LECTURE 13: TIME SERIES I

AUTOCORRELATION:

Consider $y = X\beta + u$ where y is $T \times 1$, X is $T \times K$, β is $K \times 1$ and u is $T \times 1$.

We are using T and not N for sample size to emphasize that this is a time series.

The natural order of observations in a time series suggest possible approaches to parametrizing the covariance matrix parsimoniously.

First order autoregression: $AR(1)$

This is the case where $u_t = \rho u_{t-1} + \varepsilon_t$ where ε_t are independent and identically distributed with

$E\varepsilon_t = 0$ and $V(\varepsilon_t) = \sigma^2$.

First order moving average: $MA(1)$

This is the case where $u_t = \varepsilon_t - \theta\varepsilon_{t-1}$.

Random walk: ($AR(1)$ with $p = 1$)

This is the case where $u_t - u_{t-1} = \varepsilon_t$.

Integrated moving average: $IMA(1)$

This is the case where $u_t - u_{t-1} = \varepsilon_t - \theta\varepsilon_{t-1}$.

Autoregressive moving average (1,1): $ARMA(1,1)$

$$u_t - \rho u_{t-1} = \varepsilon_t - \theta\varepsilon_{t-1}$$

Autoregressive of order p: $AR(p)$

$$u_t = \rho_1 u_{t-1} + \rho_2 u_{t-2} + ... + \rho_p u_{t-p} + \varepsilon_t.$$

Moving average of order p: $MA(p)$

$$u_t = \varepsilon_t - \sum_{i=1}^{p} \theta_i \varepsilon_{t-i}$$

Proposition: A first order autoregressive ($AR(1)$) process is an infinite order moving average($MA(\infty)$) process.

Proof:

$$u_t = \rho(\rho u_{t-2} + \varepsilon_{t-1}) + \varepsilon_t = (\varepsilon_t + \rho\varepsilon_{t-1} + \rho^2\varepsilon_{t-2} + ...).$$

Thus

$$u_t = \textstyle\sum_{r=0}^{\infty} \rho^r \varepsilon_{t-r}$$

$AR(1)$ arises frequently in economic time series.

Let $u_t = \rho u_{t-1} + \varepsilon_t$ which is an $AR(1)$ process.

Note that $Eu_t = 0$ and $V(u_t) = \sigma^2(1+\rho^2+\rho^4+...) = \sigma^2/(1-\rho^2)$.

Also note that

$$
\begin{aligned}
cov(u_t u_{t-1}) &= \rho\sigma^2 + \rho^3\sigma^2 + \rho^5\sigma^2 + ... \\
&= \rho\sigma^2/(1-\rho^2) = \rho V(u_t),
\end{aligned}
$$

and similarly

$cov(u_t u_{t-s}) = \rho^s V(u_t) = \rho^s\sigma^2/(1-\rho^2)$. Thus

$$
Euu' = \frac{\sigma^2}{1-\rho^2}\begin{bmatrix} 1 & \rho & \rho^2 & \dots & \rho^{T-1} \\ \rho & 1 & \rho & \dots & \rho^{T-2} \\ . & . & . & \dots & . \\ \rho^{T-1} & \rho^{T-2} & \rho^{T-3} & \dots & 1 \end{bmatrix}
$$

This is a symmetric matrix.

This is a variance-covariance matrix characterized by two parameters which fits into the GLS framework.

Consider the LS estimator $\hat{\beta}$ under the assumption of an $AR(1)$ process for the u_t's:

1. What are the properties of $\hat{\beta}$?

2. What is the associated variance estimate?

In the LS method, $V(\hat{\beta})$ is estimated by $s^2(X'X)^{-1}$. *Is this correct in the AR case?*

Under the assumption of an $AR(1)$ error process, $V(\hat{\beta})$ should be $(\sigma^2/1-\rho^2))(X'X)^{-1}X'VX(X'X)^{-1}$.

with V representing the variance-covariance matrix above.

If X variables are trending up and $\rho > 0$ (usually ≈ 0.8 or 0.9), the s^2 will probably underestimate $\sigma^2/(1-\rho^2)$ and $(X'X)^{-1}X'VX(X'X)^{-1}$.

Point: We can seriously understate standard errors if we ignore autocorrelation.

"SPURIOUS REGRESSIONS IN ECONOMETRICS":

(Granger-Newbold)

(Journal of Econometrics, 1974)

Consider a simple regression model.

Let $y_t = \alpha + \beta x_t + \varepsilon_t$.

Suppose the true process with ε and ε^*independent are

$y_t = \rho y_{t-1} + \varepsilon_t$ and

$x_t = \rho^* x_{t-1} + \varepsilon_t^*$

The data are really independent $AR(1)$ processes.

Suppose we regress y on x. Then if $T = 20$ and $\rho = \rho^* = 0.9$, then $ER^2 = 0.47$ and $F \approx 18$.

This falsely indicated a significant contribution of x.

Sampling experiments for $y_t = \alpha + \beta x_t + \varepsilon_t$ with $T = 50$ and y, x independent random walks were carried out, and t-statistics on β in 100 trials were calculated.

If these statistics were actually distributed as t, we would expect t to be less than 2, 95 times. We actually observe t to be less than 2, 23 times, and t greater that 2, 77 times. There is spurious significance. The situation only becomes worse with more regressors.

Point: High R^2 does not "balance out" the effects of autocorrelation. Good time-series fits are not to be believed without diagnostic tests.

TESTING FOR AUTOCORRELATION:

The important thing is to look at the residuals.

Definition: The Durbin-Watson statistic ("d" or DW") is

$$d = \frac{\sum_{t=2}^{T}(e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t^2} = \frac{e'Ae}{e'e}$$

where

$$A = \begin{pmatrix} 1 & -1 & 0 & . \\ -1 & 2 & -1 & . \\ 0 & -1 & 2 & . \\ . & . & . & . \end{pmatrix}$$

Which is a $T \times T$ symmetric matrix

In other words, d is the sum of squared successive differences divided by sum of squares.

The Durbin-Watson statistic is probably the most commonly used test for autocorrelation, although the Durbin h-statistic is appropriate in wider circumstances and should usually be calculated as well.

Distribution of d:

Note: We want to calculate the distribution under the hypothesis that $\rho = 0$, i.e. no autocorrelation. Then a surprisingly large value indicated autocorrelation.

Intuition:

$$E(\varepsilon_t - \varepsilon_{t-1})^2 = \sigma^2 + \sigma^2 - 2cov(\varepsilon_t, \varepsilon_{t-1}) = 2\sigma^2$$

Then, why is $Ed \neq 2$?

1. There is one less term in the numerator

2. The use if e rather that ε makes the distribution depends on x.

Note: d is a ratio of quadric forms in normals.

Why isn't it distributed a F?

Durbin-Watson test:

Durbin and Watson give bounds d_L and d_U which are both less than 2.

If $d > d_L$, then reject the null hypothesis of no autocorrelation. This indicated positive autocorrelation.

If $d_L < d < d_U$, then the result is ambiguous.

If the statistic d calculated from the sample is greater than 2, the indication is negative autocorrelation. Then use the bounds of d_L and d_U, and check against $4 - d$.

If $4 - d < d_L$, then reject the null.

If $4 - d > d_U$, then do not reject.

Interpretation of the Durbin-Watson test:

1. This is a test for general autocorrelation, not just for $AR(1)$ processes.

2. This test cannot be used when regressors include lagged values of y, for example,

$$y_t = \alpha + \beta_0 y_{t-1} + \beta_1 x_t + \varepsilon_t.$$

Other tests are available in this case.

Other tests:

1. Wallis test: This is used for quarterly data. The test statistic is

$$d_4 = \frac{\sum_{t=5}^{t}(e_t - e_{t-4})^2}{\sum_{t=1}^{T} e_t^2}.$$

2. Durbin's h test: This is used when there are lagged y's. We regress e_t on e_{t-1}, x_t and as many lagged y's as are included in the regression. Then test (with "t") the coefficient of e_{t-1}. A significant coefficient on e_{t-1} indicates presence of autocorrelation. Note that this test is quite easy to do and it "works" when the Durbin-Watson test doesn't. This is a good test to use.

ESTIMATION WITH AN AR(1) ERROR PROCESS:

Consider $y = X\beta + u$ where $u_t = \rho u_{t-1} + \varepsilon_t$ with $E(u) = 0$ and

$$Euu' = \frac{\sigma^2}{1-\rho^2}\begin{bmatrix} 1 & \rho & \rho^2 & \ldots & \rho^{T-1} \\ \rho & 1 & \rho & \ldots & \rho^{T-2} \\ . & . & . & \ldots & . \\ \rho^{T-1} & \rho^{T-2} & \rho^{T-3} & \ldots & 1 \end{bmatrix} = \frac{\sigma^2}{1-\rho}\Omega.$$

Thus

$$\Omega^{-1} = \frac{1}{1-\rho^2}\begin{bmatrix} 1 & -\rho & .. & . & 0 \\ -\rho & 1+\rho^2 & .. & . & -\rho \\ . & . & .. & . & . \\ -\rho & . & .. & 1+\rho^2 & -\rho \\ 0 & . & .. & -\rho & 1 \end{bmatrix} = P'P$$

which is a "band" matrix. So,

$$P = \frac{1}{\sqrt{1-\rho^2}}\begin{bmatrix} \sqrt{1-\rho^2} & 0 & .. & . & . \\ -\rho & 1 & .. & . & . \\ 0 & -\rho & .. & . & . \\ . & . & .. & . & . \\ . & . & .. & -\rho & 1 \end{bmatrix}.$$

Matrix P will be used to transform the model.

The first transformed observation is

$$\sqrt{1-\rho^2 y_1} = \sum_{h=1}^{K} \beta_h x_{h,1}\sqrt{1-\rho^2} + u_1\sqrt{1-\rho^2},$$

and all others are

$$y_t - \rho y_{t-1} = \sum_{h=1}^{K} \beta_h (x_{h,t} - \rho x_{h,t-1}) + u_t - \rho u_{t-1}.$$

Note that $x_{h,t}$ denotes the t^{th} observation on the h^{th} explanatory variable.

The GLS transformation puts the model back in standard form as expected.

Notes:

1. Given ρ, the estimation is by the LS method. We write the sum of squares as $S(\rho)$. Then minimization with respect to ρ is a simple numerical problem.

2. ML can also be reduced to a one-dimensional maximization problem which is straightforward.

3. Early two-step methods which often dropped the first observation are less satisfactory. Never use the Cochrane-Orcutt (CORC) procedure.

4. The extension to higher-order AR or MA processes is straightforward.

