Web-based Supplementary Material for “Local Adaptive Grouped Regularization and its Oracle Properties for Varying Coefficient Regression"

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1. Lemmas

Lemma 1.

$$E\left[\sum_{i=1}^{n} q_1\left(\boldsymbol{Z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}), Y_i\right)\boldsymbol{Z}_i K_h\left(\|\boldsymbol{s}-\boldsymbol{s}_i\|\right)\right] = \begin{pmatrix} 2^{-1}n^{1/2}h^3 f(\boldsymbol{s})\kappa_2\boldsymbol{\Gamma}(\boldsymbol{s})\left(\nabla^2_{uu}\boldsymbol{\beta}(\boldsymbol{s}) + \nabla^2_{vv}\boldsymbol{\beta}(\boldsymbol{s})\right)^T \\ \boldsymbol{0}_{2p} \end{pmatrix} + o_p\left(h^2\boldsymbol{1}_{3p}\right)$$

and

$$\begin{aligned} Var\left[\sum_{i=1}^{n} q_1\left(\boldsymbol{Z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}), Y_i\right)\boldsymbol{Z}_i K_h\left(\|\boldsymbol{s}-\boldsymbol{s}_i\|\right)\right] =& f(\boldsymbol{s})\mathrm{diag}\left\{\nu_0,\nu_2,\nu_2\right\}\otimes\boldsymbol{\Gamma}(\boldsymbol{s}) + o\left(1\right) \\ =& \Lambda + o\left(1\right) \end{aligned}$$

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Proof. **Expectation**: For $j = 1, \ldots, p$, by a Taylor expansion of $\beta_j(\boldsymbol{s}_i)$ around $\boldsymbol{s}$,

$$\beta_j(\boldsymbol{s}_i) = \beta_j(\boldsymbol{s}) + \nabla\beta_j(\boldsymbol{s})(\boldsymbol{s}_i - \boldsymbol{s}) + (\boldsymbol{s}_i - \boldsymbol{s})^T \left\{\nabla^2\beta_j(\boldsymbol{s})\right\} (\boldsymbol{s}_i - \boldsymbol{s}) + o\left(h^2\right)$$

and thus, for $\boldsymbol{x} \in \mathbb{R}^p$,

$$\boldsymbol{x}_i^T \boldsymbol{\beta}(\boldsymbol{s}_i) = \sum_{j=1}^{p} x_{ij} \left[\beta_j(\boldsymbol{s}) + \nabla\beta_j(\boldsymbol{s})^T(\boldsymbol{s}_i - \boldsymbol{s}) + \tilde{\beta}''_{ij}\right] + o\left(h^2\right).$$

Letting $\boldsymbol{z}_i^T = \left\{(1, s_{i,1} - s_1, s_{i,2} - s_2) \otimes \boldsymbol{x}_i^T\right\}$ and $\boldsymbol{\zeta}(\boldsymbol{s}) = \left(\boldsymbol{\beta}(\boldsymbol{s})^T, \nabla_u\boldsymbol{\beta}(\boldsymbol{s})^T, \nabla_v\boldsymbol{\beta}(\boldsymbol{s})^T\right)^T$, we have that

$$\begin{aligned}
\boldsymbol{x}_i^T \boldsymbol{\beta}(\boldsymbol{s}_i) - \boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}) =& \boldsymbol{x}_i^T \tilde{\boldsymbol{\beta}}''_i + o\left(h^2\right) \\
=& O_p\left(h^2\right).
\end{aligned}$$

By a Taylor expansion around $\boldsymbol{x}^T\boldsymbol{\beta}(\boldsymbol{s}_i)$, then,

$$\begin{aligned}
q_1\left(\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}), \mu(\boldsymbol{s}_i, \boldsymbol{z}_i)\right) =& q_1\left(\boldsymbol{x}_i^T\boldsymbol{\beta}(\boldsymbol{s}_i), \mu(\boldsymbol{s}_i, \boldsymbol{z})\right) \\
&- q_2\left(\boldsymbol{x}_i^T\boldsymbol{\beta}(\boldsymbol{s}_i), \mu(\boldsymbol{s}_i, \boldsymbol{z})\right) \boldsymbol{x}_i^T \tilde{\boldsymbol{\beta}}''_i \\
&+ o\left(h^2\right).
\end{aligned}$$

And by the definitions of $q_1(\cdot)$ and $q_2(\cdot)$, we have that

$$q_1\left(\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}), \mu(\boldsymbol{s}_i, \boldsymbol{z}_i)\right) = \rho(\boldsymbol{s}_i, \boldsymbol{z}_i)\boldsymbol{x}_i^T \tilde{\boldsymbol{\beta}}''_i + o\left(h^2\right).$$

Now the expectation of Ω_n is

$$\begin{aligned}
nE\left(\omega_i | \boldsymbol{Z}_i = \boldsymbol{z}_i, \boldsymbol{s}_i\right) =& \left(1/2\right)\alpha_n \boldsymbol{z}_i q_1\left(\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}), \mu(\boldsymbol{s}_i, \boldsymbol{z}_i)\right) K\left(h^{-1}\|\boldsymbol{s} - \boldsymbol{s}_i\|\right) \\
=& \left(1/2\right)\alpha_n h^2 \boldsymbol{z}_i \left\{h^{-2}\rho(\boldsymbol{s}_i, \boldsymbol{z}_i)\boldsymbol{x}_i^T \tilde{\boldsymbol{\beta}}''_i + o\left(\mathbf{1}_{3p}\right)\right\} K\left(h^{-1}\|\boldsymbol{s} - \boldsymbol{s}_i\|\right).
\end{aligned}$$

To facilitate a change of variables, we observe that $h^{-2}\tilde{\beta}_j'' = \left(\frac{\boldsymbol{s}_i - \boldsymbol{s}}{h}\right)^T \{\nabla^2 \beta_j(\boldsymbol{s})\} \left(\frac{\boldsymbol{s}_i - \boldsymbol{s}}{h}\right)$. Thus,

$$E\left(\omega_i|\boldsymbol{s}_i\right) = (1/2)\,\alpha_n h^2 \left[\begin{pmatrix} 1 \\ h^{-1}(s_{i,1} - s_1) \\ h^{-1}(s_{i,2} - s_2) \end{pmatrix} \otimes \left\{\boldsymbol{\Gamma}(\boldsymbol{s}_i) h^{-2} \tilde{\boldsymbol{\beta}}_i''\right\} + o\left(\mathbf{1}_{3p}\right)\right] K\left(h^{-1}\|\boldsymbol{s} - \boldsymbol{s}_i\|\right).$$

And, using the symmetry of the kernel function,

$$E\left(\omega_i\right) = (1/2)\alpha_n h^4 f(\boldsymbol{s}) \begin{pmatrix} \kappa_2 \\ h\kappa_3 \\ h\kappa_3 \end{pmatrix} \otimes \left[\boldsymbol{\Gamma}(\boldsymbol{s})\left\{\nabla^2_{uu}\boldsymbol{\beta}(\boldsymbol{s}) + \nabla^2_{vv}\boldsymbol{\beta}(\boldsymbol{s})\right\}\right] + o\left(h^2\mathbf{1}_{3p}\right)$$

where $\{\nabla^2_{uu}\boldsymbol{\beta}(\boldsymbol{s}) + \nabla^2_{vv}\boldsymbol{\beta}(\boldsymbol{s})\} = \left(\nabla^2_{uu}\beta_1(\boldsymbol{s}) + \nabla^2_{vv}\beta_1(\boldsymbol{s}), \ldots, \nabla^2_{uu}\beta_p(\boldsymbol{s}) + \nabla^2_{vv}\beta_p(\boldsymbol{s})\right)^T$. Thus,

$$E\left(\Omega_n\right) = \begin{pmatrix} \alpha_n^{-1} 2^{-1} h^2 \kappa_2 f(\boldsymbol{s}) \boldsymbol{\Gamma}(\boldsymbol{s}) \left(\nabla^2_{uu}\boldsymbol{\beta}(\boldsymbol{s}) + \nabla^2_{vv}\boldsymbol{\beta}(\boldsymbol{s})\right)^T \\ \mathbf{0}_{2p} \end{pmatrix} + o_p\left(h^2\mathbf{1}_{3p}\right)$$

Variance: By the previous result, $E\left(\Omega_n\right) = O\left(h^2\right)$. Thus, $var\left(\Omega_n\right) \to E\left(\Omega_n^2\right)$, and since the observations are independent, $E\left(\Omega_n^2\right) = \sum_{i=1}^n E\left(\omega_i^2\right)$. And, by Taylor expansion around $\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}_i)$,

$$\begin{aligned} q_1^2\left(\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}), Y_i\right) = & q_1^2\left(\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}_i), Y_i\right) \\ & - q_1\left(\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}_i), Y_i\right) q_2\left(\boldsymbol{z}_i^T\boldsymbol{\zeta}(\boldsymbol{s}_i), Y_i\right) \boldsymbol{x}_i^T \tilde{\boldsymbol{\beta}}_i'' \\ & + o\left(h^2\right). \end{aligned}$$

Since $q_1(\cdot,\cdot)$ is the quasi-score function, it follows that

$$E\left(\omega_i^2|\boldsymbol{Z}_i = \boldsymbol{z}_i, \boldsymbol{s}_i\right) = \alpha_n^2 \rho(\boldsymbol{s}_i, \boldsymbol{z}_i) \boldsymbol{z}_i \boldsymbol{z}_i^T K\left(h^{-1}\|\boldsymbol{s} - \boldsymbol{s}_i\|\right) + o\left(h^2\right).$$

By the symmetry of the kernel function,

$$E\left(\omega_i^2\right) = n^{-1} f(\boldsymbol{s}) \operatorname{diag}\left\{\nu_0, \nu_2, \nu_2\right\} \otimes \boldsymbol{\Gamma}(\boldsymbol{s}) + o\left(1\right).$$

Thus,

$$Var\left(\Omega_n\right) = f(\boldsymbol{s}) \operatorname{diag}\left\{\nu_0, \nu_2, \nu_2\right\} \otimes \boldsymbol{\Gamma}(\boldsymbol{s}) + o\left(1\right).$$

$\square$

Lemma 2.

$$\begin{aligned} E\left[\sum_{i=1}^{n} q_2\left(\boldsymbol{Z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}), Y_i\right) \boldsymbol{Z}_i \boldsymbol{Z}_i^T K_h\left(\|\boldsymbol{s} - \boldsymbol{s}_i\|\right)\right] =& - f(\boldsymbol{s}) \operatorname{diag}\left\{\kappa_0, \kappa_2, \kappa_2\right\} \otimes \boldsymbol{\Gamma}(\boldsymbol{s}) + o\left(1\right) \\ =& - \Delta + o\left(1\right) \end{aligned}$$

and

$$Var\left\{\left(\sum_{i=1}^{n} q_2\left(\boldsymbol{Z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}), Y_i\right) \boldsymbol{Z}_i \boldsymbol{Z}_i^T K_h\left(\|\boldsymbol{s} - \boldsymbol{s}_i\|\right)\right)_{ij}\right\} = O\left(n^{-1} h^{-2}\right)$$

Proof. **Expectation**: The approach is similar to the proof of Lemma 1. By the Taylor expansion of $q_2\left(\boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}), \mu\left(\boldsymbol{s}_i, \boldsymbol{z}_i\right)\right)$ around $\boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}_i)$:

$$\begin{aligned} q_2\left(\boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}), \mu(\boldsymbol{s}_i, \boldsymbol{z}_i)\right) =& q_2\left(\boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}_i), \mu(\boldsymbol{s}_i, \boldsymbol{z}_i)\right) + q_3\left(\boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}_i), \mu(\boldsymbol{s}_i, \boldsymbol{z}_i)\right)\left\{\boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}) - \boldsymbol{z}_i^T \boldsymbol{\zeta}(\boldsymbol{s}_i)\right\} \\ =& - \rho(\boldsymbol{s}_i, \boldsymbol{z}_i) + o\left(1\right). \end{aligned}$$

And by the same arguments as before

$$
\begin{aligned}
E\left(\delta_i|\boldsymbol{Z}_i=\boldsymbol{z}_i,\boldsymbol{s}_i\right)=&-\alpha_n^2\rho(\boldsymbol{s}_i,\boldsymbol{z}_i)\boldsymbol{z}_i\boldsymbol{z}_i^TK\left(h^{-1}\|\boldsymbol{s}_i-\boldsymbol{s}\|\right)\\
E\left(\delta_i|\boldsymbol{s}_i\right)=&-\alpha_n^2\begin{pmatrix}1\\ h^{-1}(s_{i,1}-s_1)\\ h^{-1}(s_{i,2}-s_2)\end{pmatrix}\begin{pmatrix}1\\ h^{-1}(s_{i,1}-s_1)\\ h^{-1}(s_{i,2}-s_2)\end{pmatrix}^T\otimes\boldsymbol{\Gamma}(\boldsymbol{s}_i)K\left(h^{-1}\|\boldsymbol{s}_i-\boldsymbol{s}\|\right)\\
E\left(\delta_i\right)=&-nf\left(\boldsymbol{s}\right)\mathrm{diag}\left\{\kappa_0,\kappa_2,\kappa_2\right\}\otimes\boldsymbol{\Gamma}\left(\boldsymbol{s}\right)+o\left(n^{-1}\right)
\end{aligned}
$$

Thus,

$$
E\left(\Delta_n\right)=-f(\boldsymbol{s})\mathrm{diag}\left\{\kappa_0,\kappa_2,\kappa_2\right\}\otimes\boldsymbol{\Gamma}(\boldsymbol{s})+o\left(1\right)
$$

Variance: From the previous result, it follows that $\left\{E\left(\delta_i\right)\right\}^2=O\left(n^{-2}\right)$. By the definition of δ_i,

$$
\begin{aligned}
&E\left(\delta_i^2|\boldsymbol{Z}_i=\boldsymbol{z}_i,\boldsymbol{s}_i\right)=\\
&\alpha_n^4\boldsymbol{z}_i^T\boldsymbol{z}_iq_2^2(\boldsymbol{s}_i,\boldsymbol{z}_i)\begin{pmatrix}1\\ h^{-1}(s_{i,1}-s_1)\\ h^{-1}(s_{i,2}-s_2)\end{pmatrix}\begin{pmatrix}1\\ h^{-1}(s_{i,1}-s_1)\\ h^{-1}(s_{i,2}-s_2)\end{pmatrix}^T\boldsymbol{z}_i\boldsymbol{z}_i^TK^2\left(h^{-1}\|\boldsymbol{s}_i-\boldsymbol{s}\|\right)+o\left(1\right)
\end{aligned}
$$

And it follows that $E\left(\delta_i^2\right)=O\left(n^{-1}\alpha_n^2\right)$, and $Var\left(\Delta_n\right)=O\left(\alpha_n^2\right)$. $\square$