STAC67: Regression Analysis

Lecture 13

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Review of Lecture 12

Tests and intervals with several predictors

With normal errors, each coefficient is tested and estimated with the t distribution:

$$\frac{\hat{\beta}_k - \beta_k}{s\{\hat{\beta}_k\}} \sim t(n-p), \qquad s^2\{\hat{\beta}_k\} = \text{entry } k \text{ of the diagonal of } MSE\,(\boldsymbol{X}'\boldsymbol{X})^{-1}.$$

The test of $\beta_k = 0$ is about X_k given the other predictors.

At a new point $\boldsymbol{X}_h$, with $s^2\{\hat{Y}_h\} = MSE\,\boldsymbol{X}_h'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}_h$ and $s^2\{\text{pred}\} = MSE + s^2\{\hat{Y}_h\}$:

- mean response $E(Y_h)$: $\hat{Y}_h \pm t(1-\alpha/2;\ n-p)\, s\{\hat{Y}_h\}$;
- new observation $Y_{h(\text{new})}$: $\hat{Y}_h \pm t(1-\alpha/2;\ n-p)\, s\{\text{pred}\}$.

Beware of hidden extrapolation: a large $\boldsymbol{X}_h'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}_h$ signals a point unlike the data, even when each predictor is within its range.

The ANOVA table and the overall F test

Source	SS	df	MS	F^*
Regression	SSR	$p-1$	$MSR = SSR/(p-1)$	MSR/MSE
Error	SSE	$n-p$	$MSE = SSE/(n-p)$	
Total	SST	$n-1$		

$H_0 : \beta_1 = \beta_2 = \cdots = \beta_{p-1} = 0$ against H_a: at least one $\beta_k \neq 0$.

With normal errors, under H_0, $F^* = MSR/MSE \sim F(p-1,\ n-p)$. Reject H_0 at level α when $F^* > F(1-\alpha;\ p-1,\ n-p)$.

⚠ Rejecting says that the predictors, *taken together*, explain some variation. It does not say which ones, nor that the model is good.

The acceleration data

Model $\texttt{acc} = \beta_0 + \beta_1\,\texttt{wt} + \beta_2\,\texttt{hp} + \epsilon$, $n = 390$, $p = 3$:

Source	SS	df	MS	F^*
Regression	1794.7	2	897.3	295.7
Error	1174.3	387	3.034	
Total	2969.0	389		

$F^* = 295.7 > F(0.95;\ 2,\ 387) = 3.02$: we reject H_0. Weight and horsepower together are related to acceleration.

In R: `anova(lm(acc ~ 1, data = autompg), fit2)` compares the model with the model that has no predictor.

R^2, adjusted R^2, and F

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST}, \qquad R^2_a = 1 - \frac{SSE/(n-p)}{SST/(n-1)} = 1 - \frac{n-1}{n-p}\,\frac{SSE}{SST}.$$

R^2 never decreases when a predictor is added, even pure noise; R^2_a charges for each parameter and can decrease. Acceleration data, then with a column of noise added:

$$R^2\text{: } 0.60448 \to 0.60452, \qquad R^2_a\text{: } 0.6024 \to 0.6014.$$

Dividing the numerator and the denominator of F^* by SST:

$$F^* = \frac{SSR/(p-1)}{SSE/(n-p)} = \frac{R^2/(p-1)}{(1-R^2)/(n-p)}: \quad \text{here } \frac{0.6045/2}{(1-0.6045)/387} = 295.7.$$

With one predictor ($p = 2$), $F^* = (t^*)^2 = (n-2)\,R^2/(1-R^2)$.

Reading `summary(fit2)`

```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 18.4695924  0.3265144   56.57   <2e-16 ***
wt           0.0022919  0.0002064   11.10   <2e-16 ***
hp          -0.0932587  0.0045541  -20.48   <2e-16 ***
Residual standard error: 1.742 on 387 degrees of freedom
Multiple R-squared:  0.6045,    Adjusted R-squared:  0.6024
F-statistic: 295.7 on 2 and 387 DF,  p-value: < 2.2e-16
```

- `Estimate`, `Std. Error`: $\hat{\beta}_k$ and $s\{\hat{\beta}_k\}$, the square root of entry k of the diagonal of $MSE\,(\boldsymbol{X}'\boldsymbol{X})^{-1}$.
- `t value` $= \hat{\beta}_k / s\{\hat{\beta}_k\}$, with its p-value from $t(n-p)$.
- `Residual standard error` $= \sqrt{MSE}$, on $n-p$ degrees of freedom.
- The last line is the overall F test, on $p-1$ and $n-p$ degrees of freedom.

Why the F test works

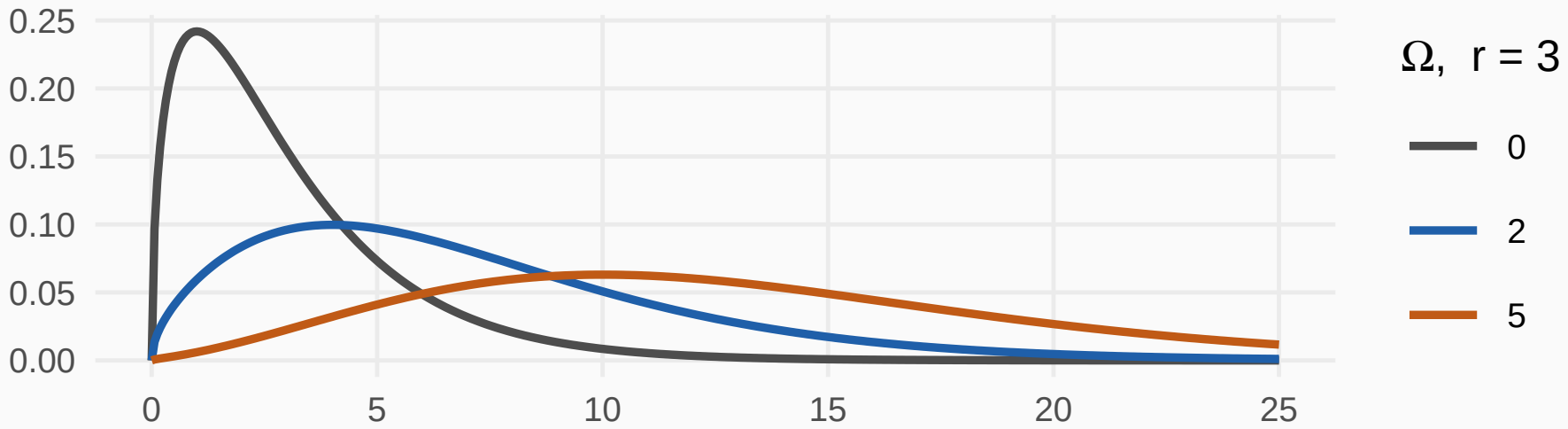
The noncentral χ^2 distribution

Recall: if $Z_1, \ldots, Z_r$ are independent $N(0,1)$, then $\sum_{i=1}^r Z_i^2 \sim \chi^2_r$.

Definition

If $Z_1, \ldots, Z_r$ are independent, with $Z_i \sim N(\mu_i, 1)$, then $W = \sum_{i=1}^r Z_i^2$ has a noncentral χ^2 distribution with r degrees of freedom and noncentrality parameter $\Omega = \frac{1}{2}\sum_{i=1}^r \mu_i^2$.

- If $\Omega = 0$ (all $\mu_i = 0$), it is the usual χ^2_r.
- $E(W) = \sum_i \left(1 + \mu_i^2\right) = r + 2\Omega$: the larger Ω, the further to the right.



Some books, and R's `dchisq(x, df, ncp)`, use $\lambda = \sum_i \mu_i^2 = 2\Omega$.

The distribution of quadratic forms

On Friday, the F distribution of MSR/MSE rested on a result we took for granted. Here it is, stated without proof.

Theorem

Let $\boldsymbol{Z} \sim N(\boldsymbol{\mu},\ \sigma^2\boldsymbol{V})$, with $\boldsymbol{V}$ nonsingular, and let $\boldsymbol{A}$ and $\boldsymbol{B}$ be constant matrices, $\boldsymbol{A}$ symmetric.

1. If $\boldsymbol{AV}$ is idempotent, then $\boldsymbol{Z}'\boldsymbol{AZ}/\sigma^2$ has a noncentral χ^2 distribution (previous slide), with $r(\boldsymbol{A})$ degrees of freedom (the rank of $\boldsymbol{A}$) and noncentrality parameter $\Omega = \boldsymbol{\mu}'\boldsymbol{A}\boldsymbol{\mu}/(2\sigma^2)$. If $\Omega = 0$, it is the usual $\chi^2_{r(\boldsymbol{A})}$.
2. $\boldsymbol{Z}'\boldsymbol{AZ}$ and $\boldsymbol{Z}'\boldsymbol{BZ}$ ($\boldsymbol{B}$ symmetric) are independent if $\boldsymbol{AVB} = \boldsymbol{0}$.
3. $\boldsymbol{Z}'\boldsymbol{AZ}$ and $\boldsymbol{BZ}$ are independent if $\boldsymbol{BVA} = \boldsymbol{0}$.

For the response, $\boldsymbol{Z} = \boldsymbol{Y}$ and $\boldsymbol{V} = \boldsymbol{I}$: the conditions become $\boldsymbol{AA} = \boldsymbol{A}$ and $\boldsymbol{AB} = \boldsymbol{0}$.

Applying it to SSE and SSR

$\boldsymbol{Y} \sim N(\boldsymbol{\mu}, \sigma^2 \boldsymbol{I})$ with $\boldsymbol{\mu} = \boldsymbol{X}\boldsymbol{\beta}$, $SSE = \boldsymbol{Y}'(\boldsymbol{I} - \boldsymbol{H})\boldsymbol{Y}$ and $SSR = \boldsymbol{Y}'(\boldsymbol{H} - \frac{1}{n}\boldsymbol{J})\boldsymbol{Y}$ (Lecture 12).

Applying it to SSE and SSR

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Both matrices are idempotent (Lecture 12), their ranks are their traces, $n - p$ and $p - 1$, and their product is $\mathbf{0}$, since $\boldsymbol{H}\boldsymbol{H} = \boldsymbol{H}$ and $\boldsymbol{J}\boldsymbol{H} = \boldsymbol{J}$:

$$\left(\boldsymbol{H} - \tfrac{1}{n}\boldsymbol{J}\right)(\boldsymbol{I} - \boldsymbol{H}) = \boldsymbol{H} - \boldsymbol{H}\boldsymbol{H} - \tfrac{1}{n}\boldsymbol{J} + \tfrac{1}{n}\boldsymbol{J}\boldsymbol{H} = \mathbf{0}.$$

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$$\left(\boldsymbol{H} - \tfrac{1}{n}\boldsymbol{J}\right)(\boldsymbol{I} - \boldsymbol{H}) = \boldsymbol{H} - \boldsymbol{H}\boldsymbol{H} - \tfrac{1}{n}\boldsymbol{J} + \tfrac{1}{n}\boldsymbol{J}\boldsymbol{H} = \mathbf{0}.$$

- $SSE/\sigma^2 \sim \chi^2_{n-p}$: its Ω is 0, because $(\boldsymbol{I} - \boldsymbol{H})\boldsymbol{X} = \mathbf{0}$.
- SSR/σ^2 is noncentral χ^2 with $p - 1$ degrees of freedom and $\Omega = \sum_i (\mu_i - \bar{\mu})^2/(2\sigma^2)$.
- SSR and SSE are independent (part 2 of the theorem).

The overall F test, justified

Under $H_0 : \beta_1 = \cdots = \beta_{p-1} = 0$, every $\mu_i = \beta_0$, so $\Omega = 0$ and $SSR/\sigma^2 \sim \chi^2_{p-1}$, independent of $SSE/\sigma^2 \sim \chi^2_{n-p}$. Hence

$$F^* = \frac{MSR}{MSE} = \frac{\big(SSR/\sigma^2\big)/(p-1)}{\big(SSE/\sigma^2\big)/(n-p)} \sim F(p-1,\, n-p) \quad \text{under } H_0 :$$

a ratio of two independent χ^2 variables, each divided by its degrees of freedom. σ^2 cancels, so F^* can be computed.

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a ratio of two independent χ^2 variables, each divided by its degrees of freedom. σ^2 cancels, so F^* can be computed.

Under H_a, the μ_i differ and $\Omega > 0$: SSR/σ^2 is pushed to the right, and F^* with it. This is why the test rejects only for large values of F^*, as $E(MSR) \geq \sigma^2$ suggested on Friday.

One linear combination of the coefficients

Estimating $c'\beta$

Many questions are about a linear combination
$\theta = \boldsymbol{c}'\boldsymbol{\beta} = c_0\beta_0 + c_1\beta_1 + \cdots + c_{p-1}\beta_{p-1}$, for a constant vector $\boldsymbol{c}$:

- $\boldsymbol{c} = (0, \ldots, 1, \ldots, 0)'$: a single coefficient β_k;
- $\boldsymbol{c} = \boldsymbol{X}_h$: the mean response at $\boldsymbol{X}_h$ (Lecture 11);
- $\boldsymbol{c} = \boldsymbol{X}_{h_1} - \boldsymbol{X}_{h_2}$: the difference between two mean responses.

Estimating $\boldsymbol{c}'\boldsymbol{\beta}$

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It is estimated by $\hat{\theta} = \boldsymbol{c}'\hat{\boldsymbol{\beta}}$, a linear function of $\hat{\boldsymbol{\beta}}$:

$$E(\hat{\theta}) = \boldsymbol{c}'\boldsymbol{\beta}, \qquad Var(\hat{\theta}) = \boldsymbol{c}'\,\boldsymbol{\sigma^2}\{\hat{\boldsymbol{\beta}}\}\,\boldsymbol{c} = \sigma^2\,\boldsymbol{c}'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{c}.$$

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With normal errors, and $s^2\{\hat{\theta}\} = MSE\,\boldsymbol{c}'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{c}$: $\dfrac{\hat{\theta} - \theta}{s\{\hat{\theta}\}} \sim t(n-p)$.

Hence the interval $\hat{\theta} \pm t(1-\alpha/2;\ n-p)\, s\{\hat{\theta}\}$, and the test of $H_0 : \theta = \theta_0$ with $t^* = (\hat{\theta} - \theta_0)/s\{\hat{\theta}\}$, as before.

Example: two cars

Model $\texttt{acc} = \beta_0 + \beta_1\,\texttt{wt} + \beta_2\,\texttt{hp} + \epsilon$. How much faster, on average, is a car of 3500 lb and 130 hp than one of 3000 lb and 100 hp?

$$\theta = E(Y \mid 3500, 130) - E(Y \mid 3000, 100) = 500\,\beta_1 + 30\,\beta_2, \qquad \boldsymbol{c} = (0, 500, 30)'.$$

Recall that `vcov(fit2)` is $MSE\,(\boldsymbol{X}'\boldsymbol{X})^{-1}$.

```
fit2 <- lm(acc ~ wt + hp, data = autompg)
cc <- c(0, 500, 30)
theta_hat <- sum(cc * coef(fit2))
s_theta <- sqrt(drop(t(cc) %*% vcov(fit2) %*% cc))
c(theta_hat = theta_hat, s_theta = s_theta)
```

```
##   theta_hat     s_theta
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```

```
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```

95% interval: $-1.65 \pm 1.966 \times 0.070 = (-1.79,\ -1.51)$ s. The heavier but more powerful car reaches 60 mph 1.5 to 1.8 s sooner on average.

The general linear hypothesis

Several restrictions at once

A general linear hypothesis imposes q linear restrictions on $\boldsymbol{\beta}$:

$$H_0 : \boldsymbol{K}'\boldsymbol{\beta} = \boldsymbol{m} \qquad \text{against} \qquad H_a : \boldsymbol{K}'\boldsymbol{\beta} \neq \boldsymbol{m},$$

where $\boldsymbol{K}'$ is a constant $q \times p$ matrix of rank q (one row per restriction) and $\boldsymbol{m}$ is a constant $q \times 1$ vector.

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Examples, with $p = 5$ parameters $(\beta_0, \beta_1, \beta_2, \beta_3, \beta_4)$:

- $H_0 : \beta_3 = \beta_4 = 0$: $\boldsymbol{K}' = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \boldsymbol{m} = \boldsymbol{0},\ q = 2.$
- $H_0 : \beta_1 = \beta_2$: $\boldsymbol{K}' = \begin{bmatrix} 0 & 1 & -1 & 0 & 0 \end{bmatrix}, \boldsymbol{m} = 0,\ q = 1.$
- The overall test: $\boldsymbol{K}' = [\,\boldsymbol{0} \mid \boldsymbol{I}_4\,], \boldsymbol{m} = \boldsymbol{0},\ q = p - 1 = 4.$

The F statistic

$\boldsymbol{K}'\hat{\boldsymbol{\beta}}$ is a linear function of $\hat{\boldsymbol{\beta}}$. Under H_0, with normal errors,

$$\boldsymbol{K}'\hat{\boldsymbol{\beta}} - \boldsymbol{m} \sim N\big(\mathbf{0},\ \sigma^2\, \boldsymbol{K}'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{K}\big).$$

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The theorem on quadratic forms, with $\boldsymbol{A}$ the inverse of $\boldsymbol{K}'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{K}$ (so $\boldsymbol{A}\boldsymbol{V} = \boldsymbol{I}$), gives a χ^2_q variable below, independent of SSE since $\hat{\boldsymbol{\beta}}$ is (part 3: $(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}'(\boldsymbol{I} - \boldsymbol{H}) = \boldsymbol{0}$). Hence

$$F^* = \frac{(\boldsymbol{K}'\hat{\boldsymbol{\beta}} - \boldsymbol{m})'\big[\boldsymbol{K}'(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{K}\big]^{-1}(\boldsymbol{K}'\hat{\boldsymbol{\beta}} - \boldsymbol{m})\,/\,q}{MSE} \sim F(q,\, n{-}p) \text{ under } H_0.$$

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Reject H_0 at level α when $F^* > F(1-\alpha;\ q,\ n-p)$.

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Reject H_0 at level α when $F^* > F(1-\alpha;\ q,\ n-p)$.

With one restriction ($q = 1$), F^* is the square of the t^* of the previous section.

In R: do displacement and cylinders matter?

Full model: `acc ~ wt + hp + disp + cyl`. $H_0 : \beta_{\text{disp}} = \beta_{\text{cyl}} = 0$, so $q = 2$.

Since `vcov(full)` is $MSE\,(\boldsymbol{X}'\boldsymbol{X})^{-1}$, the numerator and MSE combine:

```
full <- lm(acc ~ wt + hp + disp + cyl, data = autompg)
Kt <- rbind(c(0, 0, 0, 1, 0),
            c(0, 0, 0, 0, 1))
d <- Kt %*% coef(full)              # here m = 0
V <- Kt %*% vcov(full) %*% t(Kt)
F_star <- drop(t(d) %*% solve(V) %*% d) / 2
c(F_star, 1 - pf(F_star, 2, 385))
```

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## [1] 7.6362147397 0.0005594001
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```

$F^* = 7.64 > F(0.95;\, 2,\, 385) = 3.02$: reject H_0. Once weight and horsepower are in the model, displacement and cylinders together still explain some variation in acceleration.

Summary: testing coefficients

H_0	Statistic	Under H_0
$\boldsymbol{c}'\boldsymbol{\beta} = \theta_0$ (one combination)	$t^* = (\boldsymbol{c}'\hat{\boldsymbol{\beta}} - \theta_0)/s\{\boldsymbol{c}'\hat{\boldsymbol{\beta}}\}$	$t(n-p)$
$\boldsymbol{K}'\boldsymbol{\beta} = \boldsymbol{m}$ (q restrictions)	F^* from $\boldsymbol{K}'\hat{\boldsymbol{\beta}} - \boldsymbol{m}$	$F(q,\, n-p)$

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Next: the same test from two fits (extra sums of squares), then multicollinearity: why a predictor can matter jointly but not on its own.