Advanced Econometrics #4 : Quantiles and Expectiles

A. Charpentier (Université de Rennes 1)

Université de Rennes 1,

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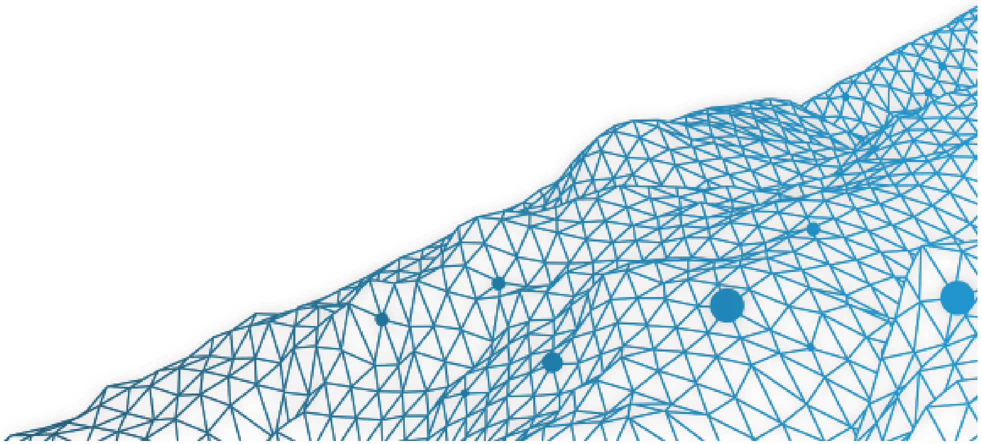


References

Motivation

Machado & Mata (2005). Counterfactual decomposition of changes in wage distributions using quantile regression, JAE.

References

Givord & d'Haultfœuillle (2013) La régression quantile en pratique, INSEE

Koenker & Bassett (1978) Regression Quantiles, Econometrica.

Koenker (2005). Quantile Regression. Cambridge University Press.

Newey & Powell (1987) Asymmetric Least Squares Estimation and Testing, Econometrica.

Quantiles

Let Y denote a random variable with cumulative distribution function F, $F(y) = \mathbb{P}[Y \leq y]$. The quantile is

$$Q(u) = \inf\left\{x \in \mathbb{R}, F(x) > u\right\}.$$

Defining halfspace depth

Given $\boldsymbol{y} \in \mathbb{R}^d$, and a direction $\boldsymbol{u} \in \mathbb{R}^d$, define the closed half space

$$H_{\boldsymbol{y},\boldsymbol{u}} = \{\boldsymbol{x} \in \mathbb{R}^d \text{ such that } \boldsymbol{u}'\boldsymbol{x} \leq \boldsymbol{u}'\boldsymbol{y}\}$$

and define depth at point $\boldsymbol{y}$ by

$$\text{depth}(\boldsymbol{y}) = \inf_{\boldsymbol{u},\boldsymbol{u}\neq\boldsymbol{0}} \{\mathbb{P}(H_{\boldsymbol{y},\boldsymbol{u}})\}$$

i.e. the smallest probability of a closed half space containing $\boldsymbol{y}$.

The empirical version is (see Tukey (1975)

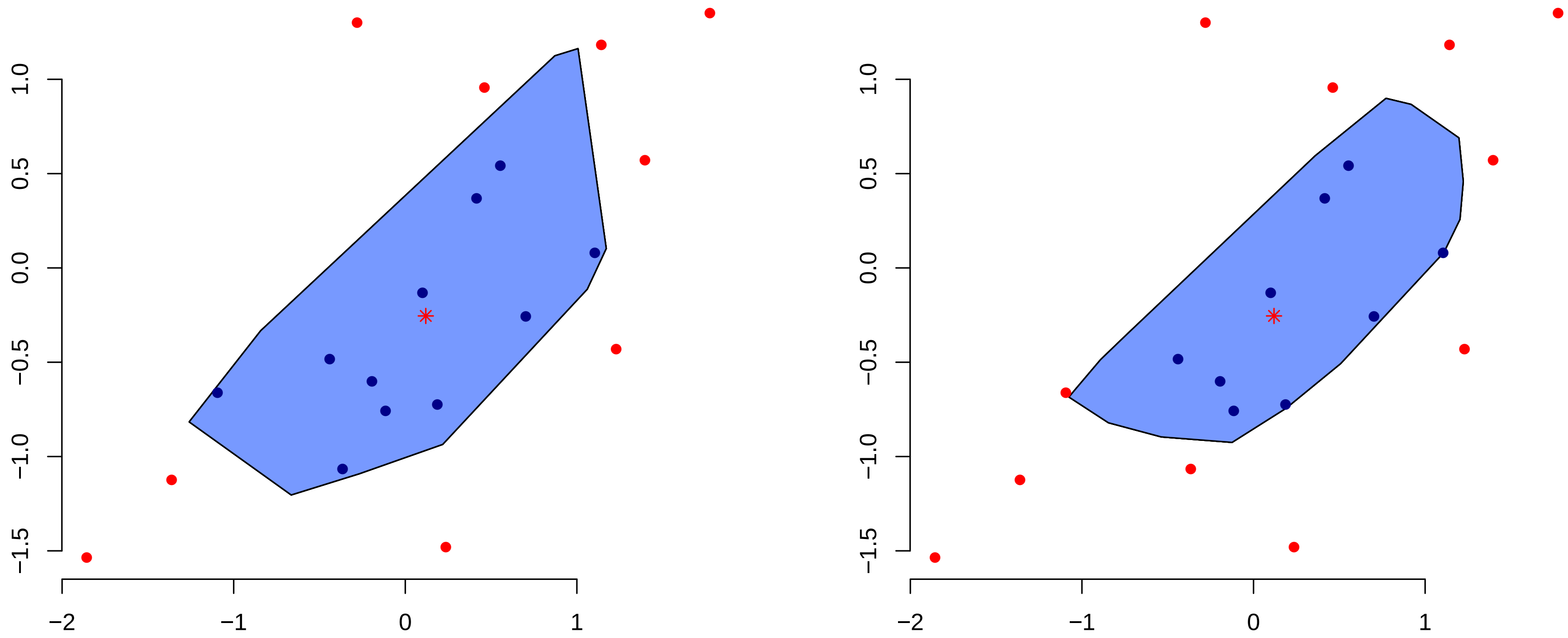
$$\text{depth}(\boldsymbol{y}) = \min_{\boldsymbol{u},\boldsymbol{u}\neq\boldsymbol{0}} \left\{ \frac{1}{n} \sum_{i=1}^{n} \mathbf{1}(\boldsymbol{X}_i \in H_{\boldsymbol{y},\boldsymbol{u}}) \right\}$$

For $\alpha > 0.5$, define the depth set as

$$D_\alpha = \{\boldsymbol{y} \in \mathbb{R} \in \mathbb{R}^d \text{ such that } \geq 1 - \alpha\}.$$

The empirical version is can be related to the bagplot, Rousseeuw *et al.*, 1999.

Empirical sets extremely sentive to the algorithm



where the blue set is the empirical estimation for D_α, $\alpha = 0.5$.

The bagplot tool

The depth function introduced here is the multivariate extension of standard univariate depth measures, e.g.

$$\text{depth}(x) = \min\{F(x), 1 - F(x^-)\}$$

which satisfies $\text{depth}(Q_\alpha) = \min\{\alpha, 1-\alpha\}$. But one can also consider

$$\text{depth}(x) = 2 \cdot F(x) \cdot [1 - F(x^-)] \text{ or } \text{depth}(x) = 1 - \left|\frac{1}{2} - F(x)\right|.$$

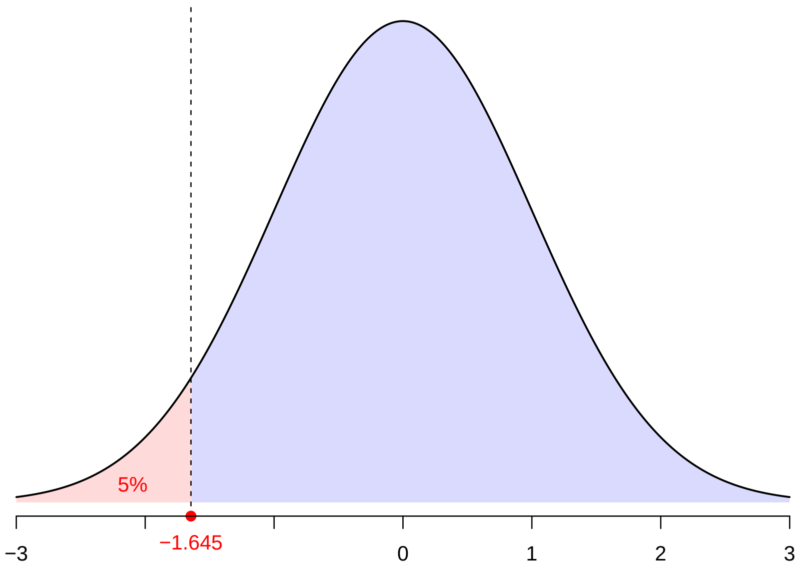
Possible extensions to functional bagplot. Consider a set of functions $f_i(x)$, $i = 1, \cdots, n$, such that

$$f_i(x) = \mu(x) + \sum_{k=1}^{n-1} z_{i,k}\varphi_k(x)$$

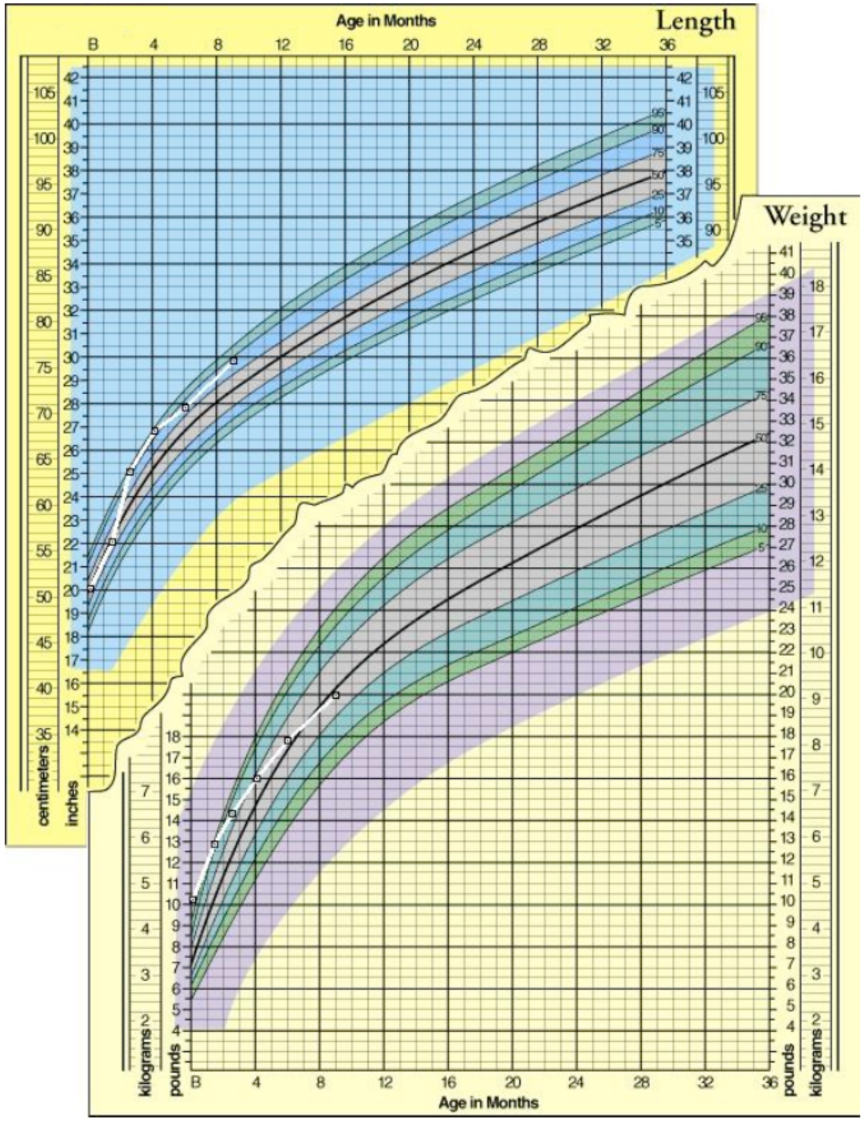
(i.e. principal component decomposition) where $\varphi_k(\cdot)$ represents the eigenfunctions. Rousseeuw et al., 1999 considered bivariate depth on the first two scores, $\boldsymbol{x}_i = (z_{i,1}, z_{i,2})$. See Ferraty & Vieu (2006).

Quantiles and Quantile Regressions

Quantiles are important quantities in many areas (inequalities, risk, health, sports, etc).



Quantiles of the $\mathcal{N}(0,1)$ distribution.



A First Model for Conditional Quantiles

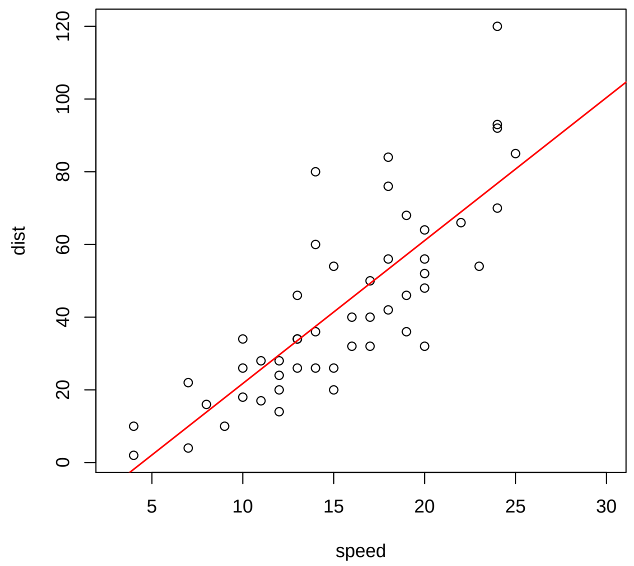
Consider a location model, $y = \beta_0 + \boldsymbol{x}^\mathsf{T}\boldsymbol{\beta} + \varepsilon$ i.e.

$$\mathbb{E}[Y|\boldsymbol{X} = \boldsymbol{x}] = \boldsymbol{x}^\mathsf{T}\boldsymbol{\beta}$$

then one can consider

$$Q(\tau|\boldsymbol{X} = \boldsymbol{x}) = \beta_0 + Q_\varepsilon(\tau) + \boldsymbol{x}^\mathsf{T}\boldsymbol{\beta}$$

where $Q_\varepsilon(\cdot)$ is the quantile function of the residuals.



OLS Regression, ℓ_2 norm and Expected Value

Let $\boldsymbol{y} \in \mathbb{R}^d$, $\overline{y} = \underset{m\in\mathbb{R}}{\text{argmin}} \left\{ \sum_{i=1}^{n} \frac{1}{n} \big[\underbrace{y_i - m}_{\varepsilon_i}\big]^2 \right\}$. It is the empirical version of

$$\mathbb{E}[Y] = \underset{m\in\mathbb{R}}{\text{argmin}} \left\{ \int \big[\underbrace{y - m}_{\varepsilon}\big]^2 dF(y) \right\} = \underset{m\in\mathbb{R}}{\text{argmin}} \left\{ \mathbb{E}\big[\|\underbrace{Y - m}_{\varepsilon}\|_{\ell_2}\big] \right\}$$

where Y is a random variable.

Thus, $\underset{m(\cdot):\mathbb{R}^k\to\mathbb{R}}{\text{argmin}} \left\{ \sum_{i=1}^{n} \frac{1}{n} \big[\underbrace{y_i - m(\boldsymbol{x}_i)}_{\varepsilon_i}\big]^2 \right\}$ is the empirical version of $\mathbb{E}[Y|\boldsymbol{X} = \boldsymbol{x}]$.

See Legendre (1805) Nouvelles méthodes pour la détermination des orbites des comètes and Gauβ (1809) Theoria motus corporum coelestium in sectionibus conicis solem ambientium.

OLS Regression, ℓ_2 norm and Expected Value

Sketch of proof: (1) Let $h(x) = \sum_{i=1}^{d}(x - y_i)^2$, then

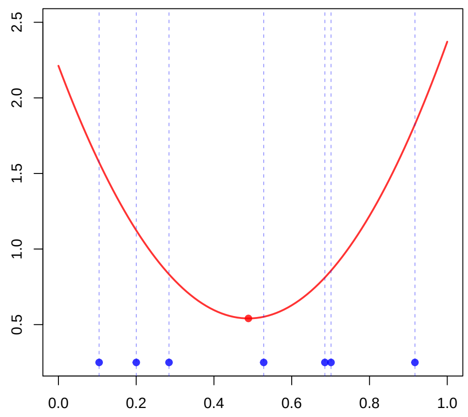
$$h'(x) = \sum_{i=1}^{d} 2(x - y_i)$$

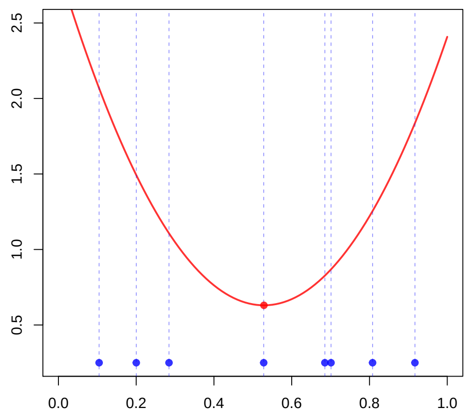
and the FOC yields $x = \frac{1}{n}\sum_{i=1}^{d} y_i = \overline{y}$.

(2) If Y is continuous, let $h(x) = \int_{\mathbb{R}}(x - y)f(y)dy$ and

$$h'(x) = \frac{\partial}{\partial x}\int_{\mathbb{R}}(x - y)^2 f(y)dy = \int_{\mathbb{R}}\frac{\partial}{\partial x}(x - y)^2 f(y)dy$$

i.e. $x = \int_{\mathbb{R}} xf(y)dy = \int_{\mathbb{R}} yf(y)dy = \mathbb{E}[Y]$





Median Regression, ℓ_1 norm and Median

Let $\boldsymbol{y} \in \mathbb{R}^d$, $\text{median}[\boldsymbol{y}] \in \underset{m\in\mathbb{R}}{\text{argmin}} \left\{ \sum_{i=1}^{n} \frac{1}{n} \underbrace{|y_i - m|}_{\varepsilon_i} \right\}$. It is the empirical version of

$$\text{median}[Y] \in \underset{m\in\mathbb{R}}{\text{argmin}} \left\{ \int \underbrace{|y - m|}_{\varepsilon} dF(y) \right\} = \underset{m\in\mathbb{R}}{\text{argmin}} \left\{ \mathbb{E}\big[\|\underbrace{Y - m}_{\varepsilon}\|_{\ell_1}\big] \right\}$$

where Y is a random variable, $\mathbb{P}[Y \leq \text{median}[Y]] \geq \frac{1}{2}$ and $\mathbb{P}[Y \geq \text{median}[Y]] \geq \frac{1}{2}$.

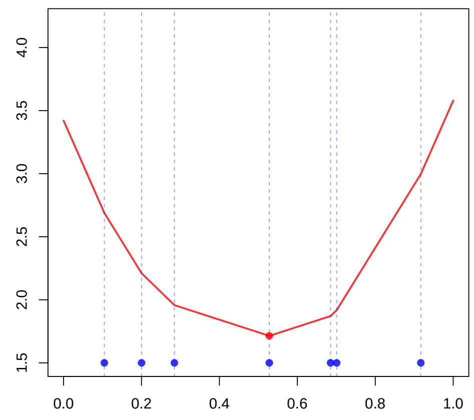
$\underset{m(\cdot):\mathbb{R}^k\rightarrow\mathbb{R}}{\text{argmin}} \left\{ \sum_{i=1}^{n} \frac{1}{n} \underbrace{|y_i - m(\boldsymbol{x}_i)|}_{\varepsilon_i} \right\}$ is the empirical version of $\text{median}[Y|\boldsymbol{X} = \boldsymbol{x}]$.

See Boscovich (1757) De Litteraria expeditione per pontificiam ditionem ad dimetiendos duos meridiani and Laplace (1793) Sur quelques points du système du monde.

Median Regression, ℓ_1 norm and Median

Sketch of proof: (1) Let $h(x)=\displaystyle\sum_{i=1}^{d}|x-y_i|$

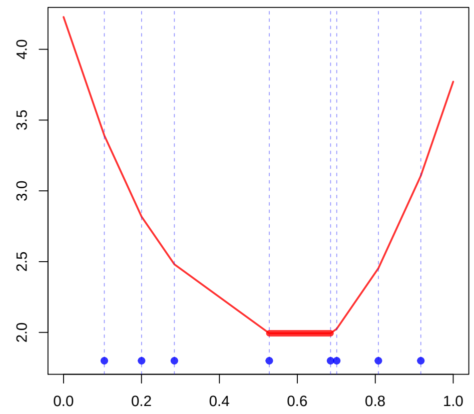
(2) If F is absolutely continuous, $dF(x)=f(x)dx$, and the median m is solution of $\displaystyle\int_{-\infty}^{m} f(x)dx=\frac{1}{2}$.



Set $h(y)=\displaystyle\int_{-\infty}^{+\infty}|x-y|f(x)dx$

$$=\int_{-\infty}^{y}(-x+y)f(x)dx+\int_{y}^{+\infty}(x-y)f(x)dx$$

Then $h'(y)=\displaystyle\int_{-\infty}^{y}f(x)dx-\int_{y}^{+\infty}f(x)dx$, and FOC yields



$$\int_{-\infty}^{y}f(x)dx=\int_{y}^{+\infty}f(x)dx=1-\int_{-\infty}^{y}f(x)dx=\frac{1}{2}$$

OLS vs. Median Regression (Least Absolute Deviation)

Consider some linear model, $y_i = \beta_0 + \boldsymbol{x}_i^\mathsf{T}\boldsymbol{\beta} + \varepsilon_i$,and define

$$(\widehat{\beta}_0^{\text{ols}}, \widehat{\boldsymbol{\beta}}^{\text{ols}}) = \text{argmin}\left\{\sum_{i=1}^n \left(y_i - \beta_0 - \boldsymbol{x}_i^\mathsf{T}\boldsymbol{\beta}\right)^2\right\}$$

$$(\widehat{\beta}_0^{\text{lad}}, \widehat{\boldsymbol{\beta}}^{\text{lad}}) = \text{argmin}\left\{\sum_{i=1}^n \left|y_i - \beta_0 - \boldsymbol{x}_i^\mathsf{T}\boldsymbol{\beta}\right|\right\}$$

Assume that $\varepsilon|\boldsymbol{X}$ has a symmetric distribution, $\mathbb{E}[\varepsilon|\boldsymbol{X}] = \text{median}[\varepsilon|\boldsymbol{X}] = 0$, then $(\widehat{\beta}_0^{\text{ols}}, \widehat{\boldsymbol{\beta}}^{\text{ols}})$ and $(\widehat{\beta}_0^{\text{lad}}, \widehat{\boldsymbol{\beta}}^{\text{lad}})$ are consistent estimators of $(\beta_0, \boldsymbol{\beta})$.

Assume that $\varepsilon|\boldsymbol{X}$ does not have a symmetric distribution, but $\mathbb{E}[\varepsilon|\boldsymbol{X}] = 0$, then $\widehat{\boldsymbol{\beta}}^{\text{ols}}$ and $\widehat{\boldsymbol{\beta}}^{\text{lad}}$ are consistent estimators of the slopes $\boldsymbol{\beta}$.

If $\text{median}[\varepsilon|\boldsymbol{X}] = \gamma$, then $\widehat{\beta}_0^{\text{lad}}$ converges to $\beta_0 + \gamma$.

OLS vs. Median Regression

Median regression is stable by monotonic transformation. If

$$\log[y_i] = \beta_0 + \boldsymbol{x}_i^\top \boldsymbol{\beta} + \varepsilon_i \text{ with median}[\varepsilon|\boldsymbol{X}] = 0,$$

then

$$\text{median}[Y|\boldsymbol{X} = \boldsymbol{x}] = \exp\left(\text{median}[\log(Y)|\boldsymbol{X} = \boldsymbol{x}]\right) = \exp\left(\beta_0 + \boldsymbol{x}_i^\top \boldsymbol{\beta}\right)$$

while

$$\mathbb{E}[Y|\boldsymbol{X} = \boldsymbol{x}] \neq \exp\left(\mathbb{E}[\log(Y)|\boldsymbol{X} = \boldsymbol{x}]\right) \;\; (= \exp\left(\mathbb{E}[\log(Y)|\boldsymbol{X} = \boldsymbol{x}]\right) \cdot [\exp(\varepsilon)|\boldsymbol{X} = \boldsymbol{x}]$$

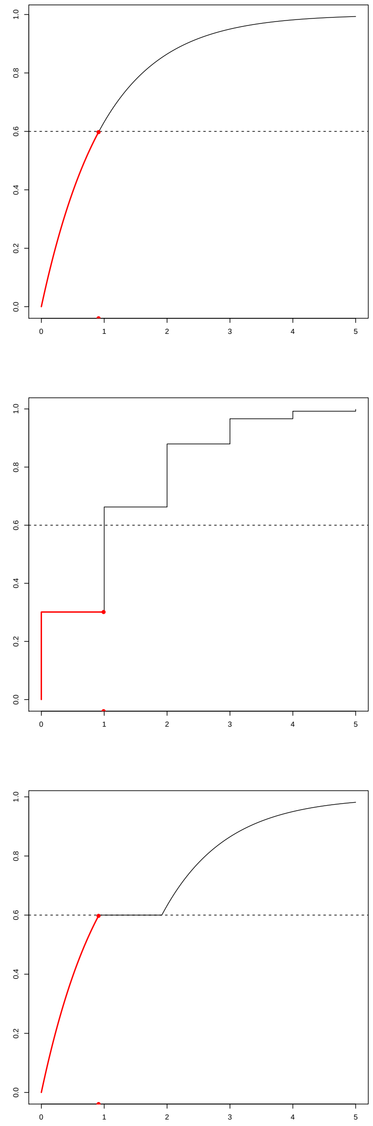
```
> ols <- lm(y~x, data=df)
> library(quantreg)
> lad <- rq(y~x, data=df, tau=.5)
```

Notations

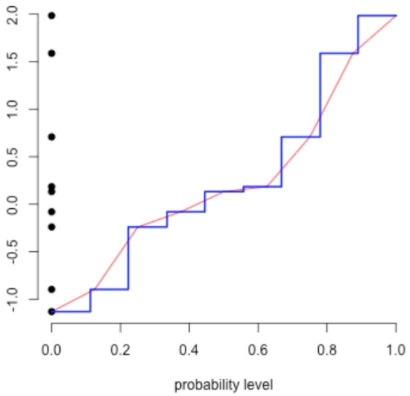
Cumulative distribution function $F_Y(y) = \mathbb{P}[Y \leq y]$.
Quantile function $Q_X(u) = \inf\{y \in \mathbb{R} : F_Y(y) \geq u\}$,
also noted $Q_X(u) = F_X^{-1} u$.

One can consider $Q_X(u) = \sup\{y \in \mathbb{R} : F_Y(y) < u\}$

For any increasing transformation t, $Q_{t(Y)}(\tau) = t(Q_Y(\tau))$
$F(y|\boldsymbol{x}) = \mathbb{P}[Y \leq y|\boldsymbol{X} = \boldsymbol{x}]$
$Q_{Y|\boldsymbol{x}}(u) = F^{-1}(u|\boldsymbol{x})$



Empirical Quantile




```
> set.seed(2); X=rnorm(9)
> Q=quantile(X,u,type=1)
```

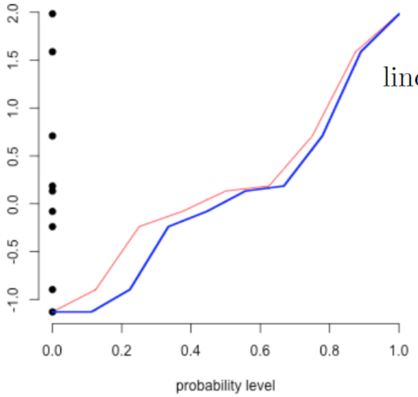
$\alpha X_{[np]:n} + (1-\alpha) X_{[np]+1:n}$

where

$X_{1:n} \leq X_{2:n} \leq \cdots \leq X_{n:n}$

Inverse of empirical distribution function

Hyndman, R. J. & Fan, Y. (1996) Sample quantiles in statistical packages *American Statistician* **50** 361–365




```
> set.seed(2); X=rnorm(9)
> Q=quantile(X,u,type=4)
```

linear interpolation between points

$\{(p(k), X_{k:n}); k = 1, \cdots, n\}$

$p(k) = \frac{k}{n}$

Linear interpolation of the empirical cdf

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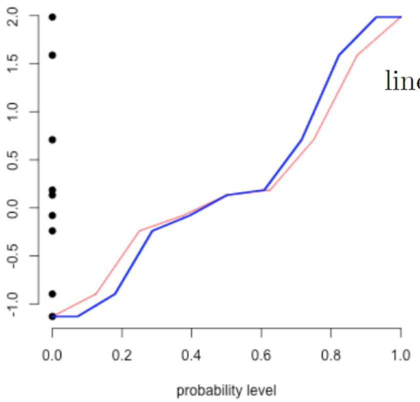


```
> set.seed(2); X=rnorm(9)
> Q=quantile(X,u,type=6)
```

linear interpolation between points

$\{(p(k), X_{k:n}); k = 1, \cdots, n\}$

$p(k) = \frac{k}{n+1}$

Minitab SPSS

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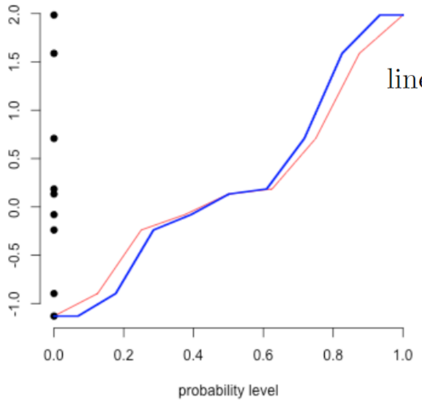


```
> set.seed(2); X=rnorm(9)
> Q=quantile(X,u,type=9)
```

linear interpolation between points

$\{(p(k), X_{k:n}); k = 1, \cdots, n\}$

$p(k) = \frac{k-3/8}{n+1/4}$

Approximately median-unbiased (when Gaussian)

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Quantile regression ?

In OLS regression, we try to evaluate $\mathbb{E}[Y|\boldsymbol{X}=\boldsymbol{x}]=\displaystyle\int_{\mathbb{R}} ydF_{Y|\boldsymbol{X}=\boldsymbol{x}}(y)$

In quantile regression, we try to evaluate

$$Q_u(Y|\boldsymbol{X}=\boldsymbol{x})=\inf\left\{y:F_{Y|\boldsymbol{X}=\boldsymbol{x}}(y)\geq u\right\}$$

as introduced in Newey & Powell (1987) Asymmetric Least Squares Estimation and Testing.

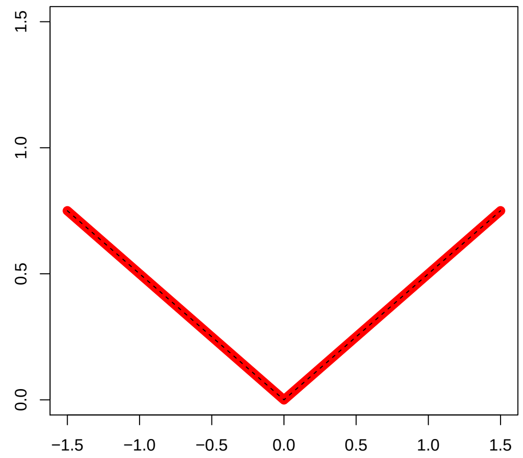
Li & Racine (2007) Nonparametric Econometrics: Theory and Practice suggested

$$\widehat{Q}_u(Y|\boldsymbol{X}=\boldsymbol{x})=\inf\left\{y:\widehat{F}_{Y|\boldsymbol{X}=\boldsymbol{x}}(y)\geq u\right\}$$

where $\widehat{F}_{Y|\boldsymbol{X}=\boldsymbol{x}}(y)$ can be some kernel-based estimator.

Quantiles and Expectiles

Consider the following risk functions

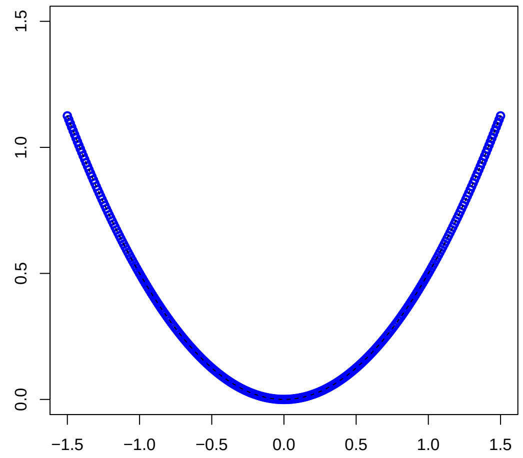


$$\mathcal{R}^{\mathsf{q}}_{\tau}(u) = u \cdot \big(\tau - \mathbf{1}(u<0)\big),\ \ \tau \in [0,1]$$

with $\mathcal{R}^{\mathsf{q}}_{1/2}(u) \propto |u| = \|u\|_{\ell_1}$, and

$$\mathcal{R}^{\mathsf{e}}_{\tau}(u) = u^2 \cdot \big(\tau - \mathbf{1}(u<0)\big),\ \ \tau \in [0,1]$$

with $\mathcal{R}^{\mathsf{e}}_{1/2}(u) \propto u^2 = \|u\|^2_{\ell_2}$.



$$Q_Y(\tau) = \underset{m}{\text{argmin}}\Big\{\mathbb{E}\Big(\mathcal{R}^{\mathsf{q}}_{\tau}(Y-m)\Big)\Big\}$$

which is the median when $\tau = 1/2$,

$$E_Y(\tau) = \underset{m}{\text{argmin}}\Big\{\mathbb{E}\Big(\mathcal{R}^{\mathsf{e}}_{\tau}(X-m)\Big)\Big\}$$

which is the expected value when $\tau = 1/2$.

Quantiles and Expectiles

One can also write

$$\text{quantile: argmin}\left\{\sum_{i=1}^{n}\omega_\tau^{\mathsf{q}}(\varepsilon_i)\big|\underbrace{y_i-q_i}_{\varepsilon_i}\big|\right\}\text{ where }\omega_\tau^{\mathsf{q}}(\epsilon)=\begin{cases}1-\tau\text{ if }\epsilon\leq 0\\ \tau\text{ if }\epsilon>0\end{cases}$$

$$\text{expectile: argmin}\left\{\sum_{i=1}^{n}\omega_\tau^{\mathsf{e}}(\varepsilon_i)\big(\underbrace{y_i-q_i}_{\varepsilon_i}\big)^2\right\}\text{ where }\omega_\tau^{\mathsf{e}}(\epsilon)=\begin{cases}1-\tau\text{ if }\epsilon\leq 0\\ \tau\text{ if }\epsilon>0\end{cases}$$

Expectiles are unique, not quantiles...

Quantiles satisfy $\mathbb{E}[\text{sign}(Y-Q_Y(\tau))]=0$

Expectiles satisfy $\tau\mathbb{E}\big[(Y-e_Y(\tau))_+\big]=(1-\tau)\mathbb{E}\big[(Y-e_Y(\tau))_-\big]$

(those are actually the first order conditions of the optimization problem).

Quantiles and M-Estimators

There are connections with M-estimators, as introduced in Serfling (1980) Approximation Theorems of Mathematical Statistics, chapter 7.

For any function $h(\cdot,\cdot)$, the M-functional is the solution β of

$$\int h(y,\beta)dF_Y(y)=0$$

, and the M-estimator is the solution of

$$\int h(y,\beta)d\widehat{F}_n(y)=\frac{1}{n}\sum_{i=1}^n h(y_i,\beta)=0$$

Hence, if $h(y,\beta)=y-\beta$, $\beta=\mathbb{E}[Y]$ and $\widehat{\beta}=\overline{y}$.

And if $h(y,\beta)=\mathbf{1}(y<\beta)-\tau$, with $\tau\in(0,1)$, then $\beta=F_Y^{-1}(\tau)$.

Quantiles, Maximal Correlation and Hardy-Littlewood-Polya

If $x_1 \leq \cdots \leq x_n$ and $y_1 \leq \cdots \leq y_n$, then $\sum_{i=1}^{n} x_i y_i \geq \sum_{i=1}^{n} x_i y_{\sigma(i)}$, $\forall \sigma \in \mathcal{S}_n$, and $\boldsymbol{x}$ and $\boldsymbol{y}$ are said to be comonotonic.

The continuous version is that X and Y are comonotonic if

$$\mathbb{E}[XY] \geq \mathbb{E}[X\tilde{Y}] \text{ where } \tilde{Y} \overset{\mathcal{L}}{=} Y,$$

One can prove that

$$Y = Q_Y(F_X(X)) = \underset{\tilde{Y}\sim F_Y}{\text{argmax}}\{\mathbb{E}[X\tilde{Y}]\}$$

Expectiles as Quantiles

For every $Y \in L^1$, $\tau \mapsto e_Y(\tau)$ is continuous, and striclty increasing

if Y is absolutely continuous, $\dfrac{\partial e_Y(\tau)}{\partial \tau} = \dfrac{\mathbb{E}[|X - e_Y(\tau)|]}{(1-\tau)F_Y(e_Y(\tau)) + \tau(1 - F_Y(e_Y(\tau)))}$

if $X \leq Y$, then $e_X(\tau) \leq e_Y(\tau)$ $\forall \tau \in (0,1)$

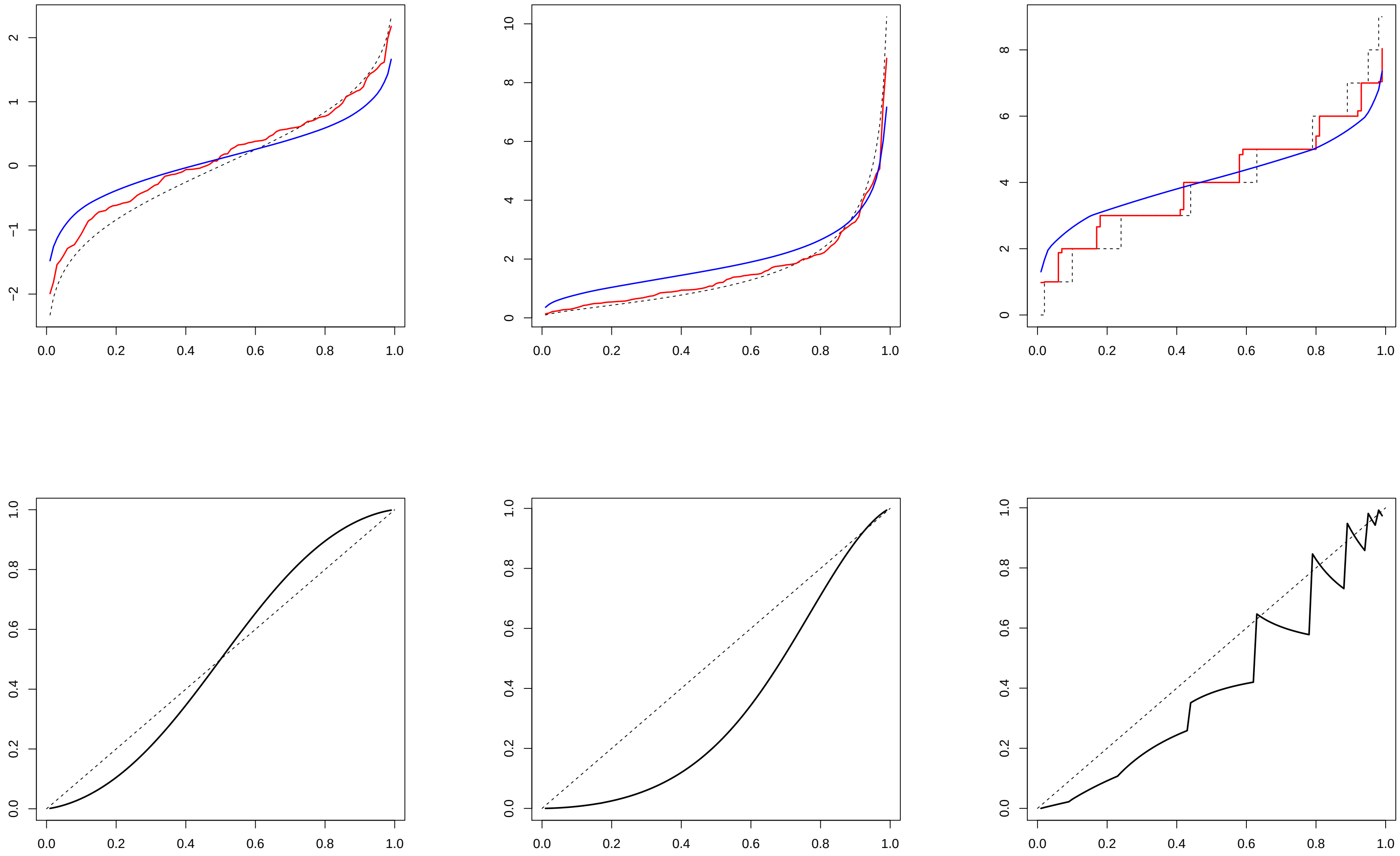
"Expectiles have properties that are similar to quantiles" Newey & Powell (1987) Asymmetric Least Squares Estimation and Testing. The reason is that expectiles of a distribution F are quantiles a distribution G which is related to F, see Jones (1994) Expectiles and M-quantiles are quantiles: let

$$G(t) = \frac{P(t) - tF(t)}{2[P(t) - tF(t)] + t - \mu} \text{ where } P(s) = \int_{-\infty}^{s} y dF(y).$$

The expectiles of F are the quantiles of G.

```
> x <- rnorm(99)
> library(expectreg)
> e <- expectile(x, probs = seq(0, 1, 0.1))
```

Expectiles as Quantiles



Elicitable Measures

"elicitable" means "being a minimizer of a suitable expected score"

T is an elicatable function if there exits a scoring function $S : \mathbb{R}\times\mathbb{R}\to[0,\infty)$ such that

$$T(Y)=\underset{x\in\mathbb{R}}{\text{argmin}}\left\{\int_{\mathbb{R}} S(x,y)dF(y)\right\}=\underset{x\in\mathbb{R}}{\text{argmin}}\left\{\mathbb{E}\big[S(x,Y)\big]\text{ where }Y\sim F.\right\}$$

see Gneiting (2011) Making and evaluating point forecasts.

Example: mean, $T(Y)=\mathbb{E}[Y]$ is elicited by $S(x,y)=\|x-y\|_{\ell_2}^2$

Example: median, $T(Y)=\text{median}[Y]$ is elicited by $S(x,y)=\|x-y\|_{\ell_1}$

Example: quantile, $T(Y)=Q_Y(\tau)$ is elicited by $S(x,y)=\tau(y-x)_+ + (1-\tau)(y-x)_-$

Example: expectile, $T(Y)=E_Y(\tau)$ is elicited by $S(x,y)=\tau(y-x)_+^2 + (1-\tau)(y-x)_-^2$

Elicitable Measures

Remark: all functionals are not necessarily elicitable, see Osband (1985)

Providing incentives for better cost forecasting

The variance is not elicitable

The elicitability property implies a property which is known as convexity of the level sets with respect to mixtures (also called Betweenness property) : if two lotteries F, and G are equivalent, then any mixture of the two lotteries is also equivalent with F and G.

Empirical Quantiles

Consider some i.id. sample $\{y_1, \cdots, y_n\}$ with distribution F. Set

$$Q_\tau = \text{argmin}\left\{\mathbb{E}\left[\mathcal{R}_\tau^{\mathfrak{q}}(Y-q)\right]\right\} \text{ where } Y \sim F \text{ and } \widehat{Q}_\tau \in \text{argmin}\left\{\sum_{i=1}^n \mathcal{R}_\tau^{\mathfrak{q}}(y_i - q)\right\}$$

Then as $n \to \infty$

$$\sqrt{n}(\widehat{Q}_\tau - Q_\tau) \xrightarrow{\mathcal{L}} \mathcal{N}\left(0, \frac{\tau(1-\tau)}{f^2(Q_\tau)}\right)$$

Sketch of the proof: $y_i = Q_\tau + \varepsilon_i$, set $h_n(q) = \dfrac{1}{n}\displaystyle\sum_{i=1}^n \big(\mathbf{1}(y_i < q) - \tau\big)$, which is a non-decreasing function, with

$$\mathbb{E}\left[Q_\tau + \frac{u}{\sqrt{n}}\right] = F_Y\left(Q_\tau + \frac{u}{\sqrt{n}}\right) \sim f_Y(Q_\tau)\frac{u}{\sqrt{n}}$$

$$\text{Var}\left[Q_\tau + \frac{u}{\sqrt{n}}\right] \sim \frac{F_Y(Q_\tau)[1 - F_Y(Q_\tau)]}{n} = \frac{\tau(1-\tau)}{n}.$$

Empirical Expectiles

Consider some i.id. sample $\{y_1, \cdots, y_n\}$ with distribution F. Set

$$\mu_\tau = \text{argmin}\left\{\mathbb{E}\big[\mathcal{R}^{\mathsf{e}}_\tau(Y-m)\big]\right\} \text{ where } Y \sim F \text{ and } \widehat{\mu}_\tau = \text{argmin}\left\{\sum_{i=1}^n \mathcal{R}^{\mathsf{e}}_\tau(y_i-m)\right\}$$

Then as $n \to \infty$

$$\sqrt{n}\big(\widehat{\mu}_\tau - \mu_\tau\big) \xrightarrow{\mathcal{L}} \mathcal{N}\left(0, s^2\right)$$

for some s^2, if $\text{Var}[Y] < \infty$. Define the identification function

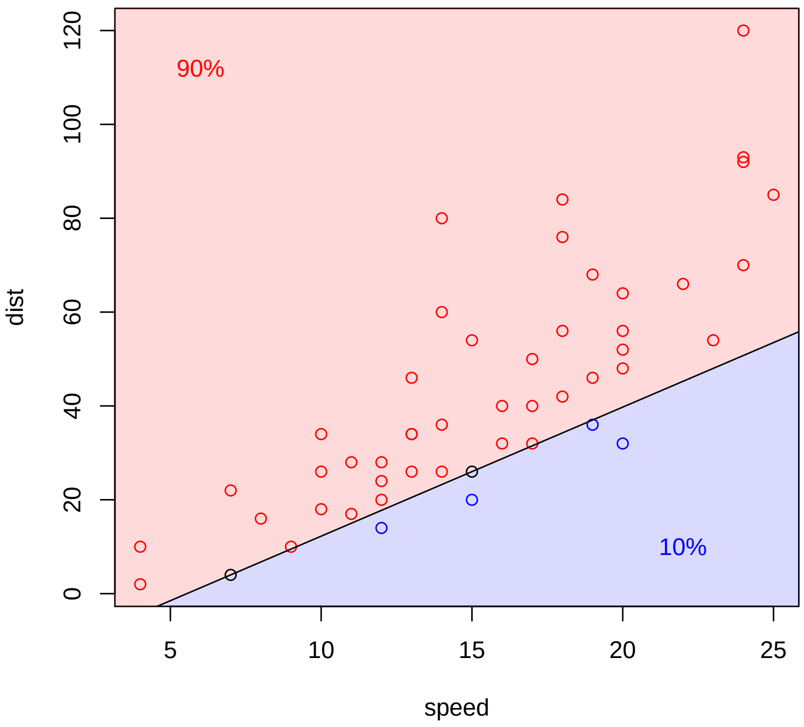
$$\mathcal{I}_\tau(x,y) = \tau(y-x)_+ + (1-\tau)(y-x)_- \qquad \text{(elicitable score for quantiles)}$$

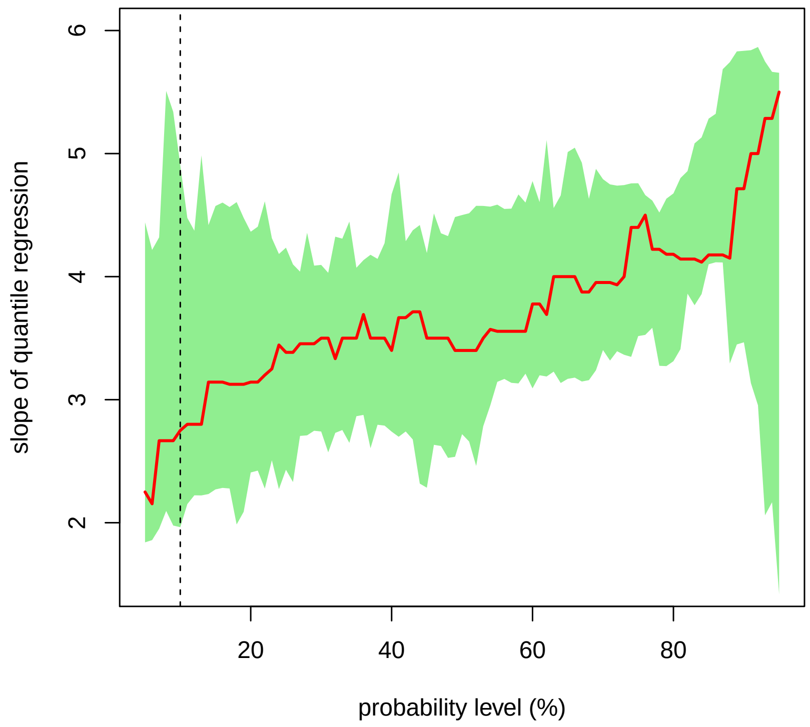
so that μ_τ is solution of $\mathbb{E}\big[\mathcal{I}(\mu_\tau, Y)\big] = 0$. Then

$$s^2 = \frac{\mathbb{E}[\mathcal{I}(\mu_\tau, Y)^2]}{(\tau[1-F(\mu_\tau)] + [1-\tau]F(\mu_\tau))^2}.$$

Quantile Regression

We want to solve, here, $\min\left\{\sum_{i=1}^{n}\mathcal{R}_{\tau}^{\mathsf{q}}(y_i-\boldsymbol{x}_i^{\mathsf{T}}\beta)\right\}$





$$y_i=\boldsymbol{x}_i^{\mathsf{T}}\boldsymbol{\beta}+\varepsilon_i \text{ so that } \widehat{Q}_{y|\boldsymbol{x}}(\tau)=\boldsymbol{x}^{\mathsf{T}}\widehat{\boldsymbol{\beta}}+F_{\varepsilon}^{-1}(\tau)$$

Geometric Properties of the Quantile Regression

Observe that the median regression will always have two supporting observations.

Start with some regression line, $y_i = \beta_0 + \beta_1 x_i$

Consider small translations $y_i = (\beta_0 \pm \epsilon) + \beta_1 x_i$

We minimize $\displaystyle\sum_{i=1}^{n} \big| y_i - (\beta_0 + \beta_1 x_i) \big|$

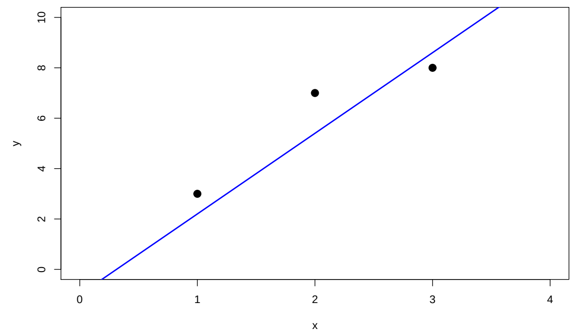
From line blue, a shift up decrease the sum by ϵ

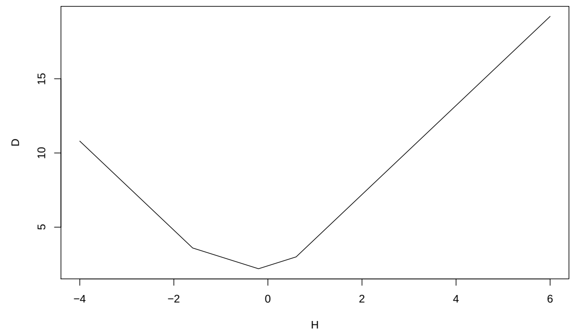
until we meet point on the left

an additional shift up will increase the sum

We will necessarily pass through one point

(observe that the sum is piecwise linear in ϵ)





Geometric Properties of the Quantile Regression

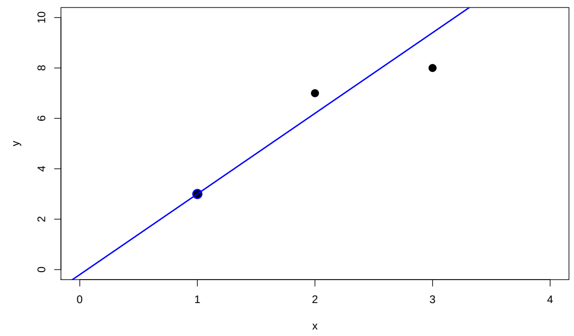
Consider now rotations of the line around the support point

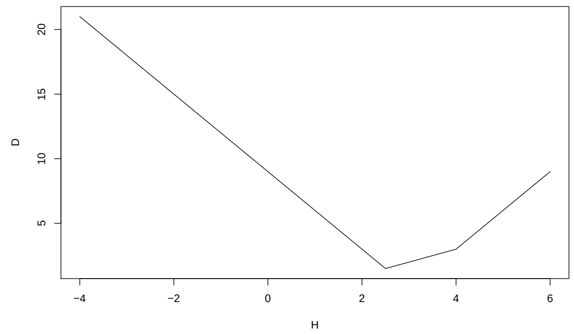
If we rotate up, we increase the sum of absolute difference (large impact on the point on the right)

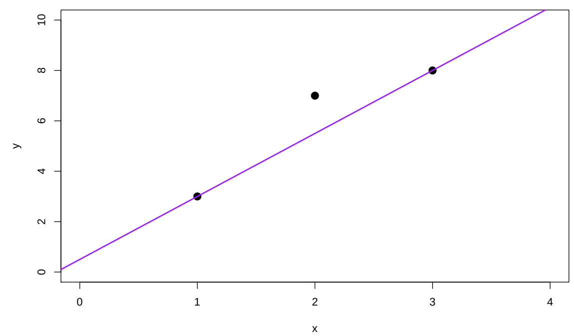
If we rotate down, we decrease the sum, until we reach the point on the right

Thus, the median regression will always have two supportting observations.

```
> library(quantreg)
> fit <- rq(dist~speed, data=cars, tau=.5)
> which(predict(fit)==cars$dist)
 1 21 46
 1 21 46
```







Distributional Aspects

OLS are equivalent to MLE when $Y - m(\boldsymbol{x}) \sim \mathcal{N}(0, \sigma^2)$, with density

$$g(\epsilon) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{\epsilon^2}{2\sigma^2}\right)$$

Quantile regression is equivalent to Maximum Likelihood Estimation when $Y - m(\boldsymbol{x})$ has an asymmetric Laplace distribution

$$g(\epsilon) = \frac{\sqrt{2}}{\sigma}\frac{\kappa}{1+\kappa^2} \exp\left(-\frac{\sqrt{2}\kappa^{\mathbf{1}(\epsilon>0)}}{\sigma\kappa^{\mathbf{1}(\epsilon<0)}}|\epsilon|\right)$$

Quantile Regression and Iterative Least Squares

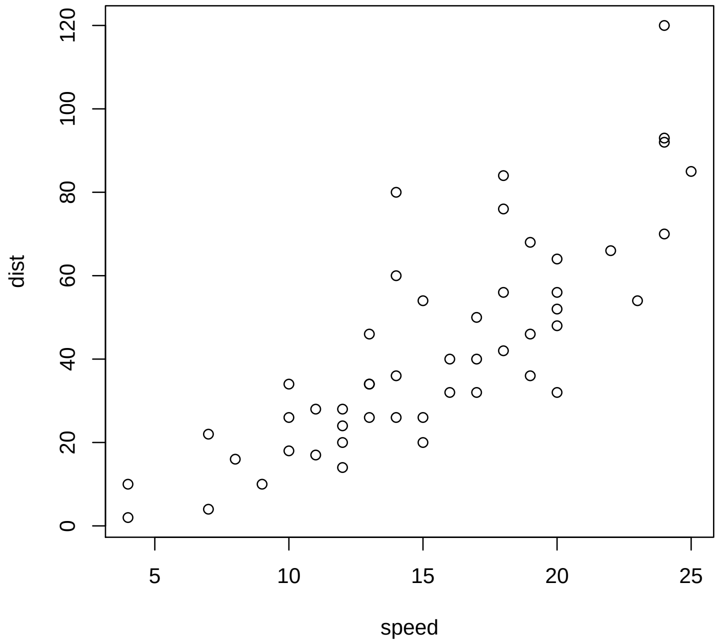
start with some $\boldsymbol{\beta}^{(0)}$ e.g. $\boldsymbol{\beta}^{\text{ols}}$

at stage k :

let $\varepsilon_i^{(k)} = y_i - \boldsymbol{x}_i^\top \boldsymbol{\beta}^{(k-1)}$

define weights $\omega_i^{(k)} = \mathcal{R}'_\tau(\varepsilon_i^{(k)})$

compute weighted least square to estimate $\boldsymbol{\beta}^{(k)}$



One can also consider a smooth approximation of $\mathcal{R}^{\text{q}}_\tau(\cdot)$, and then use Newton-Raphson.

Optimization Algorithm

Primal problem is

$$\min_{\boldsymbol{\beta},\boldsymbol{u},\boldsymbol{v}} \left\{\tau\mathbf{1}^\top\boldsymbol{u} + (1-\tau)\mathbf{1}^\top\boldsymbol{v}\right\} \text{ s.t. } \boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{u} - \boldsymbol{v}, \text{ with } \boldsymbol{u},\boldsymbol{v} \in \mathbb{R}_+^n$$

and the dual version is

$$\max_{\boldsymbol{d}} \left\{\boldsymbol{y}^\top\boldsymbol{d}\right\} \text{ s.t. } \boldsymbol{X}^\top\boldsymbol{d} = (1-\tau)\boldsymbol{X}^\top\mathbf{1} \text{ with } \boldsymbol{d} \in [0,1]^n$$

Koenker & D'Orey (1994) A Remark on Algorithm AS 229: Computing Dual Regression Quantiles and Regression Rank Scores suggest to use the simplex method (default method in R)

Portnoy & Koenker (1997) The Gaussian hare and the Laplacian tortoise suggest to use the interior point method

Simplex Method

The beer problem: we want to produce beer, either blonde, or brown

$$\begin{cases} \text{barley}: & 14\text{kg} \\ \text{corn}: & 2\text{kg} \\ \text{price}: & 30€ \end{cases}$$

$$\begin{cases} \text{barley}: & 10\text{kg} \\ \text{corn}: & 5\text{kg} \\ \text{price}: & 40€ \end{cases}$$

$$\begin{cases} \text{barley}: & 280\text{kg} \\ \text{corn}: & 100\text{kg} \end{cases}$$

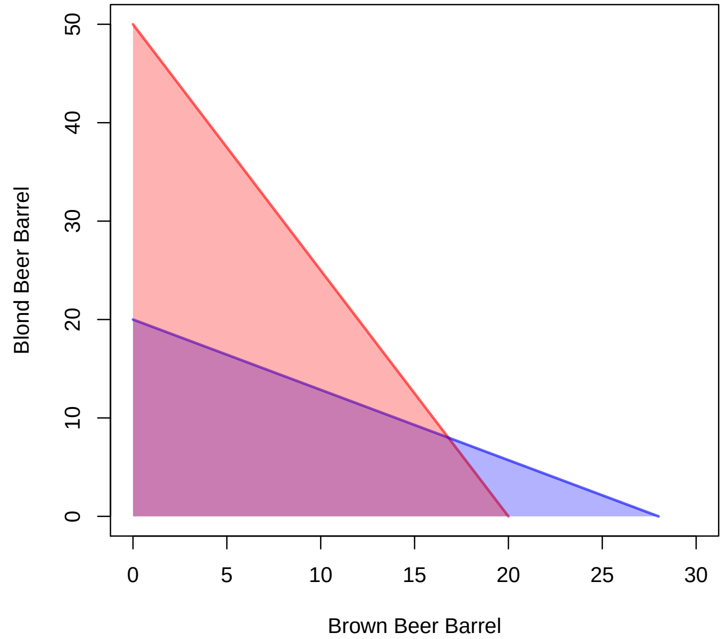
Admissible sets :

$$10q_{\text{brown}} + 14q_{\text{blond}} \leq 280 \qquad (10x_1 + 14x_2 \leq 280)$$

$$2q_{\text{brown}} + 5q_{\text{blond}} \leq 100 \qquad (2x_1 + 5x_2 \leq 100)$$

What should we produce to maximize the profit ?

$$\max\left\{40q_{\text{brown}} + 30q_{\text{blond}}\right\} \quad \left(\max\left\{40x_1 + 30x_2\right\}\right)$$



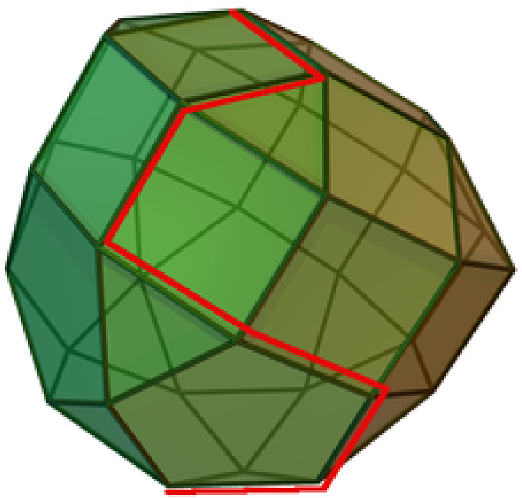
Simplex Method

First step: enlarge the space, $10x_1 + 14x_2 \leq 280$ becomes $10x_1 + 14x_2 - u_1 = 280$ (so called slack variables)

$$\max \left\{40x_1 + 30x_2\right\}$$
$$\text{s.t. } 10x_1 + 14x_2 + u_1 = 280$$
$$2x_1 + 5x_2 + u_2 = 100$$
$$x_1, x_2, u_1, u_2 \geq 0$$

summarized in the following table, see wikibook

	x_1	x_2	u_1	u_2	
(1)	10	14	1	0	280
(2)	2	5	0	1	100
max	40	30	0	0	



Simplex Method

Consider a linear programming problem written in a standard form.

$$\min\left\{\boldsymbol{c}^\top\boldsymbol{x}\right\} \tag{1}$$

subject to

$$A\boldsymbol{x}=\boldsymbol{b}\,, \tag{2}$$

$$\boldsymbol{x}\geq\boldsymbol{0}\,. \tag{3}$$

Where $\boldsymbol{x}\in\mathbb{R}^n$, A is a $m\times n$ matrix, $\boldsymbol{b}\in\mathbb{R}^m$ and $\boldsymbol{c}\in\mathbb{R}^n$.

Assume that $\text{rank}(A)=m$ (rows of A are linearly independent)

Introduce slack variables to turn inequality constraints into equality constraints with positive unknowns : any inequality $a_1\,x_1+\cdots+a_n\,x_n\leq c$ can be replaced by $a_1\,x_1+\cdots+a_n\,x_n+u=c$ with $u\geq 0$.

Replace variables which are not sign-constrained by differences : any real number x can be written as the difference of positive numbers $x=u-v$ with $u,v\geq 0$.

Simplex Method

Example :

$$\text{maximize } \{x_1 + 2\,x_2 + 3\,x_3\}$$

subject to

$$x_1 + x_2 - x_3 = 1\,,$$
$$-2\,x_1 + x_2 + 2\,x_3 \geq -5\,,$$
$$x_1 - x_2 \leq 4\,,$$
$$x_2 + x_3 \leq 5\,,$$
$$x_1 \geq 0\,,$$
$$x_2 \geq 0\,.$$

$$\text{minimize } \{-x_1 - 2\,x_2 - 3\,u + 3\,v\}$$

subject to

$$x_1 + x_2 - u + v = 1\,,$$
$$2\,x_1 - x_2 - 2\,u + 2\,v + s_1 = 5\,,$$
$$x_1 - x_2 + s_2 = 4\,,$$
$$x_2 + u - v + s_3 = 5\,,$$
$$x_1, x_2, u, v, s_1, s_2, s_3 \geq 0\,.$$

Simplex Method

Write the coefficients of the problem into a tableau

x_1	x_2	u	v	s_1	s_2	s_3	
1	1	−1	1	0	0	0	1
2	−1	−2	2	1	0	0	5
1	−1	0	0	0	1	0	4
0	1	1	−1	0	0	1	5
−1	−2	−3	3	0	0	0	0

with constraints on top and coefficients of the objective function are written in a separate bottom row (with a 0 in the right hand column)

we need to choose an initial set of basic variables which corresponds to a point in the feasible region of the linear program-ming problem.

E.g. x_1 and s_1, s_2, s_3

Simplex Method

Use Gaussian elimination to (1) reduce the selected columns to a permutation of the identity matrix (2) eliminate the coefficients of the objective function

x_1	x_2	u	v	s_1	s_2	s_3	
1	1	−1	1	0	0	0	1
0	−3	0	0	1	0	0	3
0	−2	1	−1	0	1	0	3
0	1	1	−1	0	0	1	5
0	−1	−4	4	0	0	0	1

the objective function row has at least one negative entry

Simplex Method

x_1	x_2	u	v	s_1	s_2	s_3	
1	1	−1	1	0	0	0	1
0	−3	0	0	1	0	0	3
0	*−2*	*1*	*−1*	*0*	*1*	*0*	*3*
0	1	1	−1	0	0	1	5
0	−1	−4	4	0	0	0	1

This new basic variable is called the entering variable. Correspondingly, one formerly basic variable has then to become nonbasic, this variable is called the leaving variable.

Simplex Method

The entering variable shall correspond to the column which has the most negative entry in the cost function row

the most negative cost function coefficient in column 3, thus u shall be the entering variable

The leaving variable shall be chosen as follows : Compute for each row the ratio of its right hand coefficient to the corresponding coefficient in the entering variable column. Select the row with the smallest finite positive ratio. The leaving variable is then determined by the column which currently owns the pivot in this row.

The smallest positive ratio of right hand column to entering variable column is in row 3, as $\dfrac{3}{1} < \dfrac{5}{1}$. The pivot in this row points to s_2 as the leaving variable.

Simplex Method

x_1	x_2	u	v	s_1	s_2	s_3	
1	1	−1	1	0	0	0	1
0	−3	0	0	1	0	0	3
0	−2	1	−1	0	1	0	3
0	1	1	−1	0	0	1	5
0	−1	−4	4	0	0	0	1

Simplex Method

After going through the Gaussian elimination once more, we arrive at

x_1	x_2	u	v	s_1	s_2	s_3	
1	−1	0	0	0	1	0	4
0	−3	0	0	1	0	0	3
0	−2	1	−1	0	1	0	3
0	*3*	*0*	*0*	*0*	*−1*	*1*	*2*
0	−9	0	0	0	4	0	13

Here x_2 will enter and s_3 will leave

Simplex Method

After Gaussian elimination, we find

x_1	x_2	u	v	s_1	s_2	s_3	
1	0	0	0	0	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{14}{3}$
0	0	0	0	1	-1	1	5
0	0	1	-1	0	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{13}{3}$
0	1	0	0	0	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
0	0	0	0	0	1	3	19

There is no more negative entry in the last row, the cost cannot be lowered

Simplex Method

The algorithm is over, we now have to read off the solution (in the last column)

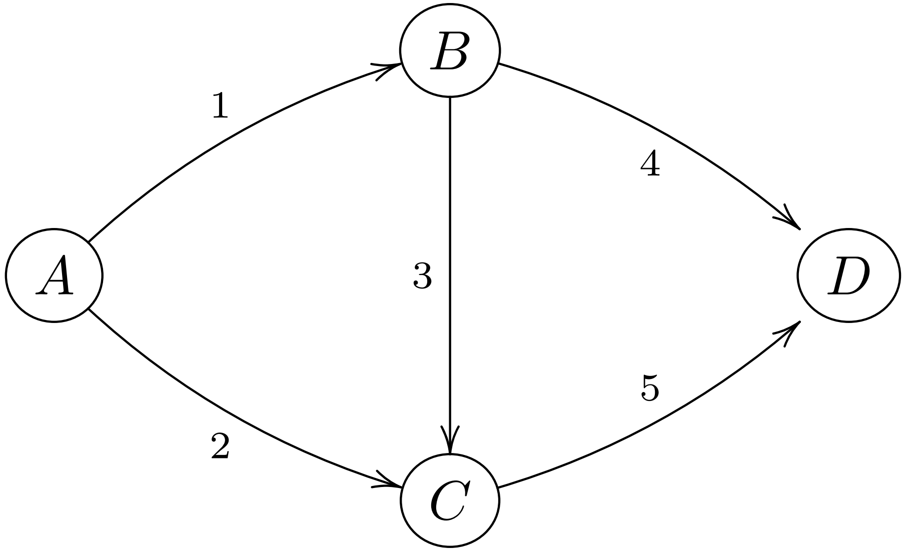
$$x_1 = \frac{14}{3},\ x_2 = \frac{2}{3},\ x_3 = u = \frac{13}{3},\ s_1 = 5,\ v = s_2 = s_3 = 0$$

and the minimal value is -19

Duality

Consider a transportation problem.

Some good is available at location A (at no cost) and may be transported to locations B, C, and D according to the following directed graph



On each of the edges, the unit cost of transportation is c_j for $j = 1, \ldots, 5$.

At each of the vertices, b_i units of the good are sold, where $i = B, C, D$.

How can the transport be done most efficiently?

Duality

Let x_j denotes the amount of good transported through edge j

We have to solve

$$\text{minimize } \{c_1\,x_1 + \cdots + c_5\,x_5\} \tag{4}$$

subject to

$$x_1 - x_3 - x_4 = b_B\;, \tag{5}$$

$$x_2 + x_3 - x_5 = b_C\;, \tag{6}$$

$$x_4 + x_5 = b_D\;. \tag{7}$$

Constraints mean here that nothing gets lost at nodes B, C, and D, except what is sold.

Duality

Alternatively, instead of looking at minimizing the cost of transportation, we seek to maximize the income from selling the good.

$$\text{maximize } \{y_B\, b_B + y_C\, b_C + y_D\, b_D\} \tag{8}$$

subject to

$$y_B - y_A \leq c_1\,, \tag{9}$$

$$y_C - y_A \leq c_2\,, \tag{10}$$

$$y_C - y_B \leq c_3\,, \tag{11}$$

$$y_D - y_B \leq c_4\,, \tag{12}$$

$$y_D - y_C \leq c_5\,. \tag{13}$$

Constraints mean here that the price difference cannot not exceed the cost of transportation.

Duality

Set

$$\boldsymbol{x} = \begin{pmatrix} x_1 \\ \vdots \\ x_5 \end{pmatrix}, \boldsymbol{y} = \begin{pmatrix} y_B \\ y_C \\ y_D \end{pmatrix}, \text{and } A = \begin{pmatrix} 1 & 0 & -1 & -1 & 0 \\ 0 & 1 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix},$$

The first problem - primal problem - is here

$$\text{minimize } \{\boldsymbol{c}^\top \boldsymbol{x}\}$$
$$\text{subject to } A\boldsymbol{x} = \boldsymbol{b}, \boldsymbol{x} \geq \boldsymbol{0}.$$

and the second problem - dual problem - is here

$$\text{maximize } \{\boldsymbol{y}^\top \boldsymbol{b}\}$$
$$\text{subject to } \boldsymbol{y}^\top A \leq \boldsymbol{c}^\top.$$

Duality

The minimal cost and the maximal income coincide, i.e., the two problems are equivalent. More precisely, there is a strong duality theorem

Theorem The primal problem has a nondegenerate solution $\boldsymbol{x}$ if and only if the dual problem has a nondegenerate solution $\boldsymbol{y}$. And in this case $\boldsymbol{y}^\top\boldsymbol{b} = \boldsymbol{c}^\top\boldsymbol{x}$.

See Dantzig & Thapa (1997) Linear Programming

Interior Point Method

See Vanderbei *et al.* (1986) A modification of Karmarkar's linear programming algorithm for a presentation of the algorithm, Potra & Wright (2000) Interior-point methods for a general survey, and and Meketon (1986) Least absolute value regression for an application of the algorithm in the context of median regression.

Running time is of order $n^{1+\delta}k^3$ for some $\delta > 0$ and $k = \dim(\boldsymbol{\beta})$ (it is $(n+k)k^2$ for OLS, see wikipedia).

Quantile Regression Estimators

OLS estimator $\widehat{\boldsymbol{\beta}}^{\text{ols}}$ is solution of

$$\widehat{\boldsymbol{\beta}}^{\text{ols}} = \text{argmin}\left\{\mathbb{E}\left[\left(\mathbb{E}[Y|\boldsymbol{X}=\boldsymbol{x}] - \boldsymbol{x}^\mathsf{T}\boldsymbol{\beta}\right)^2\right]\right\}$$

and Angrist, Chernozhukov & Fernandez-Val (2006) Quantile Regression under Misspecification proved that

$$\widehat{\boldsymbol{\beta}}_\tau = \text{argmin}\left\{\mathbb{E}\left[\omega_\tau(\boldsymbol{\beta})\left(Q_\tau[Y|\boldsymbol{X}=\boldsymbol{x}] - \boldsymbol{x}^\mathsf{T}\boldsymbol{\beta}\right)^2\right]\right\}$$

(under weak conditions) where

$$\omega_\tau(\boldsymbol{\beta}) = \int_0^1 (1-u) f_{y|\boldsymbol{x}}(u\boldsymbol{x}^\mathsf{T}\boldsymbol{\beta} + (1-u)Q_\tau[Y|\boldsymbol{X}=\boldsymbol{x}])du$$

$\widehat{\boldsymbol{\beta}}_\tau$ is the best weighted mean square approximation of the tru quantile function, where the weights depend on an average of the conditional density of Y over $\boldsymbol{x}^\mathsf{T}\boldsymbol{\beta}$ and the true quantile regression function.

Assumptions to get Consistency of Quantile Regression Estimators

As always, we need some assumptions to have consistency of estimators.

- observations $(Y_i, \boldsymbol{X}_i)$ must (conditionnaly) i.id.
- regressors must have a bounded second moment, $\mathbb{E}\big[\|\boldsymbol{X}_i\|^2\big] < \infty$
- error terms ε are continuously distributed given $\boldsymbol{X}_i$, centered in the sense that their median should be 0,

$$\int_{-\infty}^{0} f_{\varepsilon}(\epsilon)d\epsilon = \frac{1}{2}.$$

- "local identification" property : $\big[f_{\varepsilon}(0)\boldsymbol{X}\boldsymbol{X}^{\top}\big]$ is positive definite

Quantile Regression Estimators

Under those weak conditions, $\widehat{\boldsymbol{\beta}}_\tau$ is asymptotically normal:

$$\sqrt{n}(\widehat{\boldsymbol{\beta}}_\tau - \boldsymbol{\beta}_\tau) \xrightarrow{\mathcal{L}} \mathcal{N}(0, \tau(1-\tau)D_\tau^{-1}\Omega_x D_\tau^{-1}),$$

where

$$D_\tau = \mathbb{E}\big[f_\varepsilon(0)\boldsymbol{X}\boldsymbol{X}^\top\big] \text{ and } \Omega_x = \mathbb{E}\big[\boldsymbol{X}^\top\boldsymbol{X}\big].$$

hence, the asymptotic variance of $\widehat{\boldsymbol{\beta}}$ is

$$\widehat{\text{Var}}\big[\widehat{\boldsymbol{\beta}}_\tau\big] = \frac{\tau(1-\tau)}{[\widehat{f}_\varepsilon(0)]^2}\left(\frac{1}{n}\sum_{i=1}^n \boldsymbol{x}_i^\top \boldsymbol{x}_i\right)^{-1}$$

where $\widehat{f}_\varepsilon(0)$ is estimated using (e.g.) an histogram, as suggested in Powell (1991) Estimation of monotonic regression models under quantile restrictions, since

$$D_\tau = \lim_{h\downarrow 0}\mathbb{E}\left(\frac{\mathbf{1}(|\varepsilon|\leq h)}{2h}\boldsymbol{X}\boldsymbol{X}^\top\right) \sim \frac{1}{2nh}\sum_{i=1}^n \mathbf{1}(|\varepsilon_i|\leq h)\boldsymbol{x}_i\boldsymbol{x}_i^\top = \widehat{D}_\tau.$$

Quantile Regression Estimators

There is no first order condition, in the sense $\partial V_n(\boldsymbol{\beta},\tau)/\partial\boldsymbol{\beta}=\mathbf{0}$ where

$$V_n(\boldsymbol{\beta},\tau)=\sum_{i=1}^{n}\mathcal{R}_\tau^{\mathsf{q}}(y_i-\boldsymbol{x}_i^\mathsf{T}\boldsymbol{\beta})$$

There is an asymptotic first order condition,

$$\frac{1}{\sqrt{n}}\sum_{i=1}^{n}\boldsymbol{x}_i\psi_\tau(y_i-\boldsymbol{x}_i^\mathsf{T}\boldsymbol{\beta})=\mathcal{O}(1),\ \text{as } n\rightarrow\infty,$$

where $\psi_\tau(\cdot)=\mathbf{1}(\cdot<0)-\tau$, see Huber (1967) The behavior of maximum likelihood estimates under nonstandard conditions.

One can also define a Wald test, a Likelihood Ratio test, etc.

Quantile Regression Estimators

Then the confidence interval of level $1-\alpha$ is then

$$\left[\widehat{\beta}_\tau \pm z_{1-\alpha/2}\sqrt{\widehat{\text{Var}}\big[\widehat{\boldsymbol{\beta}}_\tau\big]}\right]$$

An alternative is to use a boostrap strategy (see #2)

- generate a sample $(y_i^{(b)}, \boldsymbol{x}_i^{(b)})$ from $(y_i, \boldsymbol{x}_i)$
- estimate $\boldsymbol{\beta}_\tau^{(b)}$ by

$$\widehat{\boldsymbol{\beta}}_\tau^{(b)} = \text{argmin}\left\{\mathcal{R}_\tau^{\mathsf{q}}\left(y_i^{(b)} - \boldsymbol{x}_i^{(b)\mathsf{T}}\boldsymbol{\beta}\right)\right\}$$

- set $\widehat{\text{Var}}^\star\big[\widehat{\boldsymbol{\beta}}_\tau\big] = \dfrac{1}{B}\displaystyle\sum_{b=1}^{B}\big(\widehat{\boldsymbol{\beta}}_\tau^{(b)} - \widehat{\boldsymbol{\beta}}_\tau\big)^2$

For confidence intervals, we can either use Gaussian-type confidence intervals, or empirical quantiles from bootstrap estimates.

Quantile Regression Estimators

If $\boldsymbol{\tau} = (\tau_1, \cdots, \tau_m)$, one can prove that

$$\sqrt{n}(\widehat{\boldsymbol{\beta}}_{\boldsymbol{\tau}} - \boldsymbol{\beta}_{\boldsymbol{\tau}}) \overset{\mathcal{L}}{\to} \mathcal{N}(\mathbf{0}, \Sigma_{\boldsymbol{\tau}}),$$

where $\Sigma_{\boldsymbol{\tau}}$ is a block matrix, with

$$\Sigma_{\tau_i,\tau_j} = (\min\{\tau_i, \tau_j\} - \tau_i\tau_j)D_{\tau_i}^{-1}\Omega_x D_{\tau_j}^{-1}$$

see Kocherginsky *et al.* (2005) Practical Confidence Intervals for Regression Quantiles for more details.

Quantile Regression: Transformations

Scale equivariance

For any $a > 0$ and $\tau \in [0, 1]$

$$\hat{\boldsymbol{\beta}}_\tau(aY, \boldsymbol{X}) = a\hat{\boldsymbol{\beta}}_\tau(Y, \boldsymbol{X}) \text{ and } \hat{\boldsymbol{\beta}}_\tau(-aY, \boldsymbol{X}) = -a\hat{\boldsymbol{\beta}}_{1-\tau}(Y, \boldsymbol{X})$$

Equivariance to reparameterization of design

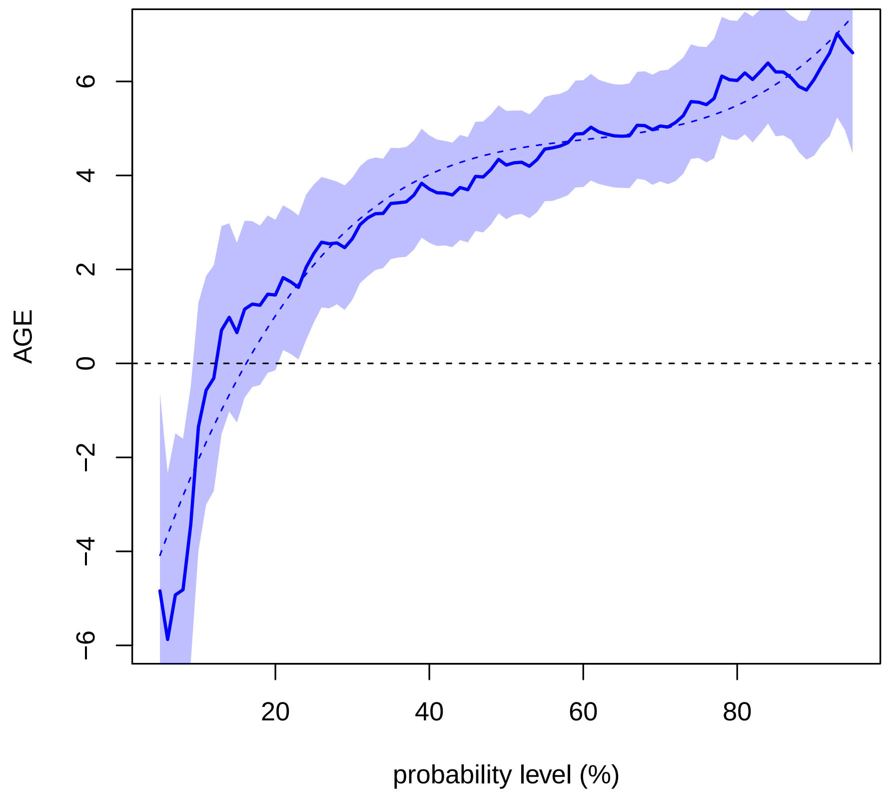
Let $\boldsymbol{A}$ be any $p \times p$ nonsingular matrix and $\tau \in [0, 1]$

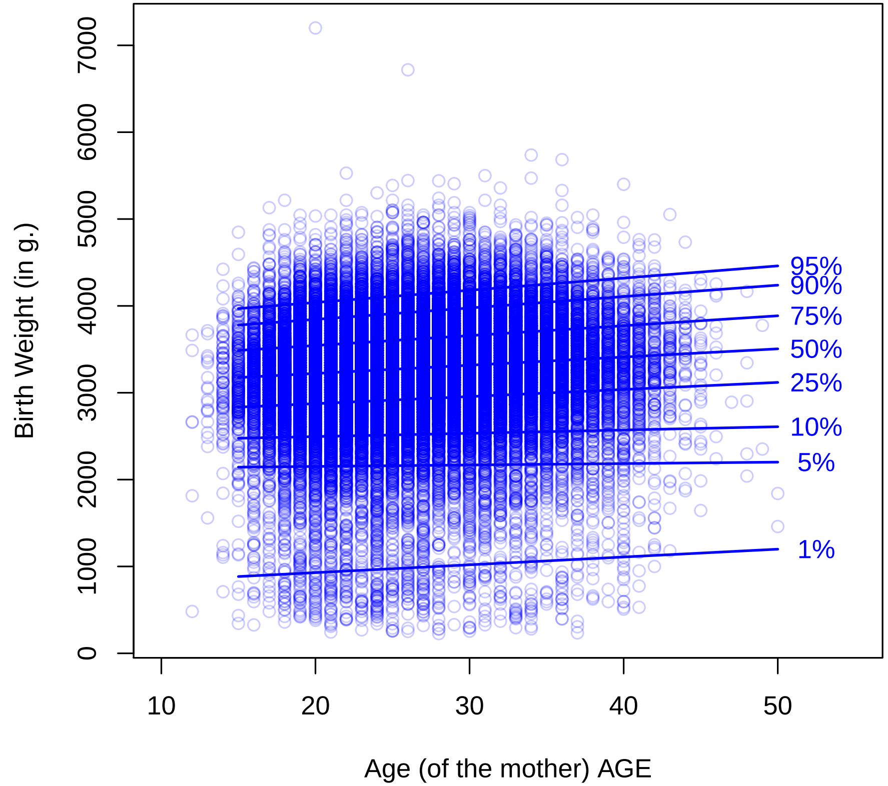
$$\hat{\boldsymbol{\beta}}_\tau(Y, \boldsymbol{X}\boldsymbol{A}) = \boldsymbol{A}^{-1}\hat{\boldsymbol{\beta}}_\tau(Y, \boldsymbol{X})$$

Visualization, $\tau \mapsto \widehat{\beta}_\tau$

See Abreveya (2001) The effects of demographics and maternal behavior...

```
> base=read.table("http://freakonometrics.free.fr/natality2005.txt")
```



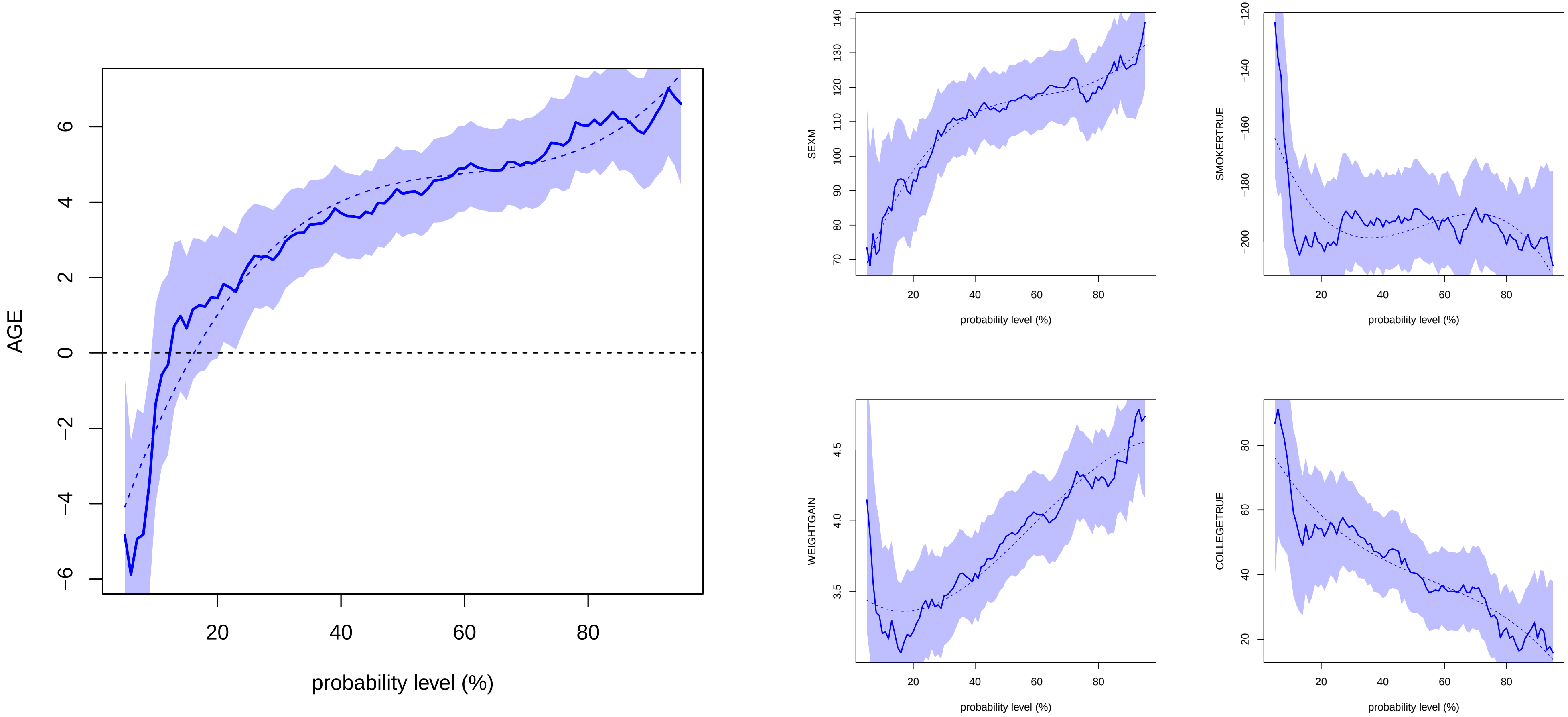


Visualization, $\tau \mapsto \widehat{\beta}_\tau$

```
> base=read.table("http://freakonometrics.free.fr/natality2005.txt",
    header=TRUE,sep=";")
> u=seq(.05,.95,by=.01)
> library(quantreg)
>  coefstd=function(u) summary(rq(WEIGHT~SEX+SMOKER+WEIGHTGAIN+
    BIRTHRECORD+AGE+ BLACKM+ BLACKF+COLLEGE,data=sbase,tau=u))$
    coefficients[,2]
> coefest=function(u) summary(rq(WEIGHT~SEX+SMOKER+WEIGHTGAIN+
    BIRTHRECORD+AGE+ BLACKM+ BLACKF+COLLEGE,data=sbase,tau=u))$
    coefficients[,1]
CS=Vectorize(coefstd)(u)
CE=Vectorize(coefest)(u)
```

Visualization, $\tau \mapsto \widehat{\beta}_\tau$

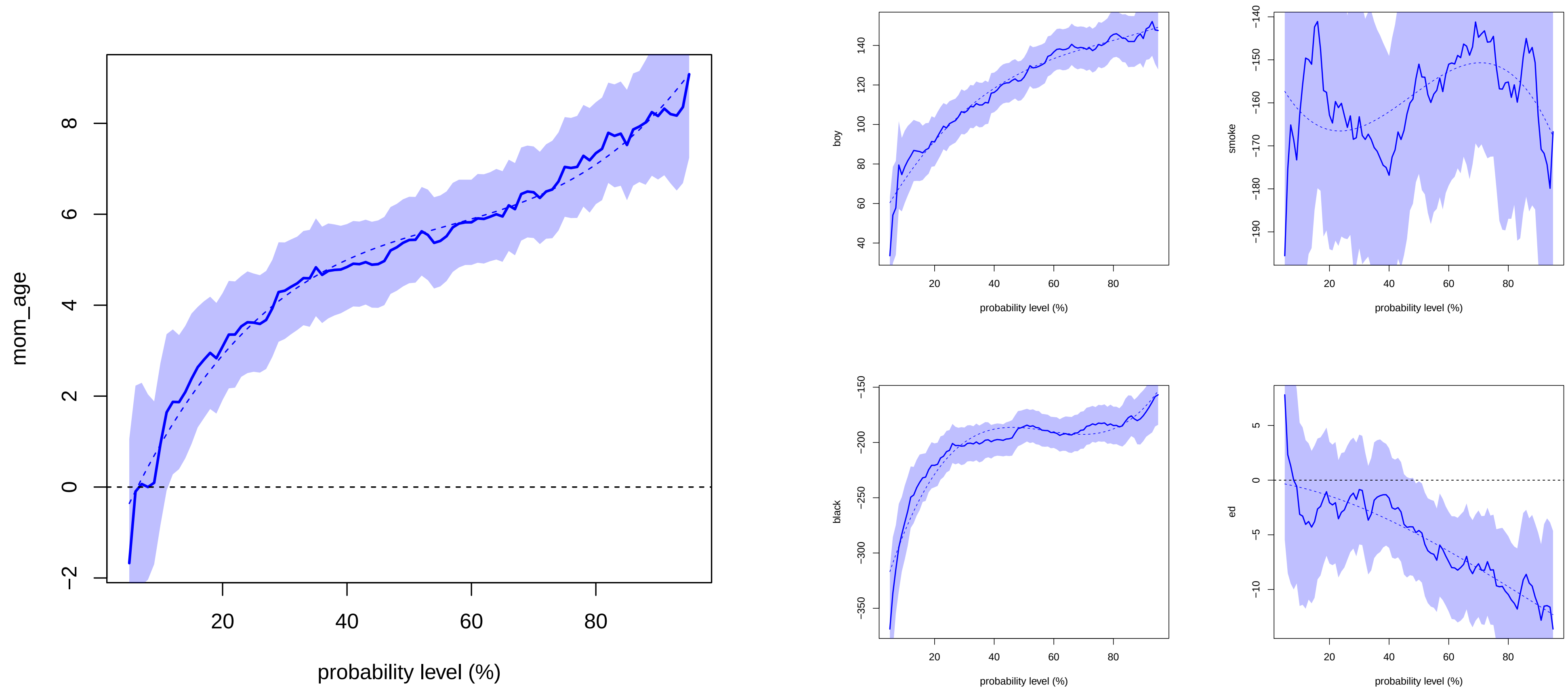
See Abreveya (2001) The effects of demographics and maternal behavior on the distribution of birth outcomes



Visualization, $\tau \mapsto \widehat{\beta}_\tau$

See Abreveya (2001) The effects of demographics and maternal behavior...

```
> base=read.table("http://freakonometrics.free.fr/BWeight.csv")
```

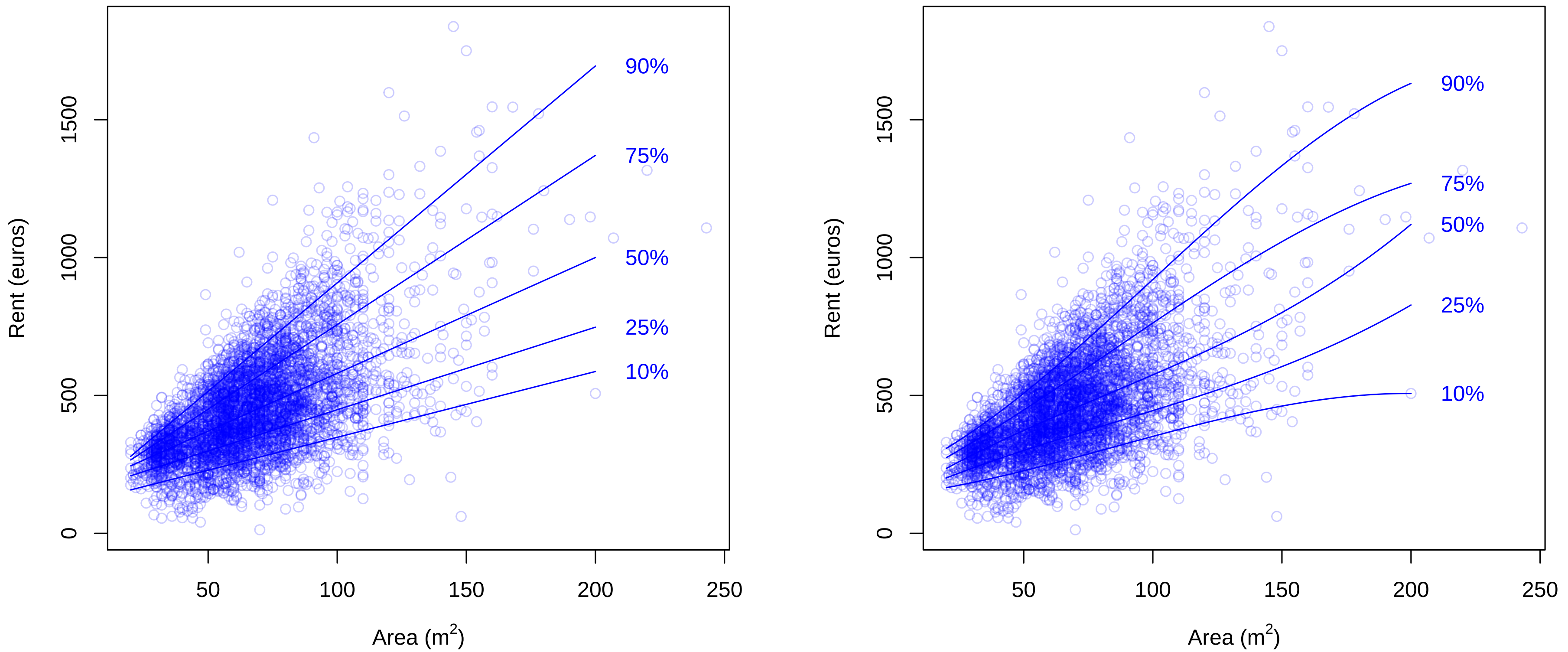


Quantile Regression, with Non-Linear Effects

Rents in Munich, as a function of the area, from Fahrmeir *et al.* (2013)

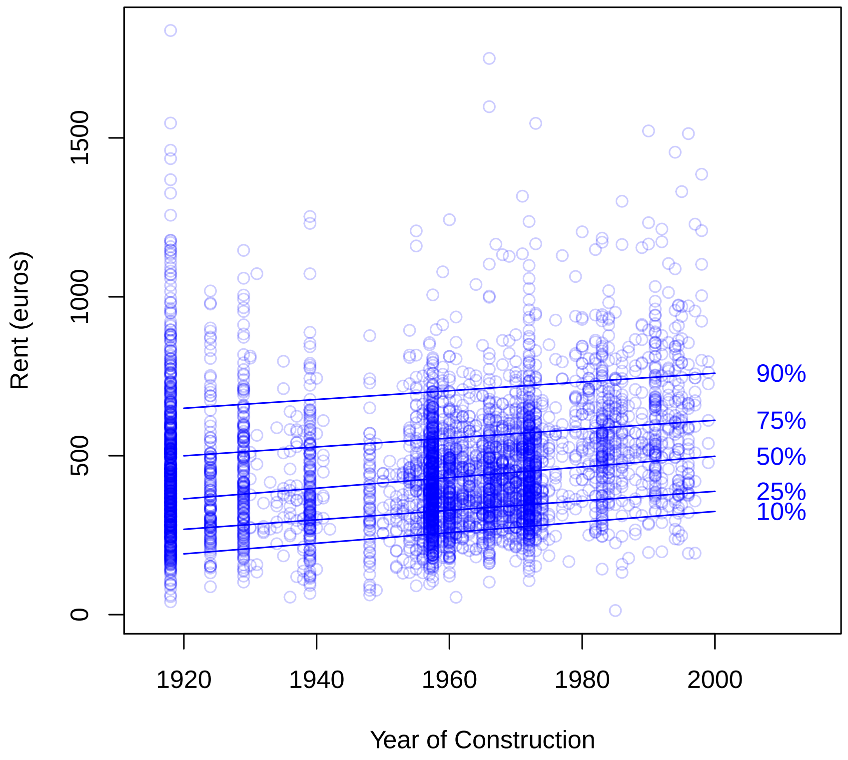
Regression: Models, Methods and Applications

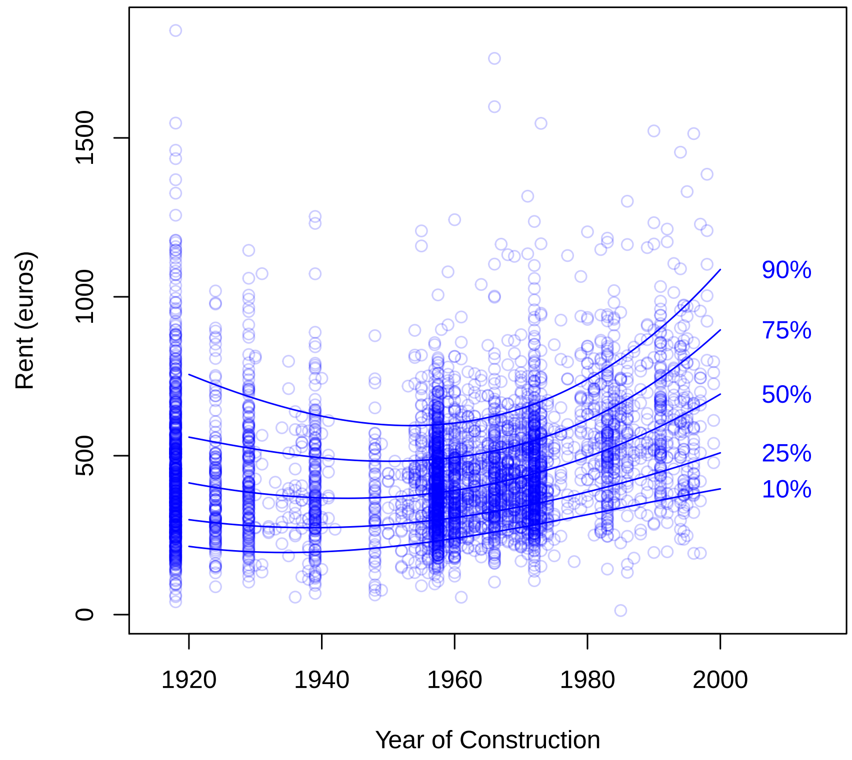
```
> base=read.table("http://freakonometrics.free.fr/rent98_00.txt")
```



Quantile Regression, with Non-Linear Effects

Rents in Munich, as a function of the year of construction, from Fahrmeir *et al.* (2013) Regression: Models, Methods and Applications

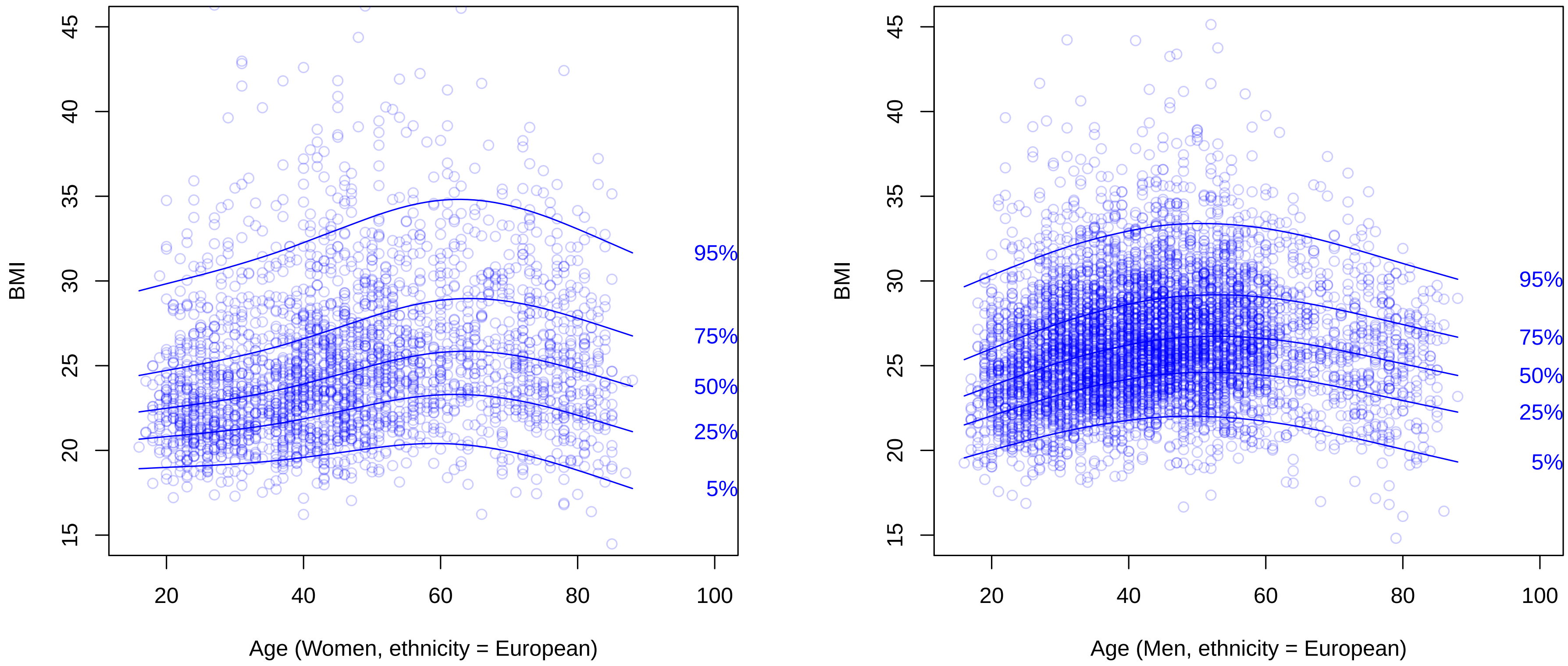




Quantile Regression, with Non-Linear Effects

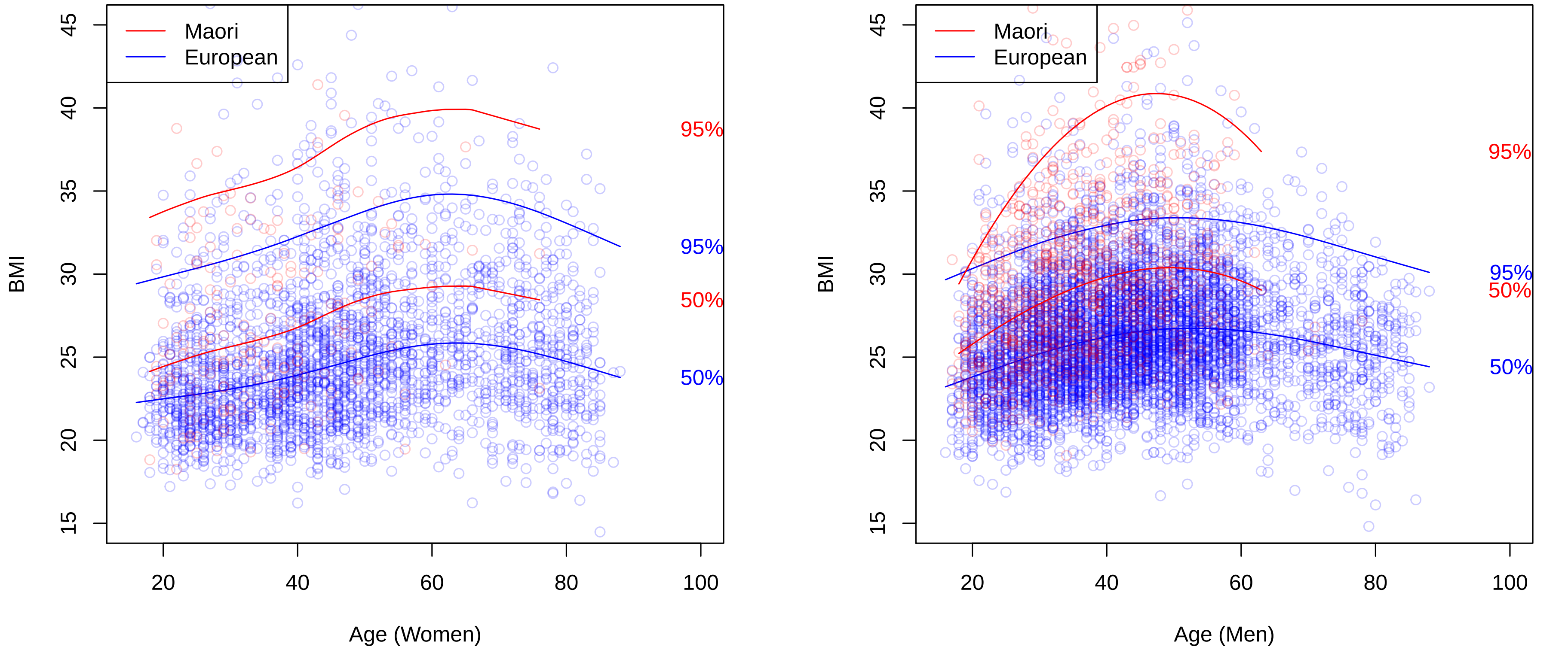
BMI as a function of the age, in New-Zealand, from Yee (2015) Vector Generalized Linear and Additive Models, for Women and Men

```
> library(VGAMdata); data(xs.nz)
```



Quantile Regression, with Non-Linear Effects

BMI as a function of the age, in New-Zealand, from Yee (2015) Vector Generalized Linear and Additive Models, for Women and Men



Quantile Regression, with Non-Linear Effects

One can consider some local polynomial quantile regression, e.g.

$$\min\left\{\sum_{i=1}^{n}\omega_i(\boldsymbol{x})\mathcal{R}_\tau^{\mathsf{q}}\left(y_i-\beta_0-(\boldsymbol{x}_i-\boldsymbol{x})^{\mathsf{T}}\boldsymbol{\beta}_1\right)\right\}$$

for some weights $\omega_i(\boldsymbol{x})=H^{-1}K(H^{-1}(\boldsymbol{x}_i-\boldsymbol{x}))$, see Fan, Hu & Truong (1994) Robust Non-Parametric Function Estimation.

Asymmetric Maximum Likelihood Estimation

Introduced by Efron (1991) Regression percentiles using asymmetric squared error loss. Consider a linear model, $y_i = \boldsymbol{x}_i^\top \boldsymbol{\beta} + \varepsilon_i$. Let

$$S(\boldsymbol{\beta}) = \sum_{i=1}^{n} Q_\omega(y_i - \boldsymbol{x}_i^\top \boldsymbol{\beta}), \text{ where } Q_\omega(\epsilon) = \begin{cases} \epsilon^2 \text{ if } \epsilon \leq 0 \\ w\epsilon^2 \text{ if } \epsilon > 0 \end{cases} \text{ where } w = \frac{\omega}{1-\omega}$$

One might consider $\omega_\alpha = 1 + \dfrac{z_\alpha}{\varphi(z_\alpha) + (1-\alpha)z_\alpha}$ where $z_\alpha = \Phi^{-1}(\alpha)$.

Efron (1992) Poisson overdispersion estimates based on the method of asymmetric maximum likelihood introduced asymmetric maximum likelihood (AML) estimation, considering

$$S(\boldsymbol{\beta}) = \sum_{i=1}^{n} Q_\omega(y_i - \boldsymbol{x}_i^\top \boldsymbol{\beta}), \text{ where } Q_\omega(\epsilon) = \begin{cases} D(y_i, \boldsymbol{x}_i^\top \boldsymbol{\beta}) \text{ if } y_i \leq \boldsymbol{x}_i^\top \boldsymbol{\beta} \\ wD(y_i, \boldsymbol{x}_i^\top \boldsymbol{\beta}) \text{ if } y_i > \boldsymbol{x}_i^\top \boldsymbol{\beta} \end{cases}$$

where $D(\cdot,\cdot)$ is the deviance. Estimation is based on Newton-Raphson (gradient descent).

Noncrossing Solutions

See Bondell *et al.* (2010) Non-crossing quantile regression curve estimation.

Consider probabilities $\boldsymbol{\tau} = (\tau_1, \cdots, \tau_q)$ with $0 < \tau_1 < \cdots < \tau_q < 1$.

Use parallelism : add constraints in the optimization problem, such that

$$\boldsymbol{x}_i^{\mathsf{T}}\widehat{\boldsymbol{\beta}}_{\tau_j} \geq \boldsymbol{x}_i^{\mathsf{T}}\widehat{\boldsymbol{\beta}}_{\tau_{j-1}} \quad \forall i \in \{1, \cdots, n\}, j \in \{2, \cdots, q\}.$$

Quantile Regression on Panel Data

In the context of panel data, consider some fixed effect, α_i so that

$$y_{i,t} = \boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta}_\tau + \alpha_i + \varepsilon_{i,t} \text{ where } Q_\tau(\varepsilon_{i,t}|\boldsymbol{X}_i) = 0$$

Canay (2011) A simple approach to quantile regression for panel data suggests an estimator in two steps,

- use a standard OLS fixed-effect model $y_{i,t} = \boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta} + \alpha_i + u_{i,t}$, i.e. consider a within transformation, and derive the fixed effect estimate $\widehat{\boldsymbol{\beta}}$

$$(y_{i,t} - \overline{y}_i) = \big(\boldsymbol{x}_{i,t} - \overline{\boldsymbol{x}}_{i,t}\big)^{\mathsf{T}}\boldsymbol{\beta} + (u_{i,t} - \overline{u}_i)$$

- estimate fixed effects as $\widehat{\alpha}_i = \dfrac{1}{T}\displaystyle\sum_{t=1}^{T}\big(y_{i,t} - \boldsymbol{x}_{i,t}^{\mathsf{T}}\widehat{\boldsymbol{\beta}}\big)$
- finally, run a standard quantile regression of $y_{i,t} - \widehat{\alpha}_i$ on $\boldsymbol{x}_{i,t}$'s.

See rqpd package.

Quantile Regression with Fixed Effects (QRFE)

In a panel linear regression model, $y_{i,t} = \boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta} + u_i + \varepsilon_{i,t}$,

where u is an unobserved individual specific effect.

In a fixed effects models, u is treated as a parameter. Quantile Regression is

$$\min_{\boldsymbol{\beta},\boldsymbol{u}} \left\{ \sum_{i,t} \mathcal{R}_{\alpha}^{\mathsf{q}}(y_{i,t} - [\boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta} + u_i]) \right\}$$

Consider Penalized QRFE, as in Koenker & Bilias (2001) Quantile regression for duration data,

$$\min_{\boldsymbol{\beta}_1,\cdots,\boldsymbol{\beta}_\kappa,\boldsymbol{u}} \left\{ \sum_{k,i,t} \omega_k \mathcal{R}_{\alpha_k}^{\mathsf{q}}(y_{i,t} - [\boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta}_k + u_i]) + \lambda \sum_{i} |u_i| \right\}$$

where ω_k is a relative weight associated with quantile of level α_k.

Quantile Regression with Random Effects (QRRE)

Assume here that $y_{i,t} = \boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta} + \underbrace{u_i + \varepsilon_{i,t}}_{=\eta_{i,t}}$.

Quantile Regression Random Effect (QRRE) yields solving

$$\min_{\boldsymbol{\beta}} \left\{ \sum_{i,t} \mathcal{R}_{\alpha}^{\mathsf{q}}(y_{i,t} - \boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta}) \right\}$$

which is a weighted asymmetric least square deviation estimator.

Let $\Sigma = [\sigma_{s,t}(\alpha)]$ denote the matrix

$$\sigma_{ts}(\alpha) = \begin{cases} \alpha(1-\alpha) & \text{if } t = s \\ \mathbb{E}[\mathbf{1}\{\varepsilon_{it}(\alpha) < 0, \varepsilon_{is}(\alpha) < 0\}] - \alpha^2 & \text{if } t \neq s \end{cases}$$

If $(nT)^{-1}\boldsymbol{X}^{\mathsf{T}}\{\mathbb{I}_n \otimes \Sigma_{T\times T}(\alpha)\}\boldsymbol{X} \to \mathbf{D}_0$ as $n \to \infty$ and $(nT)^{-1}\boldsymbol{X}^{\mathsf{T}}\Omega_f\boldsymbol{X} = \mathbf{D}_1$, then

$$\sqrt{nT}\left(\widehat{\boldsymbol{\beta}}^Q(\alpha) - \boldsymbol{\beta}^Q(\alpha)\right) \xrightarrow{\mathcal{L}} \mathcal{N}\left(0, \mathbf{D}_1^{-1}\mathbf{D}_0\mathbf{D}_1^{-1}\right).$$

Quantile Treatment Effects

Doksum (1974) Empirical Probability Plots and Statistical Inference for Nonlinear Models introduced QTE - Quantile Treatement Effect - when a person might have two Y's : either Y_0 (without treatment, $D = 0$) or Y_1 (with treatement, $D = 1$),

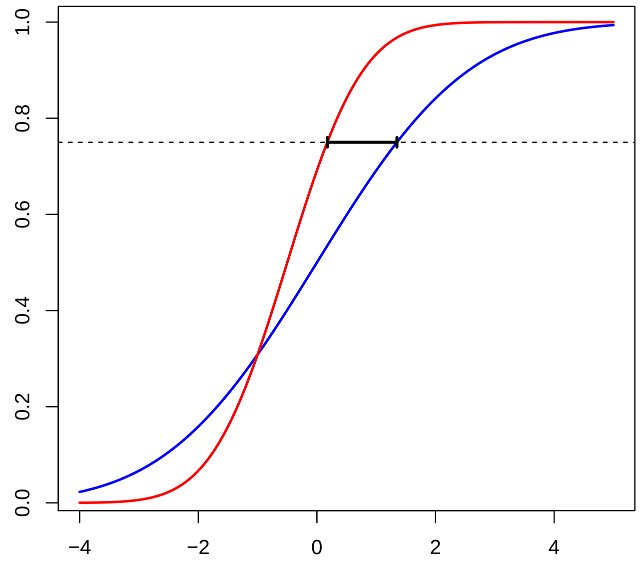
$$\delta_\tau = Q_{Y_1}(\tau) - Q_{Y_0}(\tau)$$

which can be studied on the context of covariates.

Run a quantile regression of y on $(d, \boldsymbol{x})$,

$$y = \beta_0 + \delta d + \boldsymbol{x}_i^\mathsf{T}\boldsymbol{\beta} + \varepsilon_i \;\; : \;\text{shifting effect}$$

$$y = \beta_0 + \boldsymbol{x}_i^\mathsf{T}\big[\boldsymbol{\beta} + \delta d\big] + \varepsilon_i \;\; : \;\text{scaling effect}$$



Quantile Regression for Time Series

Consider some GARCH(1,1) financial time series,

$$y_t = \sigma_t \varepsilon_t \text{ where } \sigma_t = \alpha_0 + \alpha_1 \cdot |y_{t-1}| + \beta_1 \sigma_{t-1}.$$

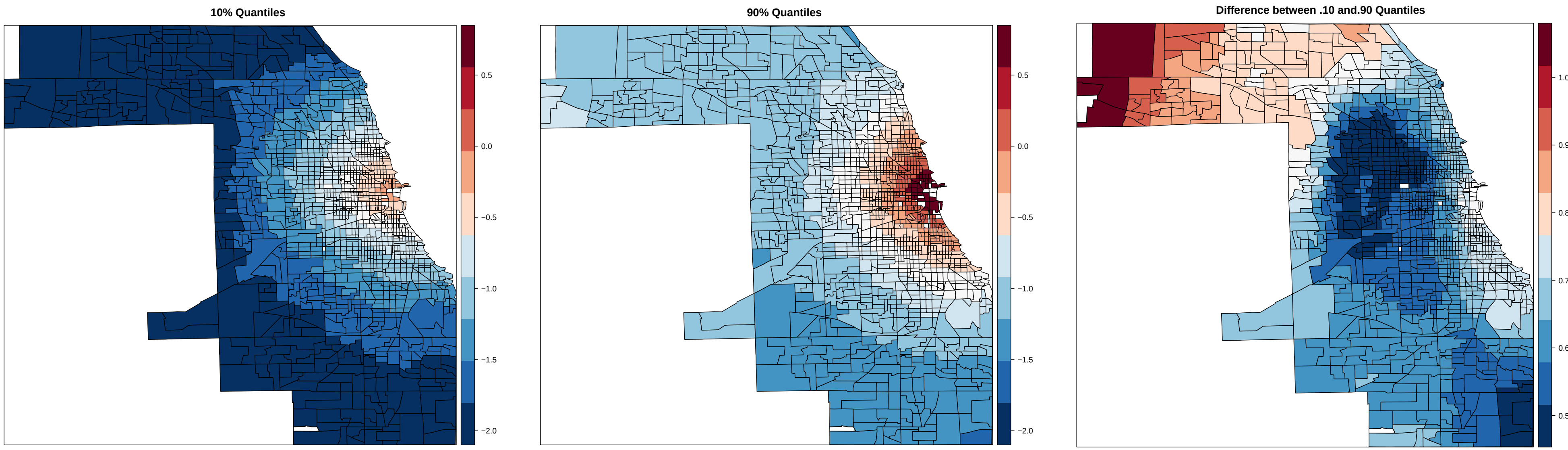
The quantile function conditional on the past - $\mathcal{F}_{t-1} = \underline{Y}_{t-1}$ - is

$$Q_{y|\mathcal{F}_{t-1}}(\tau) = \underbrace{\alpha_0 F_\varepsilon^{-1}(\tau)}_{\tilde{\alpha}_0} + \underbrace{\alpha_1 F_\varepsilon^{-1}(\tau)}_{\tilde{\alpha}_1} \cdot |y_{t-1}| + \beta_1 Q_{y|\mathcal{F}_{t-2}}(\tau)$$

i.e. the conditional quantile has a GARCH(1,1) form, see Conditional Autoregressive Value-at-Risk, see Manganelli & Engle (2004) CAViaR: Conditional Autoregressive Value at Risk by Regression Quantiles

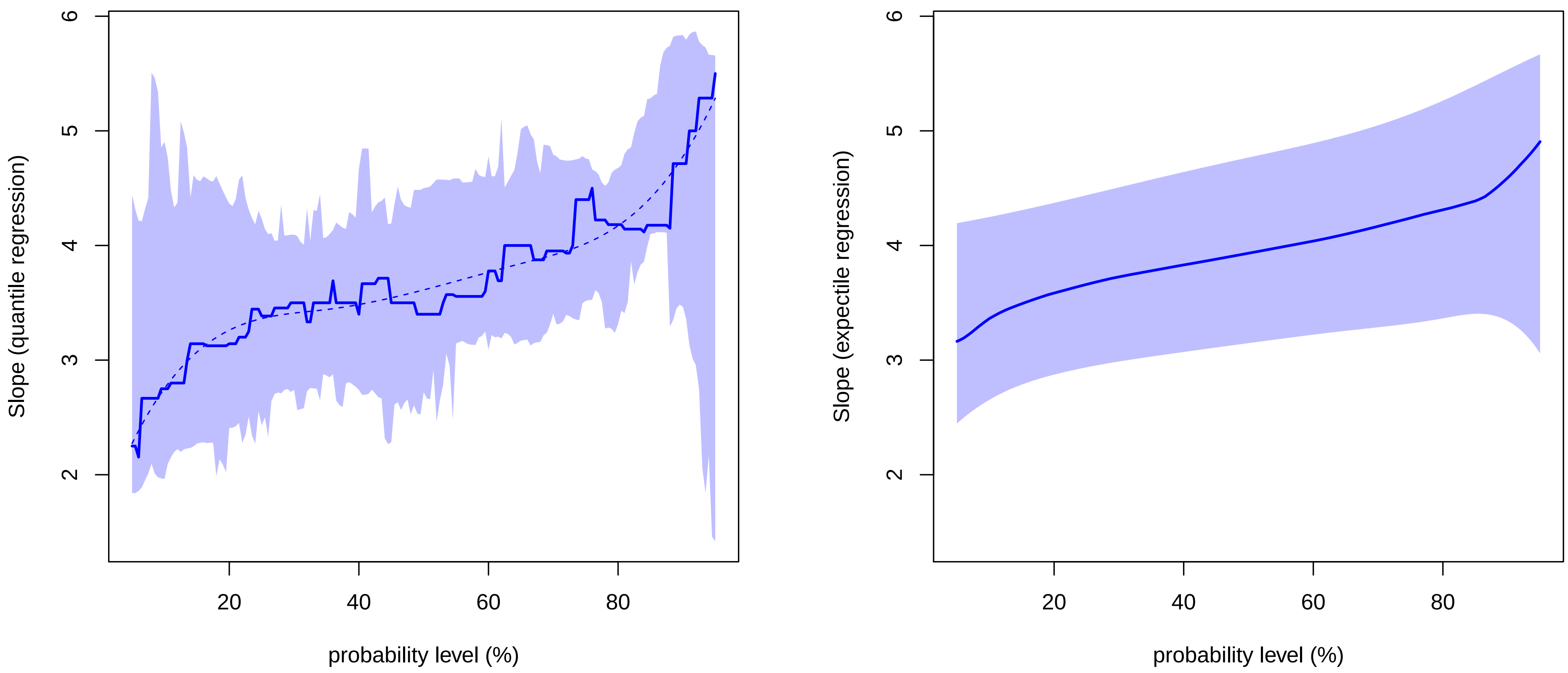
Quantile Regression for Spatial Data

```
> library(McSpatial)
> data(cookdata)
> fit <- qregcpar(LNFAR~DCBD, nonpar=~LATITUDE+LONGITUDE, taumat=c
    (.10,.90), kern="bisq", window=.30, distance="LATLONG", data=
    cookdata)
```



Expectile Regression

Quantile regression vs. Expectile regression, on the same dataset (cars)



see Koenker (2014) Living Beyond our Means for a comparison quantiles-expectiles

Expectile Regression

Solve here $\min_{\boldsymbol{\beta}}\left\{\sum_{i=1}^{n}\mathcal{R}_{\tau}^{\mathsf{e}}(y_i-\boldsymbol{x}_i^{\mathsf{T}}\boldsymbol{\beta})\right\}$ where $\mathcal{R}_{\tau}^{\mathsf{e}}(u)=u^2\cdot\big(\tau-\mathbf{1}(u<0)\big)$

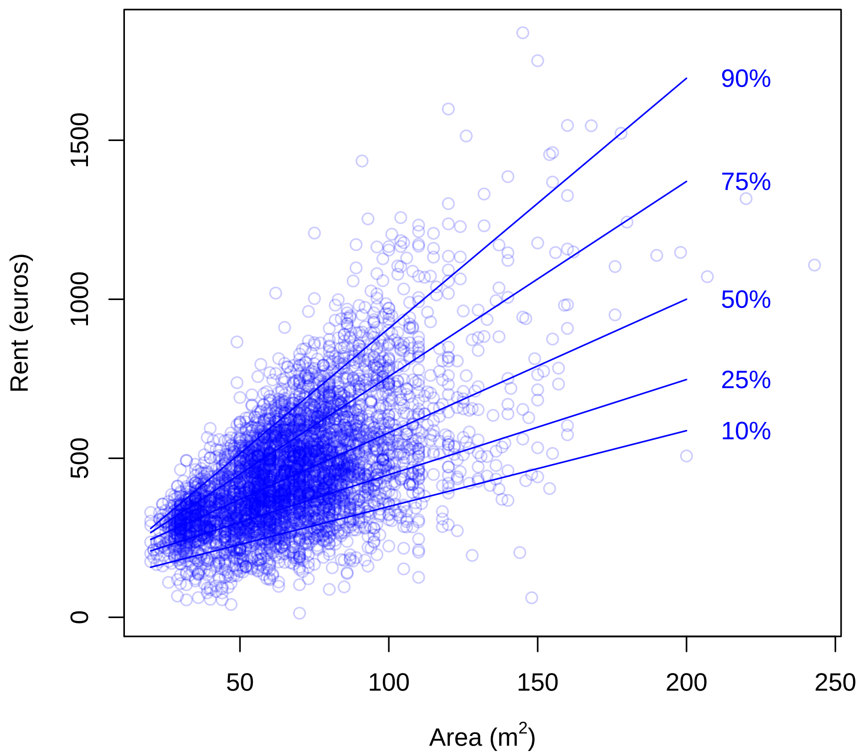
"*this estimator can be interpreted as a maximum likelihood estimator when the disturbances arise from a normal distribution with unequal weight placed on positive and negative disturbances*" Aigner, Amemiya & Poirier (1976) Formulation and Estimation of Stochastic Frontier Production Function Models.

See Holzmann & Klar (2016) Expectile Asymptotics for statistical properties.

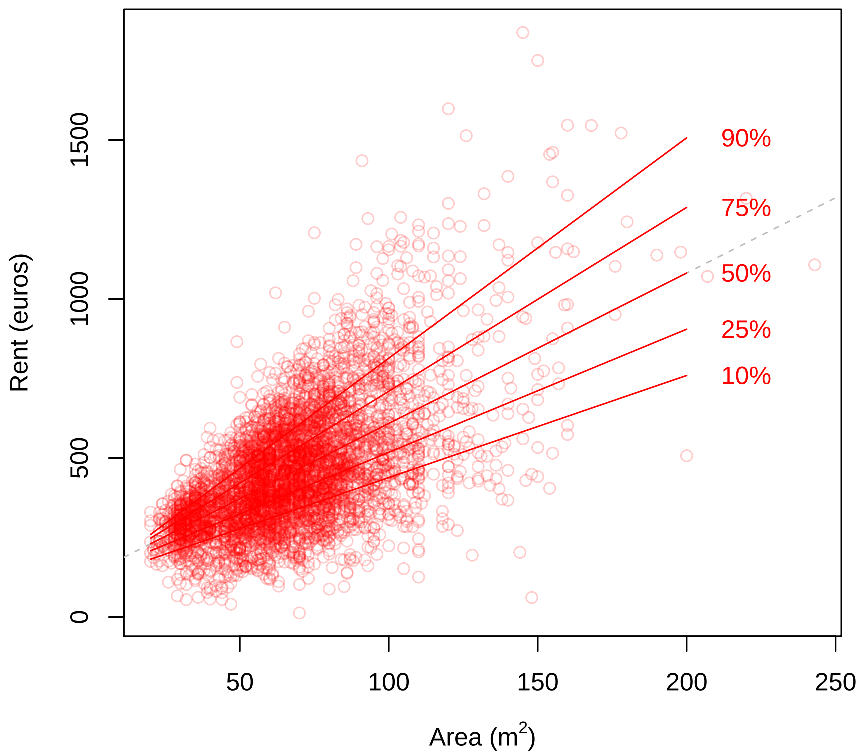
Expectiles can (also) be related to Breckling & Chambers (1988) M-Quantiles.

Comparison quantile regression and expectile regression, see Schulze-Waltrup *et al.* (2014) Expectile and quantile regression - David and Goliath?

Expectile Regression, with Linear Effects



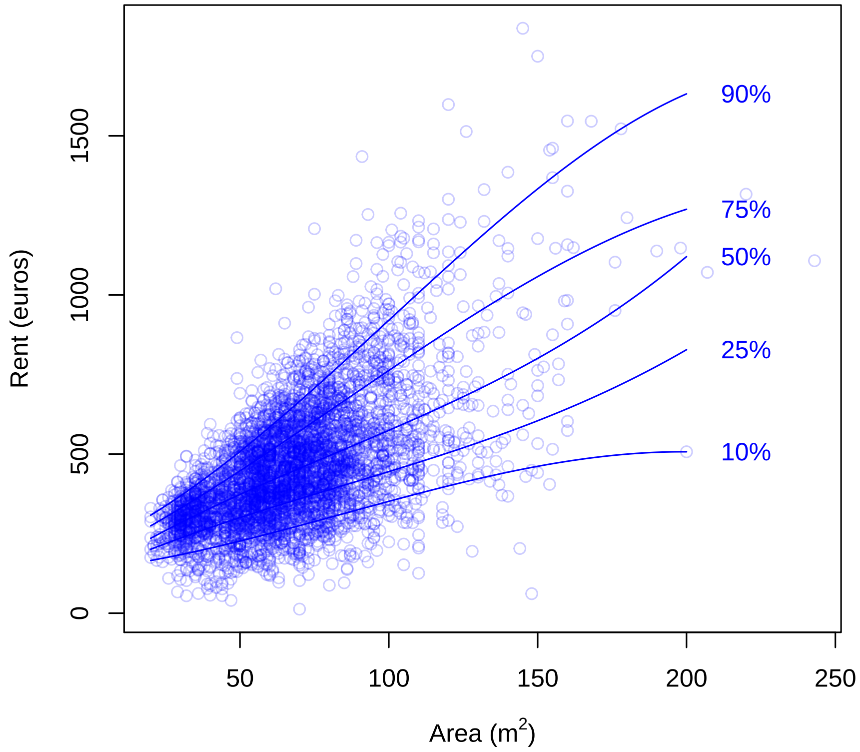
Quantile Regressions



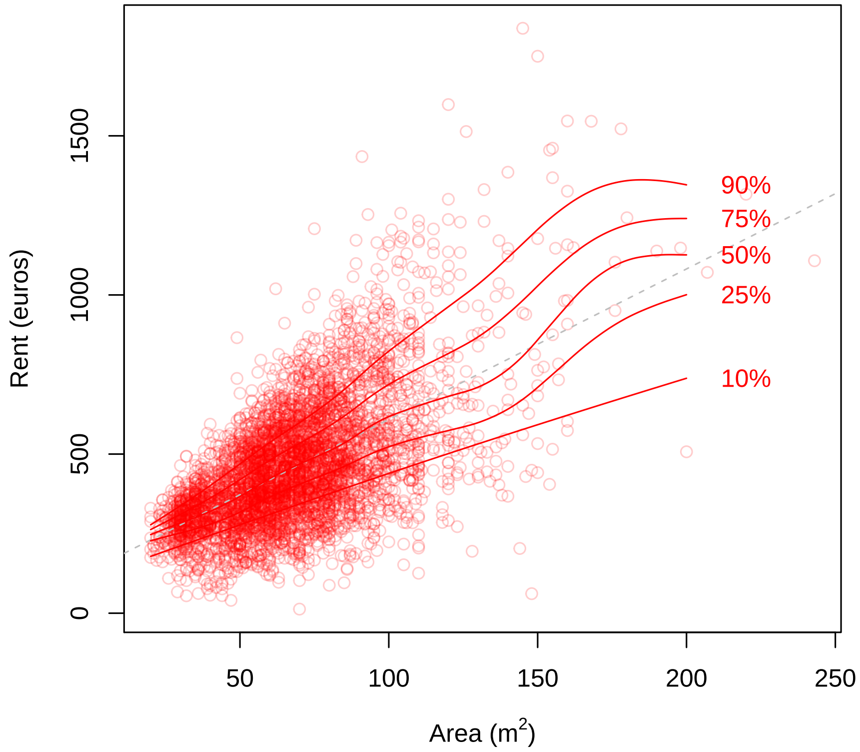
Expectile Regressions

Expectile Regression, with Non-Linear Effects

See Zhang (1994) Nonparametric regression expectiles



Quantile Regressions



Expectile Regressions

Expectile Regression, with Linear Effects

```
> library(expectreg)
> coefstd=function(u) summary(expectreg.ls(WEIGHT~SEX+SMOKER+
    WEIGHTGAIN+BIRTHRECORD+AGE+ BLACKM+ BLACKF+COLLEGE,data=sbase,
    expectiles=u,ci = TRUE))[,2]
> coefest=function(u) summary(expectreg.ls(WEIGHT~SEX+SMOKER+
    WEIGHTGAIN+BIRTHRECORD+AGE+ BLACKM+ BLACKF+COLLEGE,data=sbase,
    expectiles=u,ci = TRUE))[,1]
> CS=Vectorize(coefstd)(u)
> CE=Vectorize(coefest)(u)
```

Expectile Regression, with Random Effects (ERRE)

Quantile Regression Random Effect (QRRE) yields solving

$$\min_{\boldsymbol{\beta}}\left\{\sum_{i,t}\mathcal{R}^{\mathsf{e}}_{\alpha}(y_{i,t}-\boldsymbol{x}_{i,t}^{\mathsf{T}}\boldsymbol{\beta})\right\}$$

One can prove that

$$\widehat{\boldsymbol{\beta}}^{\mathsf{e}}(\tau)=\left(\sum_{i=1}^{n}\sum_{t=1}^{T}\widehat{\omega}_{i,t}(\tau)\boldsymbol{x}_{it}\boldsymbol{x}_{it}^{\mathsf{T}}\right)^{-1}\left(\sum_{i=1}^{n}\sum_{t=1}^{T}\widehat{\omega}_{i,t}(\tau)\boldsymbol{x}_{it}y_{it}\right),$$

where $\widehat{\omega}_{it}(\tau)=\left|\tau-\mathbf{1}(y_{it}<\boldsymbol{x}_{it}^{\mathsf{T}}\widehat{\boldsymbol{\beta}}^{\mathsf{e}}(\tau))\right|$.

Expectile Regression with Random Effects (ERRE)

If $W = \text{diag}(\omega_{11}(\tau), \ldots \omega_{nT}(\tau))$, set

$$\overline{W} = \mathbb{E}(W), H = \boldsymbol{X}^{\mathsf{T}}\overline{W}\boldsymbol{X} \text{ and } \Sigma = \boldsymbol{X}^{\mathsf{T}}\mathbb{E}(W\varepsilon\varepsilon^{\mathsf{T}}W)\boldsymbol{X}.$$

and then

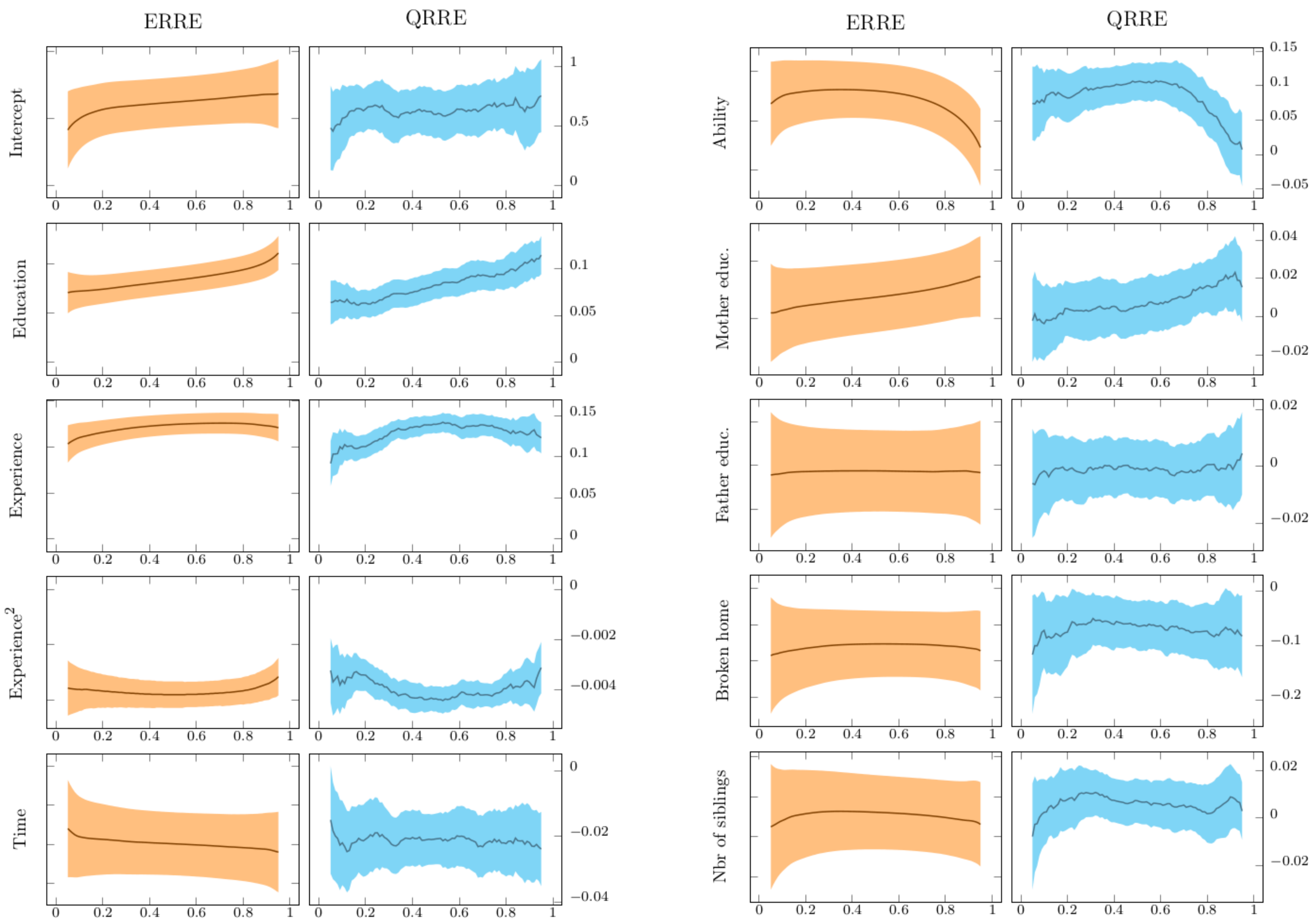
$$\sqrt{nT}\{\widehat{\boldsymbol{\beta}}^{\mathsf{e}}(\tau) - \boldsymbol{\beta}^{\mathsf{e}}(\tau)\} \xrightarrow{\mathcal{L}} \mathcal{N}(0, H^{-1}\Sigma H^{-1}),$$

see Barry *et al.* (2016) Quantile and Expectile Regression for random effects model.

See, for expectile regressions, with R,

```
> library(expectreg)
> fit <- expectreg.ls(rent_euro ~ area, data=munich, expectiles=.75)
> fit <- expectreg.ls(rent_euro ~ rb(area,"pspline"), data=munich,
    expectiles=.75)
```

Application to Real Data



Extensions

The mean of Y is $\nu(F_Y) = \int_{-\infty}^{+\infty} y dF_Y(y)$

The quantile of level τ for Y is $\nu_\tau(F_Y) = F_Y^{-1}(\tau)$

More generaly, consider some functional $\nu(F)$ (Gini or Theil index, entropy, etc), see Foresi & Peracchi (1995) The Conditional Distribution of Excess Returns

Can we estimate $\nu(F_{Y|\boldsymbol{x}})$?

Firpo *et al.* (2009) Unconditional Quantile Regressions suggested to use influence function regression

Machado & Mata (2005) Counterfactual decomposition of changes in wage distributions and Chernozhukov *et al.* (2013) Inference on counterfactual distributions suggested indirect distribution function.

Influence function of index $\nu(F)$ at y is

$$IF(y, \nu, F) = \lim_{\varepsilon \downarrow 0} \frac{\nu((1-\epsilon)F + \epsilon\delta_y) - \nu(F)}{\epsilon}$$