $h_2 = h_{2N} > 0$. Motivated by the local linear fitting, a simple choice of $\boldsymbol{Q}_{it}$ suggested by Cai and Li (2008) is a $(2q)\times 1$ vector

$$\boldsymbol{Q}_{it} = \begin{pmatrix} \boldsymbol{W}_{it} \\ \boldsymbol{W}_{it}\otimes(U_{it}-u_0)/h_2 \end{pmatrix},$$

which is used at the last stage. Note that it is assumed that $\boldsymbol{\beta}(\cdot)$ is twice continuously differentiable.

3. ASYMPTOTIC THEORIES

In this section, we derive the asymptotic results of both estimators $\hat{\gamma}$ and $\hat{\boldsymbol{\beta}}(u_0)$. The detailed proofs are relegated to the Appendices. Firstly, we give some notations and definitions which will be used in the rest of the paper. Denote $\mu_j = \int_{-\infty}^{\infty}u^jK(u)du$ and $v_j = \int_{-\infty}^{\infty}u^jK^2(u)du$ with $j \geq 0$. Let $\sigma^2(\boldsymbol{v}) = Var(\epsilon_{it}\mid \boldsymbol{V}_{it} = \boldsymbol{v})$, $\boldsymbol{\Omega} = \boldsymbol{\Omega}(u_0) = E(\boldsymbol{V}_{it}\boldsymbol{X}'_{it}\mid u_0)$, $\tilde{\boldsymbol{\Omega}} = \tilde{\boldsymbol{\Omega}}(u_0) = E(\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\mid u_0)$, $\boldsymbol{\Phi} = \boldsymbol{\Phi}(u_0) = Var(\boldsymbol{V}_{it}\epsilon_{it}\mid u_0)$, $\sigma_{1t}(\boldsymbol{V}_{i1},\boldsymbol{V}_{it}) = E(\epsilon_{i1}\epsilon_{it}\mid \boldsymbol{V}_{i1},\boldsymbol{V}_{it})$, and $\boldsymbol{G}_{1t}(U_{i1},U_{it}) = E\{\boldsymbol{V}_{i1}\boldsymbol{V}'_{it}\sigma_{1t}\mid U_{i1},U_{it}\}$. Moreover, define $\boldsymbol{S} = \boldsymbol{S}(u_0) = \begin{pmatrix} \tilde{\boldsymbol{\Omega}} & \boldsymbol{0} \\ \boldsymbol{0} & \mu_2\tilde{\boldsymbol{\Omega}} \end{pmatrix}$. Next, note that $\boldsymbol{\Phi}_N = \boldsymbol{\Omega}_N\boldsymbol{\theta} + \boldsymbol{\Phi}_N^* + \boldsymbol{\Psi}_N + \boldsymbol{\Lambda}_N$, where

$$\boldsymbol{\Phi}_N^* = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}K_{h_1}(U_{it}-u_0)\boldsymbol{Q}_{it}\epsilon_{it},$$

$$\boldsymbol{\Psi}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}K_{h_1}(U_{it}-u_0)\boldsymbol{Q}_{it}\sum_{j=1}^{d}\psi_j(U_{it},u_0)X_{itj},$$

$$\text{and}\quad \boldsymbol{\Lambda}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}K_{h_1}(U_{it}-u_0)\boldsymbol{Q}_{it}\sum_{j=1}^{d}\Lambda_j(U_{it},u_0)X_{itj}$$

with $\psi_j(U_{it},u_0) = \dot{\theta}_j(u_0)(U_{it}-u_0) + \frac{1}{2}\ddot{\theta}_j(u_0)(U_{it}-u_0)^2$ and $\Lambda_j(U_{it},u_0) = \theta_j(U_{it}) - \theta_j(u_0) - \dot{\theta}_j(u_0)(U_{it}-u_0) - \frac{1}{2}\ddot{\theta}_j(u_0)(U_{it}-u_0)^2$. Substituting it into (4), we have

$$(\hat{\boldsymbol{\theta}}-\boldsymbol{\theta}) - (\boldsymbol{\Omega}'_N\boldsymbol{\Omega}_N)^{-1}\boldsymbol{\Omega}'_N\boldsymbol{\Psi}_N - (\boldsymbol{\Omega}'_N\boldsymbol{\Omega}_N)^{-1}\boldsymbol{\Omega}'_N\boldsymbol{\Lambda}_N = (\boldsymbol{\Omega}'_N\boldsymbol{\Omega}_N)^{-1}\boldsymbol{\Omega}'_N\boldsymbol{\Phi}_N^*. \tag{8}$$

It is showed that the second term on the left side determines the bias, the last term on the left can be asymptotically ignored, and the term on the right follows the asymptotic normality. To establish the asymptotic results for the proposed estimators, following assumptions are needed although they might not be the weakest ones.

Assumptions.

A1. $\{(\boldsymbol{W}_{it},\boldsymbol{X}_{it},Y_{it},U_{it},\epsilon_{it})\}$ are independently and identically distributed across the i index for each fixed t and strictly stationary over t for each fixed i, $E\|\boldsymbol{W}_{it}\boldsymbol{X}'_{it}\|^2 < \infty$,

$E\|\boldsymbol{W}_{it}\boldsymbol{W}_{it}'\|^2 < \infty$, $E(\epsilon_{it}) = 0$, and $E|\epsilon_{it}|^4 < \infty$, where $\|\cdot\|^2$ is the standard L_2-norm for a finite-dimensional matrix.

A2. For each $t \geq 1$, $\boldsymbol{G}_{1t}(U_{i1}, U_{it})$ is continuous at (U_{i1}, U_{it}). Also, for each u_0, $\boldsymbol{\Omega}(u_0) > 0$ and $f(u_0) > 0$, which is the density function of U_{it} at u_0. Further, $sup_{t\geq 1}|\boldsymbol{G}_{1t}(u_0, u_0)f(u_0)| \leq \boldsymbol{M}(u_0) < \infty$ for some function $\boldsymbol{M}(u_0)$. Finally, $\boldsymbol{\beta}(u_0)$ and $f(u_0)$ are both twice continuously differentiable.

A3. The kernel function $K(\cdot)$ is a symmetric and bounded density with a bounded support.

A4. The variable $\boldsymbol{V}_{it}$ satisfies the instrument exogeneity condition that $E(\epsilon_{it} \mid \boldsymbol{V}_{it}) = 0$.

A5. $h_1 \to 0$, $h_2 \to 0$, $Nh_1 \to \infty$ and $Nh_2 \to \infty$ as $N \to \infty$. Furthermore, $h_1 = o(h_2)$.

To derive the asymptotic properties for $\hat{\boldsymbol{\theta}}$ and $\hat{\boldsymbol{\gamma}}$, we first prove the following preliminary results.

Proposition 1. *Under Assumptions A1–A5, we have, as follows:*

$$(i)\ \boldsymbol{\Omega}_N = f(u_0)\boldsymbol{\Omega}[1 + o_p(1)];$$

$$(ii)\ \boldsymbol{\Psi}_N = \frac{h_1^2}{2} f(u_0)\mu_2[2(\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega}\frac{\dot{f}(u_0)}{f(u_0)})\dot{\boldsymbol{\theta}} + \boldsymbol{\Omega}\ddot{\boldsymbol{\theta}}] + o_p(h_1^2);$$

$$(iii)\ \boldsymbol{\Lambda}_N = o_p(h_1^2);$$

$$(iv)\ Nh_1 Var(\boldsymbol{\Phi}_N^*) \to \frac{1}{T} f(u_0)\boldsymbol{\Phi}.$$

Clearly, by Proposition 1 and (8), we can obtain

$$(\hat{\boldsymbol{\theta}} - \boldsymbol{\theta}) - bias_{\boldsymbol{\theta}} = f^{-1}(u_0)(\boldsymbol{\Omega}'\boldsymbol{\Omega})^{-1}\boldsymbol{\Omega}'\boldsymbol{\Phi}_N^*[1 + o_p(1)], \tag{9}$$

where $bias_{\boldsymbol{\theta}} = \frac{h_1^2}{2} f(u_0)\mu_2[2((\boldsymbol{\Omega}'\boldsymbol{\Omega})^{-1}\boldsymbol{\Omega}'\dot{\boldsymbol{\Omega}} + \frac{\dot{f}(u_0)}{f(u_0)})\dot{\boldsymbol{\theta}} + \ddot{\boldsymbol{\theta}}] + o_p(h_1^2)$. The next two theorems demonstrate the consistency and asymptotic normality of $\hat{\boldsymbol{\gamma}}$, respectively.

Theorem 1. *Under Assumptions A1–A5, we have*

$$(\hat{\boldsymbol{\theta}} - \boldsymbol{\theta}) - bias_{\boldsymbol{\theta}} = o_p(h_1^2) + O_p((Nh_1)^{-1/2}), \tag{10}$$

which implies the consistency of $\hat{\boldsymbol{\theta}}$.

Remark 1. As defined earlier, $\boldsymbol{\theta} = \boldsymbol{\theta}(u_0) = (\boldsymbol{\gamma}'(u_0), \boldsymbol{\beta}'(u_0))'$ so that $\hat{\boldsymbol{\gamma}}$ is the first d_1 component in $\hat{\boldsymbol{\theta}}$. Thus, we have

$$\hat{\gamma} - \gamma = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} e_1'[(\hat{\boldsymbol{\theta}}(U_{it}) - \boldsymbol{\theta}(U_{it})) - bias_{\boldsymbol{\theta}}] + O_p(N^{-1/2})$$
$$= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}[\hat{\gamma}(U_{it}) - \gamma(U_{it}) - bias_{\gamma}(u_0)] + O_p(N^{-1/2}), \tag{11}$$

where the selection matrix $e_1' = (\boldsymbol{I}_{d_1}, \boldsymbol{0}_{d_1 \times d_2})$ and $bias_{\gamma}(u_0) = e_1' bias_{\boldsymbol{\theta}}(u_0)$.

Theorem 2. *Under Assumptions A1–A5, we have*

$$\sqrt{N}(\hat{\gamma} - \gamma - bias_{\gamma}) \xrightarrow{D} N\left(0, \frac{1}{T}\boldsymbol{\Sigma}_{\gamma}\right), \tag{12}$$

where $\boldsymbol{\Sigma}_{\gamma} = E\{e_1'[\boldsymbol{D}(U_{it})\boldsymbol{\Phi}(U_{it})\boldsymbol{D}'(U_{it}) + \frac{2}{T}\sum_{t=2}^{T}(T - t + 1)\boldsymbol{D}(U_{i1})\boldsymbol{G}_{1t}(U_{i1}, U_{it})\boldsymbol{D}'(U_{it})]e_1\}$ *with* $\boldsymbol{D}(U_{it}) = (\boldsymbol{\Omega}'(U_{it})\boldsymbol{\Omega}(U_{it}))^{-1}\boldsymbol{\Omega}'(U_{it})$ *and* $bias_{\gamma} = E[bias_{\gamma}(U_{it})]$.

Remark 2. As $Nh_1^4 \to 0$, the bias term in the above theorem shrinks toward zero, which implies that we need to undersmooth at the first step to reduce the influence of the bias term that may be brought to the second step, while in the meantime, the effect of the first-step bandwidth selection on the variance can be smoothed out by using the average method. Note that the undersmoothing condition $Nh_1^4 \to 0$ is commonly imposed for a semiparametric model.

Finally, we embrace on the nonparametric estimation of $\boldsymbol{\beta}(u_0)$. Similar to the decomposition of $\boldsymbol{\Phi}_N$, we have $\boldsymbol{T}_N = \tilde{\boldsymbol{S}}_N \boldsymbol{H}\boldsymbol{\delta} + \boldsymbol{T}_N^* + \boldsymbol{B}_N + \boldsymbol{R}_N$, where

$$\boldsymbol{T}_N^* = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_2}(U_{it} - u_0)\boldsymbol{Q}_{it}\boldsymbol{\epsilon}_{it},$$

$$\boldsymbol{B}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_2}(U_{it} - u_0)\boldsymbol{Q}_{it}\frac{1}{2}\sum_{j=1}^{d_2}\ddot{\beta}_j(u_0)(U_{it} - u_0)^2 X_{it,2j},$$

$$\text{and} \quad \boldsymbol{R}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_2}(U_{it} - u_0)\boldsymbol{Q}_{it}\sum_{j=1}^{d_2} Rj(U_{it}, u_0)X_{it,2j}$$

with $R_j(U_{it}, u_0) = \beta_j(U_{it}) - a_j - b_j(U_{it} - u_0) - \frac{1}{2}\ddot{\beta}_j(u_0)(U_{it} - u_0)^2$. Hence,

$$\boldsymbol{H}(\hat{\boldsymbol{\delta}} - \boldsymbol{\delta}) - [\tilde{\boldsymbol{S}}_N'\tilde{\boldsymbol{S}}_N]^{-1}\tilde{\boldsymbol{S}}_N'\boldsymbol{B}_N - [\tilde{\boldsymbol{S}}_N'\tilde{\boldsymbol{S}}_N]^{-1}\tilde{\boldsymbol{S}}_N'\boldsymbol{R}_N = [\tilde{\boldsymbol{S}}_N'\tilde{\boldsymbol{S}}_N]^{-1}\tilde{\boldsymbol{S}}_N'\boldsymbol{T}_N^*, \tag{13}$$

where $\boldsymbol{H} = (\boldsymbol{I}_{d_2}, h_2\boldsymbol{I}_{d_2})$ and $\tilde{\boldsymbol{S}}_N = \boldsymbol{S}_N\boldsymbol{H}^{-1} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{Q}_{it}\tilde{\boldsymbol{P}}_{it}'K_{h_2}(U_{it}-u_0)$ with $\tilde{\boldsymbol{P}}_{it} = \boldsymbol{H}^{-1}\boldsymbol{P}_{it}$. Similar to Proposition 1, we have the following preliminary results.

Proposition 2. *Under Assumptions A1–A5, we have, as follows:*

$$(i)\ \tilde{\boldsymbol{S}}_N = f(u_0)\boldsymbol{S}[1+o_p(1)];$$

$$(ii)\ \boldsymbol{B}_N = \frac{h_2^2}{2}f(u_0)\begin{pmatrix}\mu_2\tilde{\boldsymbol{\Omega}}\ddot{\boldsymbol{\beta}}\\ 0\end{pmatrix} + o_p(h_2^2);$$

$$(iii)\ \boldsymbol{R}_N = o_p(h_2^2);$$

$$(iv)\ Nh_2Var(\boldsymbol{T}_N^*) \to \frac{1}{T}f(u_0)\boldsymbol{S}^*,$$

where $e_2' = (\boldsymbol{I}_q, \boldsymbol{0}_{q\times 1})$ *is a selecting matrix and* $\boldsymbol{S}^* = \boldsymbol{S}^*(u_0) = \begin{pmatrix}\nu_0 e_2'\boldsymbol{\Phi} e_2 & \boldsymbol{0}\\ \boldsymbol{0} & \nu_2 e_2'\boldsymbol{\Phi} e_2\end{pmatrix}$.

By Proposition 2 and (12), we can obtain

$$\boldsymbol{H}(\hat{\boldsymbol{\delta}}-\boldsymbol{\delta}) - \frac{h_2^2}{2}\begin{pmatrix}\mu_2\ddot{\boldsymbol{\beta}}\\ \boldsymbol{0}\end{pmatrix} + o_p(h_2^2) = f^{-1}(u_0)(\boldsymbol{S}'\boldsymbol{S})^{-1}\boldsymbol{S}'\boldsymbol{T}_N^*[1+o_p(1)]. \tag{14}$$

The next theorem depicts the consistency and asymptotic normality of $\hat{\boldsymbol{\beta}}(u_0)$, respectively.

Theorem 3. *Under Assumptions A1–A5, we have*

$$\boldsymbol{H}\begin{pmatrix}\hat{\boldsymbol{\beta}}-\boldsymbol{\beta}\\ \hat{\dot{\boldsymbol{\beta}}}-\dot{\boldsymbol{\beta}}\end{pmatrix} - \frac{h_2^2}{2}\begin{pmatrix}\mu_2\ddot{\boldsymbol{\beta}}\\ \boldsymbol{0}\end{pmatrix} = o_p(h_2^2) + O_p\left(\frac{1}{\sqrt{Nh_2}}\right). \tag{15}$$

Also, we have the following asymptotic normality,

$$\sqrt{Nh_2}[\boldsymbol{H}\begin{pmatrix}\hat{\boldsymbol{\beta}}-\boldsymbol{\beta}\\ \hat{\dot{\boldsymbol{\beta}}}-\dot{\boldsymbol{\beta}}\end{pmatrix} - \frac{h_2^2}{2}\begin{pmatrix}\mu_2\ddot{\boldsymbol{\beta}}\\ \boldsymbol{0}\end{pmatrix} + o_p(h_2^2)] \xrightarrow{D} N(0, \frac{1}{T}f^{-1}(u_0)\boldsymbol{\Sigma}_\beta), \tag{16}$$

where $\boldsymbol{\Sigma}_\beta = (\boldsymbol{S}'\boldsymbol{S})^{-1}\boldsymbol{S}'\boldsymbol{S}^*\boldsymbol{S}(\boldsymbol{S}'\boldsymbol{S})^{-1}$.

4. A MONTE CARLO STUDY

In this section, Monte Carlo simulations are conducted to verify theoretical results in Section 3 and to demonstrate the finite sample performance of both estimators. The mean absolute deviation errors (MADE) of the estimators are computed to measure the estimation performance. The MADE is defined by

$$\text{MADE}_j = \frac{1}{G}\sum_{g=1}^{G} |\hat{\delta}_j(U_g) - \delta_j(u_g)|,$$

where $\delta(\cdot)$ is either γ_Y, γ_Z, or $\beta(\cdot)$ in (17) and $\{u_g\}_{g=1}^{G}$ are the gird points within the domain of U_{it}. Note that for both γ_Y and γ_Z, their MADE becomes the absolute deviation error (ADE).

We consider the following data generating process:

$$Y_{it} = Y_{it-1}\gamma_Y + Z_{it}\gamma_Z + \tilde{X}_{it}\beta(U_{it}) + \epsilon_{it}, \qquad \tilde{X}_{it} = W_{it} + \eta_{it}, \tag{17}$$

where the smoothing variable U_{it} and the exogenous variable Z_{it} are generated from uniform distributions $U(-3,3)$ and $U(-2,2)$, respectively. The excluded instruments W_{it} is generated independently from a uniform distribution $U(-2,2)$. The error terms ϵ_{it} and η_{it} are generated jointly from a standard bivariate normal distribution with the correlation coefficient 0.3. The coefficients are set by $\gamma_Y = 0.5$, $\gamma_Z = 3$ and $\beta(U_{it}) = 1.5e^{-U_{it}^2}$. We fix $T = 10$ and let $N = 200$, 500, and 1,000, respectively. When generating the series of Y_{it}, we set the initial value to be zero and drop the first 100 observations to reduce the impact of initial values. For a given sample size, we repeat 500 times to calculate the MADE. The bandwidth in the first step is undersmoothed and we find the estimation of γ is not very sensitive to the bandwidth selection when it is chosen within a reasonable range.

Table 1 reports the medians and the standard deviations (in parentheses) of the MADE for different estimators under different sample sizes. When the sample size increases, the medians of ADE values for $\hat{\gamma}_Y$ and $\hat{\gamma}_Z$ shrink from 0.004 to 0.001 and from 0.016 to 0.006, respectively. The standard deviations also shrink quickly when the sample size is enlarged. For $\hat{\gamma}_Y$, the standard deviation shrinks from 0.003 to 0.001, and for $\hat{\gamma}_Z$, it decreases from 0.012 to 0.005. The nonparametric estimator of $\beta(\cdot)$ shows similar results. The median of

TABLE 1
Median and Standard Deviation of the MADE Values

N	γ_Y	γ_Z	$\beta(\cdot)$
200	0.004144002	0.01629416	0.0768469
	(0.003479078)	(0.01242114)	(0.01431995)
500	0.002379212	0.009720373	0.04487873
	(0.002281685)	(0.008604812)	(0.00858833)
1000	0.001707388	0.006097411	0.03057437
	(0.001506411)	(0.005766932)	(0.006049484)

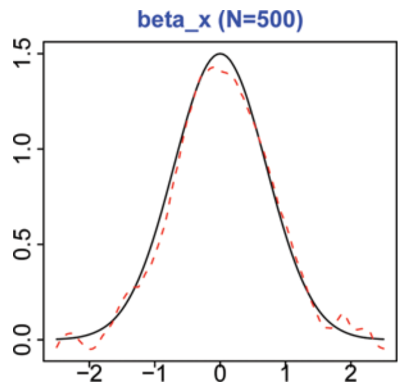

FIGURE 1 Functional Coefficient of $\beta(\cdot)$. The solid line represents the true curve, and the dotted line denotes the estimated one.

the MADE values decreases from 0.076 to 0.030 when the sample size increases from 200 to 1,000. At the same time, the standard deviation of the estimator also shrinks from 0.014 to 0.006. Compared with parametric estimations in Columns 2 and 3, the convergence speed of nonparametric estimator is relatively slow. All results show that the estimators proposed in the article are consistent estimators and all outcomes in the simulations are consistent with the theoretical results in the previous section.

Figure 1 demonstrates the estimated curve of $\beta(\cdot)$ with a sample size $N = 500$ for a typical sample. The typical example is chosen such that its MADE_β value equals to the median of the 500 MADE_β values in the repeated experiments of the case $N = 500$. The solid line represents the true curve, and the dotted line denotes the estimated one. Figure 1 shows that the nonparametric GMM estimation works very well even in a small sample.

5. CONCLUSION

This article proposes a three-stage estimation procedure for a new class of partially varying coefficients dynamic panel data models, which, as expected, has many applications in applied economics particularly in empirical growth literature. The asymptotic properties of both constant and varying coefficients are established. The Monte Carlo simulations demonstrate that the proposed estimators work very well even in small samples. However, the cross-sectional independence may be a restrictive assumption for some applications in real data. Therefore, it would be an interesting future research topic to work on a partially varying coefficients dynamic panel data model with cross sectional dependence.

APPENDIX A: PROOFS OF PROPOSITIONS

It is clear that $\boldsymbol{\Phi}_N = \boldsymbol{\Omega}_N\boldsymbol{\theta} + \boldsymbol{\Phi}_N^* + \boldsymbol{\Psi}_N + \boldsymbol{\Lambda}_N$ and $\boldsymbol{T}_N = \tilde{\boldsymbol{S}}_N\boldsymbol{H}\boldsymbol{\delta} + \boldsymbol{T}_N^* + \boldsymbol{B}_N + \boldsymbol{R}_N$. Indeed,

$$\begin{aligned}\boldsymbol{\Omega}_N\boldsymbol{\theta} + \boldsymbol{\Phi}_N^* + \boldsymbol{\Psi}_N + \boldsymbol{\Lambda}_N &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_1}(U_{it}-u_0)\boldsymbol{W}_{it}[\boldsymbol{X}_{it}'\boldsymbol{\theta} + \epsilon_{it} + \boldsymbol{X}_{it}'\boldsymbol{\theta}(U_{it}) - \boldsymbol{X}_{it}'\boldsymbol{\theta}]\\ &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_1}(U_{it}-u_0)\boldsymbol{W}_{it}Y_{it}\\ &= \boldsymbol{\Phi}_N\end{aligned}$$

and

$$\begin{aligned}\tilde{\boldsymbol{S}}_N\boldsymbol{H}\boldsymbol{\delta} + \boldsymbol{T}_N^* + \boldsymbol{B}_N + \boldsymbol{R}_N &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_2}(U_{it}-u_0)\boldsymbol{Q}_{it}[\boldsymbol{P}_{it}'\boldsymbol{\delta} + \epsilon_{it} + \boldsymbol{X}_{it}'\boldsymbol{g}(U_{it}) - \boldsymbol{P}_{it}'\boldsymbol{\delta}]\\ &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_2}(U_{it}-u_0)\boldsymbol{Q}_{it}Y_{it}\\ &= \boldsymbol{T}_N.\end{aligned}$$

Proof of Propositions 1(i) and 2(i). It is clear that

$$\begin{aligned}&E\left[\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{V}_{it}\boldsymbol{X}_{it}'\left(\frac{U_{it}-u_0}{h_1}\right)^j K_{h_1}(U_{it}-u_0)\right]\\ &= E\left[\boldsymbol{V}_{it}\boldsymbol{X}_{it}'\left(\frac{U_{it}-u_0}{h_1}\right)^j K_{h_1}(U_{it}-u_0)\right]\\ &= \int \boldsymbol{\Omega}(U_{it})\left(\frac{U_{it}-u_0}{h_1}\right)^j K_{h_1}(U_{it}-u_0)f(U_{it})dU_{it}\\ &= [\boldsymbol{\Omega}(u_0)+O(h_1)]\int u^jK(u)du[f(u_0)+O(h_1)]\\ &= \boldsymbol{\Omega}(u_0)f(u_0)\mu_j + O(h_1).\end{aligned}$$

Hence, we have

$$E(\boldsymbol{\Omega}_N) = f(u_0)\boldsymbol{\Omega}[1+o(1)].$$

Now, we consider $\tilde{\boldsymbol{S}}_N$. Indeed,

$$\tilde{\boldsymbol{S}}_N = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{Q}_{it}\tilde{\boldsymbol{P}}_{it}'K_{h_2}(U_{it}-u_0)$$

$$= \begin{pmatrix} \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}K_{h_2}(U_{it}-u_0) & \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\frac{U_{it}-u_0}{h_2}K_{h_2}(U_{it}-u_0) \\ \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\frac{U_{it}-u_0}{h_2}K_{h_2}(U_{it}-u_0) & \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\frac{(U_{it}-u_0)^2}{h_2^2}K_{h_2}(U_{it}-u_0) \end{pmatrix}.$$

For any $j = 0, 1, 2$,

$$\begin{aligned} E&\left[\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)\right] \\ &= E\left[\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)\right] \\ &= \int \tilde{\boldsymbol{\Omega}}(U_{it})\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)f(U_{it})dU_{it} \\ &= [\tilde{\boldsymbol{\Omega}}(u_0)+O(h_2)]\int u^j K(u)du[f(u_0)+O(h_2)] \\ &= \tilde{\boldsymbol{\Omega}}(u_0)f(u_0)\mu_j + O(h_2). \end{aligned}$$

Hence, we have

$$E(\tilde{\boldsymbol{S}}_N) = f(u_0)\boldsymbol{S}[1+o(1)].$$

And, for $1 \le l \le q$ and $1 \le m \le d$, let

$$s_{N,lmj} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}W_{itl}X_{itm}\left(\frac{U_{it}-u_0}{h_N}\right)^j K_h(U_{it}-u_0),$$

where $h = h_N = h_1$ or $h = h_N = h_2$, W_{itl} is the lth element of $\boldsymbol{W}_{it}$, and X_{itm} is the mth element of $\boldsymbol{X}_{it}$. Then, by the stationary assumptions, we have

$$\begin{aligned} Var(s_{N,lmj}) &= Var\left[\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}W_{itl}X_{itm}\left(\frac{U_{it}-u_0}{h_N}\right)^j K_h(U_{it}-u_0)\right] \\ &= \frac{1}{NT^2}Var\left[\sum_{t=1}^{T}W_{itl}X_{itm}\left(\frac{U_{it}-u_0}{h_N}\right)^j K_h(U_{it}-u_0)\right] \\ &= \frac{1}{NT}Var[W_{itl}X_{itm}\left(\frac{U_{it}-u_0}{h_N}\right)^j K_h(U_{it}-u_0)] \\ &\quad + \frac{2}{NT^2}\sum_{t=2}^{T}(T-t+1)Cov(W_{i1l}X_{i1m}\left(\frac{U_{i1}-u_0}{h_N}\right)^j K_h(U_{i1}-u_0), \end{aligned}$$

$$W_{itl}X_{itm}\left(\frac{U_{it}-u_0}{h_N}\right)^j K_h(U_{it}-u_0))$$
$$\equiv I_{s1}+I_{s2}.$$

By assumptions and Cauchy–Schwarz inequality, $I_{s1} \leq \frac{C}{Nh_N}$ and $|I_{s2}| \leq \frac{C}{N}$. Thus, $Var(s_{N,lmj}) \to 0$. It follows that

$$\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{V}_{it}\boldsymbol{X}_{it}'\left(\frac{U_{it}-u_0}{h_1}\right)^j K_{h_1}(U_{it}-u_0)=\boldsymbol{\Omega}(u_0)f(u_0)\mu_j+O_p(h_1)$$

and

$$\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}_{it,2}'\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)=\tilde{\boldsymbol{\Omega}}(u_0)f(u_0)\mu_j+O_p(h_2).$$

Therefore, we have

$$\boldsymbol{\Omega}_N=f(u_0)\boldsymbol{\Omega}[1+o_p(1)] \quad \text{and} \quad \tilde{\boldsymbol{S}}_N=f(u_0)\boldsymbol{S}[1+o_p(1)].$$

The proof is complete.

Proof of Propositions 1(ii) and 2(ii).

$$\begin{aligned}\boldsymbol{\Psi}_N &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}K_{h_1}(U_{it}-u_0)\boldsymbol{V}_{it}\sum_{j=1}^{d}\left[\dot{\theta}_j(u_0)(U_{it}-u_0)+\frac{1}{2}\ddot{\theta}_j(u_0)(U_{it}-u_0)^2\right]X_{itj}\\ &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}K_{h_1}(U_{it}-u_0)\boldsymbol{V}_{it}\boldsymbol{X}_{it}'\dot{\boldsymbol{\theta}}(U_{it}-u_0)\\ &\quad+\frac{1}{2NT}\sum_{i=1}^{N}\sum_{t=1}^{T}K_{h_1}(U_{it}-u_0)\boldsymbol{V}_{it}\boldsymbol{X}_{it}'\ddot{\boldsymbol{\theta}}(U_{it}-u_0)^2\\ &\equiv \boldsymbol{\Psi}_N^1+\boldsymbol{\Psi}_N^2.\end{aligned}$$

Then,

$$\begin{aligned}E(\boldsymbol{\Psi}_N^1) &= h_1E[\boldsymbol{V}_{it}\boldsymbol{X}_{it}'\frac{U_{it}-u_0}{h_1}K_{h_1}(U_{it}-u_0)]\dot{\boldsymbol{\theta}}\\ &= h_1\int\boldsymbol{\Omega}(U_{it})\frac{U_{it}-u_0}{h_1}K_{h_1}(U_{it}-u_0)f(U_{it})dU_{it}\dot{\boldsymbol{\theta}}\\ &= h_1\int[\boldsymbol{\Omega}(u_0)+\dot{\boldsymbol{\Omega}}(u_0)uh_1+o(h_1)]uK(u)[f(u_0)+\dot{f}(u_0)uh_1+o(h_1)]du\dot{\boldsymbol{\theta}}\\ &= h_1^2\mu_2[f(u_0)\dot{\boldsymbol{\Omega}}(u_0)+\dot{f}(u_0)\boldsymbol{\Omega}(u_0)]\dot{\boldsymbol{\theta}}+o(h_1^2),\end{aligned}$$

and

$$
\begin{aligned}
E(\boldsymbol{\Psi}_N^2) &= \frac{h_1^2}{2} E\left[\boldsymbol{V}_{it}(\boldsymbol{D}_i', \boldsymbol{X}_{it}')\left(\frac{U_{it}-u_0}{h_1}\right)^2 K_{h_1}(U_{it}-u_0)\right]\ddot{\boldsymbol{\theta}} \\
&= \frac{h_1^2}{2}\int \boldsymbol{\Omega}(U_{it})\left(\frac{U_{it}-u_0}{h_1}\right)^2 K_{h_1}(U_{it}-u_0) f(U_{it}) dU_{it}\ddot{\boldsymbol{\theta}} \\
&= \frac{h_1^2}{2}[\boldsymbol{\Omega}(u_0)+O(h_1)]\int u^2 K(u)du[f(u_0)+O(h_1)]\ddot{\boldsymbol{\theta}} \\
&= \frac{h_1^2}{2}[\boldsymbol{\Omega}(u_0)\mu_2 f(u_0)+O(h_1)]\ddot{\boldsymbol{\theta}} \\
&= \frac{h_1^2}{2} f(u_0)\mu_2\boldsymbol{\Omega}\ddot{\boldsymbol{\theta}} + o(h_1^2).
\end{aligned}
$$

Hence,

$$
h_1^{-2}E(\boldsymbol{\Psi}_N) = \frac{1}{2} f(u_0)\mu_2[2(\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega}\frac{\dot{f}(u_0)}{f(u_0)})\dot{\boldsymbol{\theta}} + \boldsymbol{\Omega}\ddot{\boldsymbol{\theta}}] + o(1).
$$

Now,

$$
\begin{aligned}
\boldsymbol{B}_N &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} K_{h_2}(U_{it}-u_0)\boldsymbol{Q}_{it}\frac{1}{2}\sum_{j=1}^{d_2}\ddot{\beta}_j(u_0)(U_{it}-u_0)^2 X_{it,2j} \\
&= \frac{h_2^2}{2}\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{Q}_{it}\boldsymbol{X}_{it,2}'\ddot{\boldsymbol{\beta}}(u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^2 K_{h_2}(U_{it}-u_0) \\
&= \frac{h_2^2}{2}\begin{pmatrix} \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}_{it,2}'\ddot{\boldsymbol{\beta}}(u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^2 K_{h_2}(U_{it}-u_0) \\ \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}_{it,2}'\ddot{\boldsymbol{\beta}}(u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^3 K_{h_2}(U_{it}-u_0) \end{pmatrix}.
\end{aligned}
$$

For $j = 2, 3$,

$$
\begin{aligned}
&E\left[\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{W}_{it}\boldsymbol{X}_{it,2}'\ddot{\boldsymbol{\beta}}(u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)\right] \\
&= E\left[\boldsymbol{W}_{it}\boldsymbol{X}_{it,2}'\ddot{\boldsymbol{\beta}}(u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)\right] \\
&= \int \tilde{\boldsymbol{\Omega}}(U_{it})\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0) f(U_{it}) dU_{it}\ddot{\boldsymbol{\beta}}(u_0)
\end{aligned}
$$

$$= [\tilde{\mathbf{\Omega}}(u_0) + O(h_2)] \int u^j K(u) du [f(u_0) + O(h_2)] \ddot{\boldsymbol{\beta}}(u_0)$$
$$= f(u_0) \mu_j \tilde{\mathbf{\Omega}} \ddot{\boldsymbol{\beta}} + O(h_2).$$

Hence,

$$h_2^{-2} E(\boldsymbol{B}_N) = \frac{1}{2} f(u_0) \begin{pmatrix} \mu_2 \tilde{\mathbf{\Omega}} \ddot{\boldsymbol{\beta}} \\ 0 \end{pmatrix} + o(1).$$

Similar to (i), any component of the variance of $h_1^{-2} \mathbf{\Psi}_N$ and $h_2^{-2} \boldsymbol{B}_N$ converges to zero. Therefore, we have

$$\mathbf{\Psi}_N = \frac{h_1^2}{2} f(u_0) \mu_2 \left[2(\dot{\mathbf{\Omega}} + \mathbf{\Omega} \frac{\dot{f}(u_0)}{f(u_0)}) \dot{\boldsymbol{\theta}} + \mathbf{\Omega} \ddot{\boldsymbol{\theta}} \right] + o_p(h_1^2) \quad \text{and}$$
$$\boldsymbol{B}_N = \frac{h_2^2}{2} f(u_0) \begin{pmatrix} \mu_2 \tilde{\mathbf{\Omega}} \ddot{\boldsymbol{\beta}} \\ 0 \end{pmatrix} + o_p(h_2^2).$$

Therefore, this proves the results.

Proof of Propositions 1(iii) and 2(iii).

$$E(\mathbf{\Lambda}_N) = E\left[\frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} K_{h_1}(U_{it} - u_0) \boldsymbol{V}_{it} \boldsymbol{X}_{it}' \mathbf{\Lambda}(U_{it}, u_0) \right]$$
$$= E[\boldsymbol{V}_{it} \boldsymbol{X}_{it}' \mathbf{\Lambda}(U_{it}, u_0) K_{h_1}(U_{it} - u_0)]$$
$$= \int \mathbf{\Omega}(U_{it}) \mathbf{\Lambda}(U_{it}, u_0) K_{h_1}(U_{it} - u_0) f(U_{it}) dU_{it}$$
$$= [f(u_0) + O(h_1)] \int \mathbf{\Omega}(u_0) \mathbf{\Lambda}(u_0 + uh_1, u_0) K(u) du.$$

And, for any $1 \le j \le d$,

$$\Lambda_j(u_0 + uh_1, u_0) = \theta_j(u_0 + uh_1) - \theta_j(u_0) - h_1 \dot{\theta}_j(u_0) u - \frac{h_1^2}{2} \ddot{\theta}_j(u_0) u^2 = O(h_1^3).$$

Therefore, $\mathbf{\Lambda}_N = o_p(h_1^2)$, and

$$\boldsymbol{R}_N = \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} K_{h_2}(U_{it} - u_0) \boldsymbol{Q}_{it} \frac{1}{2} \sum_{j=1}^{d_2} R_j(U_{it}, u_0) X_{it,2j}$$
$$= \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} \boldsymbol{Q}_{it} \boldsymbol{X}_{it,2}' \boldsymbol{R}(U_{it}, u_0) K_{h_2}(U_{it} - u_0)$$

$$= \begin{pmatrix} \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\boldsymbol{R}(U_{it},u_0)K_{h_2}(U_{it}-u_0) \\ \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\boldsymbol{R}(U_{it},u_0)\frac{U_{it}-u_0}{h_2}K_{h_2}(U_{it}-u_0) \end{pmatrix}.$$

For any component in the above vector, $j = 0, 1$,

$$\begin{aligned} &E\left[\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\boldsymbol{R}(U_{it},u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)\right] \\ &= E\left[\boldsymbol{W}_{it}\boldsymbol{X}'_{it,2}\boldsymbol{R}(U_{it},u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)\right] \\ &= \int \tilde{\boldsymbol{\Omega}}(U_{it})\boldsymbol{R}(U_{it},u_0)\left(\frac{U_{it}-u_0}{h_2}\right)^j K_{h_2}(U_{it}-u_0)f(U_{it})dU_{it} \\ &= [f(u_0)+O_p(h_2)]\int \tilde{\boldsymbol{\Omega}}(u_0)\boldsymbol{R}(u_0+uh_2,u_0)u^j K(u)du. \end{aligned}$$

For any $1 \leq j \leq d_2$,

$$R_j(u_0+uh_2,u_0) = \beta_j(u_0+uh_2) - \beta_j(u_0) - h_2\dot{\beta}_j(u_0)u - \frac{h_2^2}{2}\ddot{\beta}_j(u_0)u^2 = O(h_2^3).$$

Therefore, $\boldsymbol{R}_N = o_p(h_2^2)$. This completes the proof.

Proof of Propositions 1(iv) and 2(iv). Under the above assumptions, we have

$$\begin{aligned} Nh_1 Var(\boldsymbol{\Phi}_N^*) &= Nh_1 Var[\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} \boldsymbol{V}_{it}\epsilon_{it}K_{h_1}(U_{it}-u_0)] \\ &= \frac{h_1}{T^2}Var[\sum_{t=1}^{T} \boldsymbol{V}_{it}\epsilon_{it}K_{h_1}(U_{it}-u_0)] = \frac{h_1}{T}Var[\boldsymbol{V}_{it}\epsilon_{it}K_{h_1}(U_{it}-u_0)] \\ &\quad + \frac{2h_1}{T^2}\sum_{t=2}^{T}(T-t+1)Cov(\boldsymbol{V}_{i1}\epsilon_{i1}K_{h_1}(U_{i1}-u_0), \boldsymbol{V}_{it}\epsilon_{it}K_{h_1}(U_{it}-u_0)) \\ &= \frac{h_1}{T}E[\boldsymbol{V}_{it}\boldsymbol{V}'_{it}\epsilon_{it}^2 K_{h_1}^2(U_{it}-u_0)] \\ &\quad + \frac{2h_1}{T^2}\sum_{t=2}^{T}(T-t+1)E[\boldsymbol{V}_{i1}\boldsymbol{V}'_{it}\epsilon_{i1}\epsilon_{it}K_{h_1}(U_{i1}-u_0)K_{h_1}(U_{it}-u_0)] \\ &\equiv \boldsymbol{I}_3 + \boldsymbol{I}_4, \end{aligned} \tag{18}$$

and

$$
\begin{aligned}
Nh_2 Var(\boldsymbol{T}_N^*) &= Nh_2 Var\left\{\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\boldsymbol{Q}_{it}\epsilon_{it}K_{h_2}(U_{it}-u_0)\right\} \\
&= \frac{h_2}{T^2}Var\left\{\sum_{t=1}^{T}\boldsymbol{Q}_{it}\epsilon_{it}K_{h_2}(U_{it}-u_0)\right\} = \frac{h_2}{T}Var\{\boldsymbol{Q}_{it}\epsilon_{it}K_{h_2}(U_{it}-u_0)\} \\
&\quad + \frac{2h_2}{T^2}\sum_{t=2}^{T}(T-t+1)Cov(\boldsymbol{Q}_{i1}\epsilon_{i1}K_{h_2}(U_{i1}-u_0), \boldsymbol{Q}_{it}\epsilon_{it}K_{h_2}(U_{it}-u_0)) \\
&\equiv \boldsymbol{I}_5 + \boldsymbol{I}_6. \qquad (19)
\end{aligned}
$$

For the first term in (19),

$$
\begin{aligned}
&\frac{h_2}{T}Var[\boldsymbol{Q}_{it}\epsilon_{it}K_{h_2}(U_{it}-u_0)] = \frac{h_2}{T}E[\boldsymbol{Q}_{it}\boldsymbol{Q}_{it}'\epsilon_{it}^2K_{h_2}^2(U_{it}-u_0)] \\
&= \frac{h_2}{T}E\begin{pmatrix} \boldsymbol{W}_{it}\boldsymbol{W}_{it}'\epsilon_{it}^2K_{h_2}^2(U_{it}-u_0) & \boldsymbol{W}_{it}\boldsymbol{W}_{it}'\epsilon_{it}^2K_{h_2}^2(U_{it}-u_0)\dfrac{U_{it}-u_0}{h_2} \\ \boldsymbol{W}_{it}\boldsymbol{W}_{it}'\epsilon_{it}^2K_{h_2}^2(U_{it}-u_0)\dfrac{U_{it}-u_0}{h_2} & \boldsymbol{W}_{it}\boldsymbol{W}_{it}'\epsilon_{it}^2K_{h_2}^2(U_{it}-u_0)\left(\dfrac{U_{it}-u_0}{h_2}\right)^2 \end{pmatrix}.
\end{aligned}
$$

For any component in the above matrix, $j = 0, 1, 2$, $h = h_N = h_1$, or $h = h_N = h_2$,

$$
\begin{aligned}
&E\left[\boldsymbol{V}_{it}\boldsymbol{V}_{it}'\epsilon_{it}^2K_h^2(U_{it}-u_0)\left(\frac{U_{it}-u_0}{h_N}\right)^j\right] \\
&= \int \boldsymbol{\Phi}(U_{it})K_h^2(U_{it}-u_0)\left(\frac{U_{it}-u_0}{h_N}\right)^j f(U_{it})dU_{it} \\
&= \frac{1}{h_N}[f(u_0)+O(h_N)][\boldsymbol{\Phi}(u_0)+O(h_N)]\int K^2(u)u^j du \\
&= \frac{1}{h_N}[f(u_0)\boldsymbol{\Phi}(u_0)v_j + O(h_N)].
\end{aligned}
$$

Hence,

$$
\boldsymbol{I}_3 \to \frac{1}{T}f(u_0)\boldsymbol{\Phi} \quad \text{and} \quad \boldsymbol{I}_5 \to \frac{1}{T}f(u_0)\boldsymbol{S}^*.
$$

For the second term in (19),

$$
\frac{2h_2}{T^2}\sum_{t=2}^{T}(T-t+1)Cov(\boldsymbol{Q}_{i1}\epsilon_{i1}K_{h_2}(U_{i1}-u_0), \boldsymbol{Q}_{it}\epsilon_{it}K_{h_2}(U_{it}-u_0))
$$

$$= \frac{2h_2}{T^2}\sum_{t=2}^{T}(T-t+1)E[\boldsymbol{Q}_{i1}\boldsymbol{Q}_{it}'\epsilon_{i1}\epsilon_{it}K_{h_2}(U_{i1}-u_0)K_{h_2}(U_{it}-u_0)]$$

$$= \frac{2h_2}{T^2}\sum_{t=2}^{T}(T-t+1)E\begin{pmatrix} \mathbb{W} & \mathbb{W}\frac{U_{it}-u_0}{h_2} \\ \mathbb{W}\frac{U_{i1}-u_0}{h_2} & \mathbb{W}\frac{U_{i1}-u_0}{h_2}\frac{U_{it}-u_0}{h_2} \end{pmatrix},$$

where $\mathbb{W} = \boldsymbol{W}_{i1}\boldsymbol{W}_{it}'\epsilon_{i1}\epsilon_{it}K_{h_2}(U_{i1}-u_0)K_{h_2}(U_{it}-u_0)$. For any component in the above matrix, $j=0,1$ and $i=0,1$, $h=h_N=h_1$, or $h=h_N=h_2$,

$$E\left[\boldsymbol{V}_{i1}\boldsymbol{V}_{it}'\epsilon_{i1}\epsilon_{it}K_h(U_{i1}-u_0)K_h(U_{it}-u_0)\left(\frac{U_{i1}-u_0}{h_N}\right)^i\left(\frac{U_{it}-u_0}{h_N}\right)^j\right]$$
$$= E\left[E(\boldsymbol{V}_{i1}\boldsymbol{V}_{it}'\epsilon_{i1}\epsilon_{it}|U_{i1},U_{it})K_h(U_{i1}-u_0)K_h(U_{it}-u_0)\left(\frac{U_{i1}-u_0}{h_N}\right)^i\left(\frac{U_{it}-u_0}{h_N}\right)^j\right]$$
$$= E\left[\boldsymbol{G}_{1t}(U_{i1},U_{it})K_h(U_{i1}-u_0)K_h(U_{it}-u_0)\left(\frac{U_{i1}-u_0}{h_N}\right)^i\left(\frac{U_{it}-u_0}{h_N}\right)^j\right]$$
$$= f(u_0,u_0)\boldsymbol{G}_{1t}(u_0,u_0)v_iv_j + O_p(h_N).$$

Hence,

$$\boldsymbol{I}_4 \to \frac{2h_1}{T^2}f(u_0)\sum_{t=2}^{T}(T-t+1)\boldsymbol{G}_{1t}(u_0,u_0) \quad \text{and} \quad \boldsymbol{I}_6 \to \frac{2h_2}{T^2}f(u_0)\sum_{t=2}^{T}(T-t+1)\boldsymbol{G}_{1t}^*(u_0,u_0),$$

where $\boldsymbol{G}_{1t}^* = \boldsymbol{G}_{1t}^*(u_0,u_0) = \begin{pmatrix} v_0^2e_2'\boldsymbol{G}_{1t}(u_0,u_0)e_2 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0}\end{pmatrix}$. Therefore,

$$Nh_1Var(\boldsymbol{\Phi}_N^*) \to \frac{1}{T}f(u_0)\boldsymbol{\Phi}$$

and

$$Nh_2Var(\boldsymbol{T}_N^*) \to \frac{1}{T}f(u_0)\boldsymbol{S}^*.$$

Then, the proof is complete.

APPENDIX B: USEFUL LEMMAS FOR THEOREM 2

By (9), we know that for any U_{it},

$$(\hat{\boldsymbol{\theta}}(U_{it}) - \boldsymbol{\theta}(U_{it})) - bias_{\boldsymbol{\theta}} \simeq f^{-1}(U_{it})\boldsymbol{D}(U_{it})\frac{1}{NT}\sum_{j=1}^{N}\sum_{k=1}^{T}K_{h_1}(U_{jk}-U_{it})\boldsymbol{V}_{jk}\epsilon_{jk},$$

where $\boldsymbol{D}(U_{it}) = (\boldsymbol{\Omega}'(U_{it})\boldsymbol{\Omega}(U_{it}))^{-1}\boldsymbol{\Omega}'(U_{it})$. Denote ξ_i as the information set of individual i. Thus,

$$
\begin{aligned}
\hat{\gamma} - \gamma &= \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} e_1'[(\hat{\boldsymbol{\theta}}(U_{it}) - \boldsymbol{\theta}(U_{it})) - bias_{\boldsymbol{\theta}}] \\
&\simeq \frac{1}{(NT)^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{t=1}^{T}\sum_{k=1}^{T} e_1' f^{-1}(U_{it})\boldsymbol{D}(U_{it})K_{h_1}(U_{jk} - U_{it})\boldsymbol{V}_{jk}\boldsymbol{\epsilon}_{jk} \\
&= \frac{1}{N^2}\sum_{1\le i<j\le N}\frac{1}{T^2}\sum_{t=1}^{T}\sum_{k=1}^{T}[e_1' f^{-1}(U_{it})\boldsymbol{D}(U_{it})K_{h_1}(U_{jk} - U_{it})\boldsymbol{V}_{jk}\boldsymbol{\epsilon}_{jk} \\
&\quad + e_1' f^{-1}(U_{jk})\boldsymbol{D}(U_{jk})K_{h_1}(U_{it} - U_{jk})\boldsymbol{V}_{it}\boldsymbol{\epsilon}_{it}] \\
&= \frac{1}{N^2}\sum_{1\le i<j\le N}\left[\frac{1}{T}\sum_{t=1}^{T} e_1' f^{-1}(U_{it})\boldsymbol{D}(U_{it})\boldsymbol{A}(U_{it}, \xi_j) + \frac{1}{T}\sum_{k=1}^{T} e_1' f^{-1}(U_{jk})\boldsymbol{D}(U_{jk})\boldsymbol{A}(U_{jk}, \xi_i)\right] \\
&\equiv \frac{N-1}{2N}\mathbb{U}_N,
\end{aligned}
$$

where $e_1' = (\boldsymbol{I}_{d_1}, \boldsymbol{0}_{d_1\times d_2})$, which is used to extract the parametric part from the estimates of nonparametric GMM procedure using local constant fitting scheme, $\boldsymbol{A}(U_{it}, \xi_j) = \frac{1}{T}\sum_{k=1}^{T} K_{h_1}(U_{jk} - U_{it})\boldsymbol{V}_{jk}\boldsymbol{\epsilon}_{jk}$, and $\mathbb{U}_N = \frac{2}{N(N-1)}\sum_{1\le i<j\le N} p_N(\xi_i, \xi_j)$ is a U-statistic with

$$
p_N(\xi_i, \xi_j) = \frac{1}{T}\sum_{t=1}^{T} e_1' f^{-1}(U_{it})\boldsymbol{D}(U_{it})\boldsymbol{A}(U_{it}, \xi_j) + \frac{1}{T}\sum_{k=1}^{T} e_1' f^{-1}(U_{jk})\boldsymbol{D}(U_{jk})\boldsymbol{A}(U_{jk}, \xi_i).
$$

Following Theorem 3.1 in Powell et al. (1989), we define

$$
\begin{aligned}
r_N(\xi_i) &= E[p_N(\xi_i, \xi_j) \mid \xi_i], \\
\theta_N &= E[r_N(\xi_i)] = E[p_N(\xi_i, \xi_j)], \\
\hat{\mathbb{U}}_N &= \theta_N + \frac{2}{N}\sum_{i=1}^{N}[r_N(\xi_i) - \theta_N].
\end{aligned}
$$

In order to establish the asymptotic normality of $\hat{\mathbb{U}}_N$, the condition of Lemma 3.1 in Powell, Stock, and Stoker (1989) should be satisfied. It is easy to prove that $E[\|p_N(\xi_i, \xi_j)\|^2] = O(h^{-1}) = O[N(Nh_1)^{-1}]$. Thus, we have$E[\|p_N(\xi_i, \xi_j)\|^2] = o(N)$ if and only if $Nh_1 \to \infty$ as $h_1 \to 0$.

Lemma 1. *Under assumptions A1–A5,*

$$r_N(\xi_i) = e_1' \frac{1}{T} \sum_{t=1}^{T} \boldsymbol{D}(U_{it}) \boldsymbol{V}_{it} \epsilon_{it} [1 + o(1)].$$

Lemma 2. *Under assumptions A1–A5, we have as follows:*

$$(i)\quad E[r_N(\xi_i)] = 0;$$
$$(ii)\quad Var[r_N(\xi_i)] = \frac{1}{T} \Sigma_\gamma [1 + o(1)].$$

The detailed proofs of the above three lemmas are given in Appendix C.

APPENDIX C: PROOFS OF LEMMAS

Proof of Lemma 1. Firstly,

$$\begin{aligned}
&E[f^{-1}(U_{jk}) \boldsymbol{D}(U_{jk}) \boldsymbol{A}(U_{jk}, \xi_i) \mid \xi_i] \\
&= E[f^{-1}(U_{jk}) \boldsymbol{D}(U_{jk}) \frac{1}{T} \sum_{t=1}^{T} K_{h_1}(U_{it} - U_{jk}) \boldsymbol{V}_{it} \epsilon_{it} \mid \xi_i] \\
&= \frac{1}{T} \sum_{t=1}^{T} E[f^{-1}(U_{jk}) \boldsymbol{D}(U_{jk}) K_{h_1}(U_{it} - U_{jk}) \mid \xi_i] \boldsymbol{V}_{it} \epsilon_{it} \\
&= \frac{1}{T} \sum_{t=1}^{T} \int f^{-1}(U_{jk}) \boldsymbol{D}(U_{jk}) K_{h_1}(U_{it} - U_{jk}) f(U_{jk}) dU_{jk} \boldsymbol{V}_{it} \epsilon_{it} \\
&= \frac{1}{T} \sum_{t=1}^{T} [\boldsymbol{D}(U_{it}) + o(1)] \boldsymbol{V}_{it} \epsilon_{it} \\
&= \frac{1}{T} \sum_{t=1}^{T} \boldsymbol{D}(U_{it}) \boldsymbol{V}_{it} \epsilon_{it} [1 + o(1)]
\end{aligned}$$

and

$$\begin{aligned}
E[\boldsymbol{A}(U_{it}, \xi_j) \mid \xi_i] &= E\left[\frac{1}{T} \sum_{k=1}^{T} K_{h_1}(U_{jk} - U_{it}) \boldsymbol{V}_{jk} \epsilon_{jk} \mid \xi_i \right] \\
&= \frac{1}{T} \sum_{k=1}^{T} E[K_{h_1}(U_{jk} - U_{it}) E(\boldsymbol{V}_{jt} \epsilon_{jt} | U_{jk}) | \xi_i] = 0.
\end{aligned}$$

By the definition of $p_N(\xi_i, \xi_j)$,

$$\begin{aligned}
&E[p_N(v, \xi_j) \mid \xi_i] \\
&= E\left[\frac{1}{T}\sum_{t=1}^{T} e_1' f^{-1}(U_{it})\boldsymbol{D}(U_{it})\boldsymbol{A}(U_{it}, \xi_j) + \frac{1}{T}\sum_{k=1}^{T} e_1' f^{-1}(U_{jk})\boldsymbol{D}(U_{jk})\boldsymbol{A}(U_{jk}, \xi_i) \mid \xi_i\right] \\
&= \frac{1}{T}\sum_{t=1}^{T} e_1' f^{-1}(U_{it})\boldsymbol{D}(U_{it}) E[\boldsymbol{A}(U_{it}, \xi_j) \mid \xi_i] + \frac{1}{T}\sum_{k=1}^{T} e_1' E[f^{-1}(U_{jk})\boldsymbol{D}(U_{jk})\boldsymbol{A}(U_{jk}, \xi_i) \mid \xi_i] \\
&= e_1' \frac{1}{T}\sum_{t=1}^{T} \boldsymbol{D}(U_{it})\boldsymbol{V}_{it}\boldsymbol{\epsilon}_{it}[1 + o(1)].
\end{aligned}$$

The proof of the lemma is complete.

Proof of Lemma 2. It is easy to see that

$$\begin{aligned}
E[r_N(\xi_i)] &= E\{E[p_N(\xi_i, \xi_j) \mid \xi_i]\} \\
&= E\left\{e_1' \frac{1}{T}\sum_{t=1}^{T} \boldsymbol{D}(U_{it})\boldsymbol{V}_{it}\boldsymbol{\epsilon}_{it}[1 + o_p(1)]\right\} \\
&= E\left\{e_1' \frac{1}{T}\sum_{t=1}^{T} \boldsymbol{D}(U_{it}) E(\boldsymbol{V}_{it}\boldsymbol{\epsilon}_{it} \mid U_{it})[1 + o_p(1)]\right\} = 0,
\end{aligned}$$

and

$$\begin{aligned}
Var[r_N(\xi_i)] &= E[r_N(\xi_i)]^2 \\
&= E\left[e_1' \frac{1}{T}\sum_{t_1=1}^{T} \boldsymbol{D}(U_{it_1})\boldsymbol{V}_{it_1}\boldsymbol{\epsilon}_{it_1} \frac{1}{T}\sum_{t_2=1}^{T} \boldsymbol{V}'_{it_2}\boldsymbol{\epsilon}_{it_2}\boldsymbol{D}'(U_{it_2}) e_1\right][1 + o(1)] \\
&= E\left[e_1' E\left(\frac{1}{T^2}\sum_{t_1=1}^{T}\sum_{t_2=1}^{T} \boldsymbol{D}(U_{it_1})\boldsymbol{V}_{it_1}\boldsymbol{\epsilon}_{it_1}\boldsymbol{V}_{it_2}\boldsymbol{\epsilon}_{it_2}\boldsymbol{D}'(U_{it_2}) \mid U_{it_1}, U_{it_2}\right) e_1\right][1 + o(1)] \\
&= E\left\{e_1' \left[\frac{1}{T}\boldsymbol{D}(U_{it})\boldsymbol{\Phi}(U_{it})\boldsymbol{D}'(U_{it})\right.\right. \\
&\qquad \left.\left. + \frac{2}{T^2}\sum_{t=2}^{T}(T - t + 1)\boldsymbol{D}(U_{i1})\boldsymbol{G}_{1t}(U_{i1}, U_{it})\boldsymbol{D}'(U_{it})\right] e_1\right\}[1 + o(1)] \\
&\equiv \frac{1}{T}\boldsymbol{\Sigma}_\gamma[1 + o(1)].
\end{aligned}$$

This concludes the proof of the lemma.

APPENDIX D: PROOFS OF THEOREMS

Proof of Theorem 1 and (15) in Theorem 3. By the assumptions, it is easy to see that $E(\boldsymbol{T}_N^*) = 0$ and $E(\boldsymbol{\Phi}_N^*) = 0$. Hence, the proofs are straightforward from Proposition $1(iv)$ and $2(iv)$, (9), and (14). This completes the proof of the theorems.

Proof of Theorem 2. Applying Theorem 3.1 in Powell et al. (1989), we have

$$\sqrt{N}(\hat{\gamma} - \gamma - bias_{\gamma}) \xrightarrow{D} N\left(0, \frac{1}{T}\boldsymbol{\Sigma}_{\gamma}\right).$$

This completes the proof of the theorem.

Proof of (16) in Theorem 3. We use the Cramer–Wold device to derive the asymptotic normality. Denote $\omega_{it} = (\boldsymbol{S}'\boldsymbol{S})^{-1}\boldsymbol{S}'\boldsymbol{Q}_{it}\epsilon_{it}K_{h_2}(U_{it} - u_0)f^{-1}(u_0)$,$\omega_{N,it} = \sqrt{\frac{h_2}{T}}\boldsymbol{d}'\omega_{it}$, and $\omega_{N,i}^* = \sqrt{\frac{1}{T}}\sum_{t=1}^{T}\omega_{N,it}$, which only contains the information of individual i. Then,

$$\sqrt{Nh_2}\boldsymbol{d}'f^{-1}(u_0)(\boldsymbol{S}'\boldsymbol{S})^{-1}\boldsymbol{S}'\boldsymbol{T}_N^* = \frac{1}{\sqrt{NT}}\sum_{i=1}^{N}\sum_{t=1}^{T}\omega_{N,it} = \frac{1}{\sqrt{N}}\sum_{i=1}^{N}\omega_{N,i}^*.$$

According to our model setting, the information between individuals are iid. Hence, $\omega_{N,i}^*$ series is an iid series. By Lindeberg–Lévy central limit theorem for iid case, the normality of $\sqrt{Nh_2}\boldsymbol{d}'\boldsymbol{T}_N^*$ is verified. This concludes the proof of the theorem.

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