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Quantile regression with panel data

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Supplemental Web Appendix to “Quantile regression with Panel Data” by Bryan S. Graham, Jinyong Hahn, Alexandre Poirier and James L. Powell: Proofs of Theorems 8, 9 and 10

This Supplemental Web Appendix contains proofs of Theorems 8, 9 and 10 that appear in Appendix A of the main paper. All notation is as established in, and equation numbering continues in sequence with that of, the main paper.

Proof of Theorem 8

Using arguments analogous to those used in Appendix B of the main paper we can show that $\hat{\delta}(\tau) - \delta(\tau)$ has the linear representation

$$\begin{aligned} \sqrt{N} \left(\hat{\delta}(\tau) - \delta(\tau) \right) &= \left(\frac{1}{N} \sum_{i=1}^N \mathbf{W}_i^{*'} \mathbf{W}_i^* \mathbf{1}(D_i = 0) \right)^{-1} \\ &\times \frac{1}{N} \sum_{i=1}^N \mathbf{W}_i^{*'} \mathbf{X}_i^* \mathbf{1}(D_i = 0) \sqrt{N} \left(\hat{Q}_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{X}_i) - Q_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{X}_i) \right) \\ &= \left(\sum_{l=L+1}^M \mathbf{w}_l^{*'} \mathbf{w}_l^* \hat{p}_l \right)^{-1} \sum_{l=L+1}^M \mathbf{w}_l^{*'} \mathbf{x}_l^* \hat{p}_l \sqrt{N} \left(\hat{Q}_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{x}_l) - Q_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{x}_l) \right) \end{aligned} \quad (103)$$

with

$$\sum_{l=L+1}^M \mathbf{w}_l^{*'} \mathbf{w}_l^* \hat{p}_l \xrightarrow{P} \sum_{l=L+1}^M \mathbf{w}_l^{*'} \mathbf{w}_l^* p_l = \mathbb{E}[\mathbf{W}^{*'} \mathbf{W}^* | D = 0] \pi_0$$

and

$$\sum_{l=L+1}^M \mathbf{w}_l^{*'} \mathbf{x}_l^* \hat{p}_l \sqrt{N} \left(\hat{Q}_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{x}_l) - Q_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{x}_l) \right) \xrightarrow{D} \sum_{l=L+1}^M \mathbf{w}_l^{*'} \mathbf{x}_l^* \sqrt{p_l} \mathbf{Z}_Q(\tau, \mathbf{x}_l),$$

which has an asymptotic covariance equal to

$$\begin{aligned} &\mathbb{E} \left[\sum_{l=L+1}^M \mathbf{w}_l^{*'} \mathbf{x}_l^* \sqrt{p_l} \mathbf{Z}_Q(\tau, \mathbf{x}_l) \left(\sum_{l'=L+1}^M \mathbf{w}_{l'}^{*'} \mathbf{x}_{l'}^* \sqrt{p_{l'}} \mathbf{Z}_Q(\tau', \mathbf{x}_{l'}) \right)' \right] \\ &= \sum_{l=L+1}^M \sum_{l'=L+1}^M \mathbf{w}_l^{*'} \mathbf{x}_l^* (\min(\tau, \tau') - \tau\tau') \Lambda(\tau, \tau'; \mathbf{x}_l) \cdot \mathbf{1}(l = l') \mathbf{x}_l^{*'} \mathbf{w}_l^* p_l p_{l'} \\ &= (\min(\tau, \tau') - \tau\tau') \mathbb{E}[\mathbf{W}^{*'} \mathbf{X}^* \Lambda(\tau, \tau'; \mathbf{X}) \mathbf{X}^{*'} \mathbf{W}^* | D = 0] \pi_0. \end{aligned}$$

To derive the asymptotic distribution of $\sqrt{N} \left(\hat{\beta}(\cdot; \cdot) - \beta(\cdot; \cdot) \right)$ we note that

$$\begin{aligned} \sqrt{N} \left(\hat{\beta}(\tau; \mathbf{x}_l) - \beta(\tau; \mathbf{x}_l) \right) &= \mathbf{x}_l^{-1} \sqrt{N} \left(\hat{Q}_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{x}_l) - Q_{\mathbf{Y}|\mathbf{X}}(\tau|\mathbf{x}_l) \right) - \mathbf{x}_l^{-1} \mathbf{w}_l \sqrt{N} \left(\hat{\delta}(\tau) - \delta(\tau) \right) \\ &\xrightarrow{D} \mathbf{x}_l^{-1} \mathbf{Z}_Q(\tau, \mathbf{x}_l) - \mathbf{x}_l^{-1} \mathbf{w}_l \mathbf{Z}_\delta(\tau). \end{aligned} \quad (104)$$

$\mathbf{Z}_Q(\tau, \mathbf{x}_l)$ and $\mathbf{Z}_\delta(\tau)$ are independent processes, since they are computed using disjoint subpopulations (i.e., \mathbf{x}_l for $l = 1, \dots, L$ are not used in the computation of $\hat{\delta}(\tau)$). Therefore, the asymptotic variance of (104) is the sum of the variance of its component terms.

Proof of Theorem 9

Decomposing $\hat{\beta}^M(\tau)$ we see that

$$\sqrt{N} \left(\hat{\beta}^M(\tau) - \bar{\beta}^M(\tau) \right) = \sum_{l=1}^L \beta(\tau; \mathbf{x}_l) \sqrt{N} (\hat{q}_l^M - q_l^M) \quad (105)$$

$$+ \sum_{l=1}^L \sqrt{N} \left(\hat{\beta}(\tau; \mathbf{x}_l) - \beta(\tau; \mathbf{x}_l) \right) \hat{q}_l^M. \quad (106)$$

By a result similar to that in (76) in the main text, term (105) converges to a mean zero Gaussian process with covariance equal to $\frac{\mathbb{C}(\beta(\tau, \mathbf{X}), \beta(\tau', \mathbf{X}) | \mathbf{X} \in \mathbb{X}^M)}{\Pr(\mathbf{X} \in \mathbb{X}^M)}$. Term ((106)) converges to

$$\sum_{l=1}^L \sqrt{N} \left(\hat{\beta}(\tau; \mathbf{x}_l) - \beta(\tau; \mathbf{x}_l) \right) \hat{q}_l^M \xrightarrow{D} \sum_{l=1}^L \mathbf{Z}(\tau, \mathbf{x}_l) q_l^M \quad (107)$$

which has a covariance kernel equal to

$$\begin{aligned} & \mathbb{E} \left[\sum_{l=1}^L \sum_{l'=1}^L \mathbf{Z}(\tau, \mathbf{x}_l) \mathbf{Z}(\tau, \mathbf{x}_{l'}) q_l^M q_{l'}^M \right] \\ &= \mathbb{E} [\mathbf{Z}(\tau, \mathbf{x}_l) \mathbf{Z}(\tau, \mathbf{x}_{l'})] q_l^M q_{l'}^M \\ &= (\min(\tau, \tau') - \tau\tau') \sum_{l=1}^L \sum_{l'=1}^L \frac{\mathbf{x}_l^{-1} \Lambda(\tau, \tau'; \mathbf{x}_l) \mathbf{x}_l^{-1'}}{p_l} \cdot \mathbf{1}(l = l') q_l^M q_{l'}^M \\ &+ \sum_{l=1}^L \sum_{l'=1}^L \mathbf{x}_l^{-1} \mathbf{w}_l \Sigma_\delta(\tau, \tau') \mathbf{w}_{l'}' \mathbf{x}_{l'}^{-1'} q_l^M q_{l'}^M \\ &= \frac{\min(\tau, \tau') - \tau\tau'}{\Pr(\mathbf{X} \in \mathbb{X}^M)} \mathbb{E} [\mathbf{X}^{-1} \Lambda(\tau, \tau', \mathbf{X}) \mathbf{X}^{-1'} | \mathbf{X} \in \mathbb{X}^M] + \sum_{l=1}^L \mathbf{x}_l^{-1} \mathbf{w}_l q_l^M \Sigma_\delta(\tau, \tau') \sum_{l'=1}^L \mathbf{w}_{l'}' \mathbf{x}_{l'}^{-1'} q_{l'}^M \\ &= \Upsilon_1(\tau, \tau') + \Xi_0 \Sigma_\delta(\tau, \tau') \Xi_0'. \end{aligned}$$

Since terms (105) and (106) are uncorrelated, the asymptotic covariance of $\sqrt{N} \left(\hat{\beta}^M(\tau) - \bar{\beta}^M(\tau) \right)$ is equal to the sum of the covariances these two terms.

Proof of Theorem 10

We start by deriving the asymptotic distribution of the sample cumulative distribution function of $\hat{\beta}_p(U; \mathbf{X})$ with U distributed uniformly on $[0, 1]$ independently from \mathbf{X} , while conditioning on $\mathbf{X} \in \mathbb{X}^M$. The CDF

estimand at $c \in \mathbb{R}$ is denoted as $F_{B_p|\mathbf{X} \in \mathbb{X}^M}(c)$ with estimator

$$\begin{aligned}\widehat{F}_{\widehat{\beta}_p(U;\mathbf{X})|\mathbf{X} \in \mathbb{X}^M}(c) &= \frac{\frac{1}{N} \sum_{i=1}^N \left[\int_0^1 \mathbf{1}(\widehat{\beta}_p(u, \mathbf{X}_i) \leq c) du \right] \mathbf{1}(\mathbf{X}_i \in \mathbb{X}^M)}{\frac{1}{N} \sum_{i=1}^N \mathbf{1}(\mathbf{X}_i \in \mathbb{X}^M)} \\ &= \sum_{l=1}^L \left(\int_0^1 \mathbf{1}(\widehat{\beta}_p(u, \mathbf{x}_l) \leq c) du \right) \widehat{q}_l^M.\end{aligned}\quad (108)$$

The integration over $u \in (0, 1)$ can be done exactly since $\widehat{\beta}_p(u, \mathbf{x}_l)$ is piecewise linear for each $l \in \{1, \dots, L\}$ with finitely many pieces. We can express $\widehat{F}_{\widehat{\beta}_p(U;\mathbf{X})|\mathbf{X} \in \mathbb{X}^M}(c)$ as the sum of two terms:

$$\widehat{F}_{\widehat{\beta}_p(U;\mathbf{X})|\mathbf{X} \in \mathbb{X}^M}(c) - F_{B_p|\mathbf{X} \in \mathbb{X}^M}(c) = \sum_{l=1}^L \left(\left[\int_0^1 \mathbf{1}(\widehat{\beta}_p(u, \mathbf{x}_l) \leq c) du \right] - \left[\int_0^1 \mathbf{1}(\beta_p(u, \mathbf{x}_l) \leq c) du \right] \right) \widehat{q}_l^M \quad (109)$$

$$+ \sum_{l=1}^L \left[\int_0^1 \mathbf{1}(\beta_p(u, \mathbf{x}_l) \leq c) du \right] (\widehat{q}_l^M - q_l^M). \quad (110)$$

We will show that these two terms both converge in uniformly over $c \in \mathbb{R}$. For term (109), we have that $\sqrt{N} \left(\widehat{\beta}_p(\tau; \mathbf{x}_l) - \beta_p(\tau; \mathbf{x}_l) \right) \xrightarrow{D} (\mathbf{Z}(\tau, \mathbf{x}_l))_p = \mathbf{Z}_p(\tau, \mathbf{x}_l)$ over $\tau \in (0, 1)$ and all $l = 1, \dots, L$, and $(\cdot)_p$ denotes the p^{th} element of the vector. By the same argument use to show (79) in Appendix B, we have

$$\begin{aligned}& \sqrt{N} \left(\int_0^1 \mathbf{1}(\widehat{\beta}_p(u; \mathbf{x}_l) \leq c) du - \int_0^1 \mathbf{1}(\beta_p(u; \mathbf{x}_l) \leq c) du \right) \\ &= \sqrt{N} \left(\widehat{\beta}_p(F_{B_p|\mathbf{X}}(c|\mathbf{x}_l); \mathbf{x}_l) - \beta_p(F_{B_p|\mathbf{X}}(c|\mathbf{x}_l); \mathbf{x}_l) \right) f_{B_p|\mathbf{X}}(c|\mathbf{x}_l) + o_p(1) \\ &\xrightarrow{D} \mathbf{Z}_p(F_{B_p|\mathbf{X}}(c|\mathbf{x}_l), \mathbf{x}_l) f_{B_p|\mathbf{X}}(c|\mathbf{x}_l).\end{aligned}$$

This convergence is uniform in $c \in \mathbb{R}$ since $F_{B_p|\mathbf{X}}(c|\mathbf{x}_l)$ ranges between 0 and 1, and uniform in \mathbf{x}_l since its support is finite. Therefore,

$$\sum_{l=1}^L \sqrt{N} \left(\int_0^1 \mathbf{1}(\widehat{\beta}_p(u; \mathbf{x}_l) \leq c) du - \int_0^1 \mathbf{1}(\beta_p(u; \mathbf{x}_l) \leq c) du \right) \widehat{q}_l^M \xrightarrow{D} \sum_{l=1}^L \mathbf{Z}_p(F_{B_p|\mathbf{X}}(c|\mathbf{x}_l), \mathbf{x}_l) f_{B_p|\mathbf{X}}(c|\mathbf{x}_l) q_l^M \quad (111)$$

for $c \in \mathbb{R}$. Also, (110) will converge over $c \in \mathbb{R}$ to a Gaussian process $\mathbf{Z}_{2p}(c)$ with asymptotic covariance of

$$\mathbb{E} [\mathbf{Z}_{2p}(c) \mathbf{Z}_{2p}(c)'] = \frac{\mathbb{C} (F_{B_p|\mathbf{X}}(c|\mathbf{X}), F_{B_p|\mathbf{X}}(c'|\mathbf{X}) | \mathbf{X} \in \mathbb{X}^M)}{\Pr(\mathbf{X} \in \mathbb{X}^M)}.$$

Note that $\mathbf{Z}_{2p}(c)$ and $\sum_{l=1}^L \mathbf{Z}_p(F_{B_p|\mathbf{X}}(c|\mathbf{x}_l), \mathbf{x}_l) f_{B_p|\mathbf{X}}(c|\mathbf{x}_l) q_l^M$ are uncorrelated since the variation in the latter is conditional on \mathbf{X} while that in the former depends on \mathbf{X} only. Therefore,

$$\sqrt{N} \left(\widehat{F}_{\widehat{\beta}_p(U;\mathbf{X})|\mathbf{X} \in \mathbb{X}^M}(c) - F_{B_p|\mathbf{X} \in \mathbb{X}^M}(c) \right) \xrightarrow{D} \sum_{l=1}^L \mathbf{Z}_p(F_{B_p|\mathbf{X}}(c|\mathbf{x}_l), \mathbf{x}_l) f_{B_p|\mathbf{X}}(c|\mathbf{x}_l) q_l^M + \mathbf{Z}_{2p}(c)$$

for $c \in \mathbb{R}$.

Using the same invertibility argument as in (82), we see that

$$\begin{aligned} \sqrt{N} \left(\hat{\beta}_p^M(\tau) - \beta_p^M(\tau) \right) &\xrightarrow{D} \frac{\sum_{l=1}^L \mathbf{Z}_p(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l), \mathbf{x}_l) f_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l) q_l^M + \mathbf{Z}_{2p}(\beta_p^M(\tau))}{f_{B_p|\mathbf{X} \in \mathbb{X}^M}(\beta_p^M(\tau))} \\ &= \mathbf{Z}_{\beta_p}(\tau) \end{aligned} \quad (112)$$

uniformly over $\tau \in (0, 1)$.

To conclude this proof, we evaluate $\mathbb{E} [\mathbf{Z}_{\beta_p}(\tau) \mathbf{Z}_{\beta_p}(\tau')']$, the asymptotic covariance of ((112)):

$$\begin{aligned} \mathbb{E} \left[\mathbf{Z}_{\beta_p}(\tau) \mathbf{Z}_{\beta_p}(\tau')' \right] &= \frac{\sum_{l=1}^L \sum_{l'=1}^L f_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l) f_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'}) q_l^M q_{l'}^M}{f_{B_p|\mathbf{X} \in \mathbb{X}^M}(\beta_p^M(\tau)) f_{B_p|\mathbf{X} \in \mathbb{X}^M}(\beta_p^M(\tau'))} \\ &\quad \times \mathbb{E} \left[\mathbf{Z}_p(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l), \mathbf{x}_l) \mathbf{Z}_p(F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'}), \mathbf{x}_{l'}) \right] \\ &\quad + \frac{\mathbb{E} \left[\mathbf{Z}_{2p}(\beta_p^M(\tau)) \mathbf{Z}_{2p}(\beta_p^M(\tau')) \right]}{f_{B_p|\mathbf{X} \in \mathbb{X}^M}(\beta_p^M(\tau)) f_{B_p|\mathbf{X} \in \mathbb{X}^M}(\beta_p^M(\tau'))}, \end{aligned}$$

where

$$\begin{aligned} &\mathbb{E} \left[\mathbf{Z}_p(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l), \mathbf{x}_l) \mathbf{Z}_p(F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'}), \mathbf{x}_{l'}) \right] \\ &= (\min(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l), F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'})) - F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l) F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'})) \\ &\quad \times e_p' \frac{\mathbf{x}_l^{-1} \Lambda(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l), F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'}); \mathbf{x}_l) \mathbf{x}_l^{-1l'}}{p_l} e_p \cdot \mathbf{1}(l = l') \\ &\quad + e_p' \mathbf{x}_l^{-1} \mathbf{w}_l \Sigma_\delta(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l), F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'})) \mathbf{w}_l' \mathbf{x}_l^{-1l'} e_p, \end{aligned}$$

and

$$\begin{aligned} &\sum_{l=1}^L \sum_{l'=1}^L f_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l) q_l^M \mathbb{E} \left[\mathbf{Z}_p(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{x}_l), \mathbf{x}_l) \mathbf{Z}_p(F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'}), \mathbf{x}_{l'}) \right] f_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{x}_{l'}) q_{l'}^M \\ &= \mathbb{E} \left[\frac{(\min(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{X}), F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{X})) - F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{X}) F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{X}))}{\Pr(\mathbf{X} \in \mathbb{X}^M)} \right] \\ &\quad \times e_p' \mathbf{X}^{-1} \Lambda(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{X}), F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{X}); \mathbf{X}) \mathbf{X}^{-1l'} e_p f_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{X}) f_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{X}) | \mathbf{X} \in \mathbb{X}^M \\ &\quad + e_p' \mathbb{E} \left[f_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{X}) f_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\tilde{\mathbf{X}}) \mathbf{X}^{-1} \mathbf{W} \Sigma_\delta(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{X}), F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\tilde{\mathbf{X}})) \right. \\ &\quad \left. \times \tilde{\mathbf{W}}' \tilde{\mathbf{X}}^{-1l'} | \mathbf{X} \in \mathbb{X}^M, \tilde{\mathbf{X}} \in \mathbb{X}^M \right] e_p \\ &= \Upsilon_3(\tau, \tau') + \Upsilon_4(\tau, \tau'), \end{aligned} \quad (113)$$

with $\tilde{\mathbf{X}}$ is an independent copy of \mathbf{X} . Finally,

$$\begin{aligned} \mathbb{E} \left[\mathbf{Z}_{2p}(\beta_p^M(\tau)) \mathbf{Z}_{2p}(\beta_p^M(\tau')) \right] &= \frac{\mathbb{C}(F_{B_p|\mathbf{X}}(\beta_p^M(\tau)|\mathbf{X}), F_{B_p|\mathbf{X}}(\beta_p^M(\tau')|\mathbf{X}) | \mathbf{X} \in \mathbb{X}^M)}{\Pr(\mathbf{X} \in \mathbb{X}^M)} \\ &= \Upsilon_2(\tau, \tau'). \end{aligned}$$