

Introduction to survival analysis

Jorge N. Tendeiro

Department of Psychometrics and Statistics
Faculty of Behavioral and Social Sciences
University of Groningen

✉ j.n.tendeiro@rug.nl

🌐 www.jorgetendeiro.com

🔗 [jorgetendeiro/Seminar-2020-Survival-Analysis](#)

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Plan for today

Gentle introduction to survival analysis.

Main source:

Harrell, F. E., Jr. (2015). *Regression Modeling Strategies*, 2nd edition.
Springer

Chapters:

17, 18, and 20.

Survival analysis (SA)

Data:

For which the *time until the event* is of interest.

- ▶ This goes beyond *logistic regression*, which focuses on the *occurrence* of the event.

Outcome variable:

- ▶ T = Time until the event.
- ▶ Often referred to as *survival time*, *failure time*, or *event time*.

Examples

Survival time: Time until...

- ▶ death, disease, relapse.

Failure time: Time until...

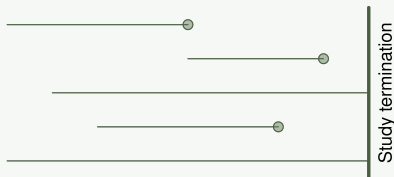
- ▶ product malfunction.

Event time: Time until...

- ▶ graduation, marriage, divorce.

Advantages of SA over typical regression models

- ▶ SA allows modeling units that did not fail up to data collection (*censored on the right* data).



- ▶ Regression could be considered to model the expected survival time. *But:*
- ▶ Survival time is often not normally distributed.
- ▶ $P(\text{survival} > t)$ is often more interesting than $\mathbb{E}(\text{survival time})$.

Censoring

Some subjects:

- ▶ Did not experiment the event up to the end of data collection;
- ▶ Withdrew from study;
- ▶ Were lost to follow-up.

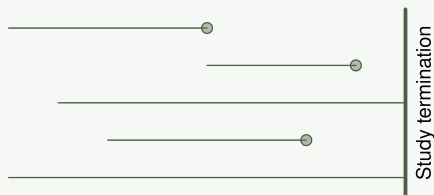
These data are right-censored.

Define random variables for the i th subject:

- ▶ T_i = time to event
- ▶ C_i = censoring time
- ▶ e_i = event indicator = $\begin{cases} 1 & \text{if event is observed } (T_i \leq C_i) \\ 0 & \text{if event is not observed } (T_i > C_i) \end{cases}$
- ▶ $Y_i = \min(T_i, C_i)$ = what occurred first (failure or censoring)

Variables $\{Y_i, e_i\}$ include all the necessary information.

Typical data set



T_i	C_i	Y_i	e_i
5	10	5	1
4	12	4	1
13+	13	13	0
5	10	5	1
15+	15	15	0

Observe the flexibility of SA data:

- Subjects may join the study at different moments.
- Censoring times may differ among subjects.

$\{Y_i, e_i\}$ does include all the necessary information.

But, *assumption*: Censoring is non-informative, i.e., it is independent of the risk of the event.

Three main functions

T = time until event.

- Survival function:

$$S(t) = P(T > t) = 1 - F(t),$$

where $F = P(T \leq t)$ is distribution function of T .

- Cumulative hazard function:

$$\Lambda(t) = -\log(S(t))$$

- Hazard function:

$$\lambda(t) = \Lambda'(t)$$

Survival function

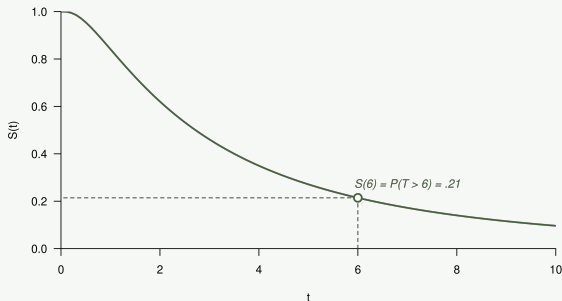
$$S(t) = P(T > t) = 1 - F(t)$$

Example:

If event = death, then $S(t)$ = prob. death occurs after time t .

Properties:

- ▶ $S(0) = 1, S(\infty) = 0$.
- ▶ Non-increasing function of t .



Cumulative hazard function

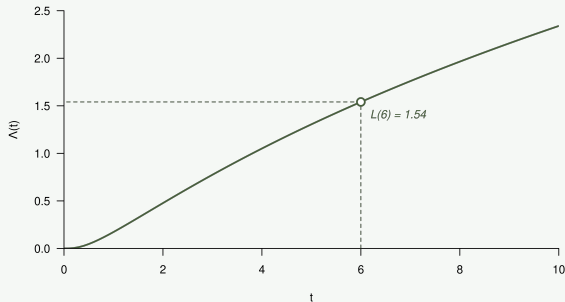
$$\Lambda(t) = -\log(S(t))$$

Idea:

Accumulated risk up until time t .

Properties:

- $\Lambda(0) = 0$.
- Non-decreasing function of t .

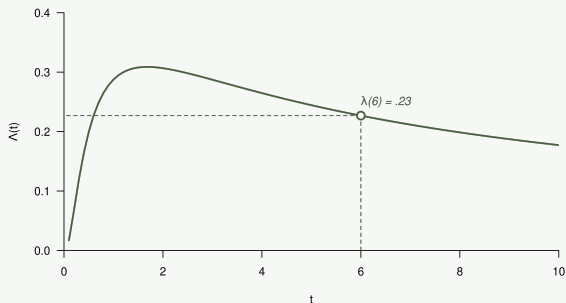


Hazard function

$$\lambda(t) = \Lambda'(t)$$

Idea:

Instantaneous event rate at time t .



Relation between the three functions

All functions are related:

Any two functions can be derived from the third function.

- ▶ The three functions are equivalent ways of describing the same random variable (T = time until event).

More generally, all the following functions give mathematically equivalent specifications of the distribution of T :

- ▶ $F(t)$: Distribution function
- ▶ $f(t)$: Density function
- ▶ $S(t)$: Survival function
- ▶ $\lambda(t)$: Hazard function
- ▶ $\Lambda(t)$: Cumulative hazard function.

Examples

Next are two primary examples of parametric survival distributions:

- ▶ the exponential distribution;
- ▶ the Weibull distribution.

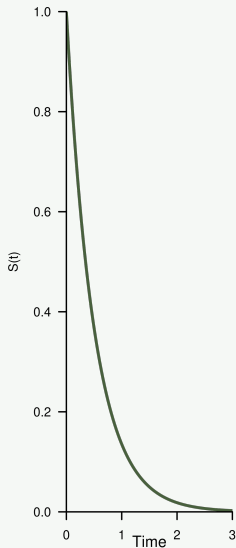
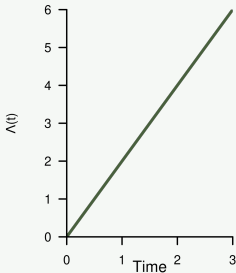
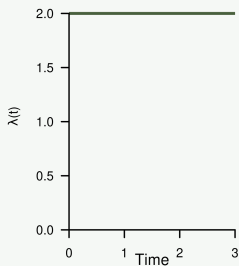
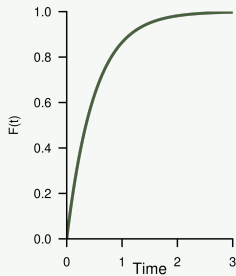
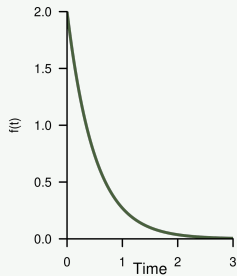
These models (still) include **no** covariates, thus:

- ▶ Each subject in the sample is assumed to have the same distribution of T .

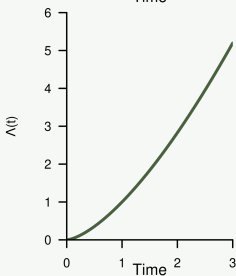
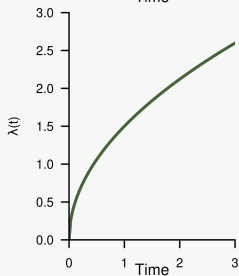
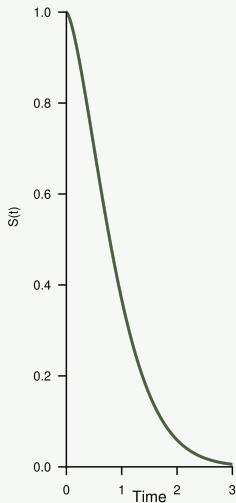
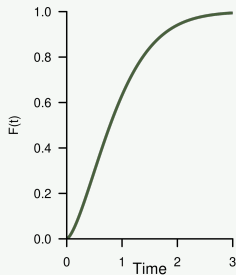
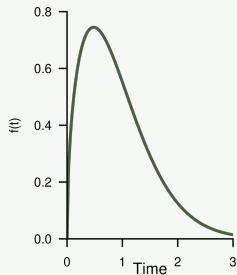
No formulas for now.

Instead: Let's plot.

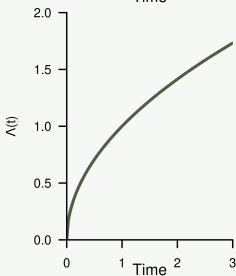
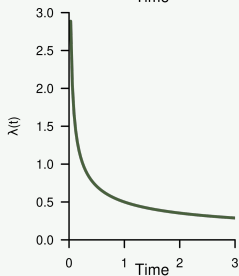
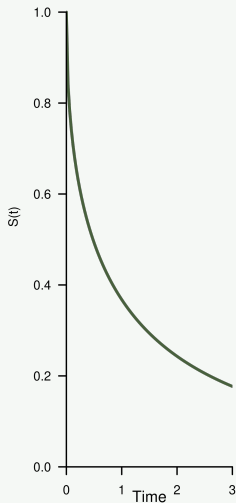
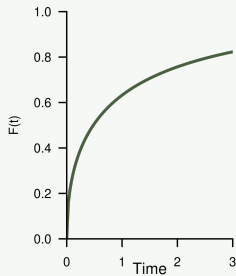
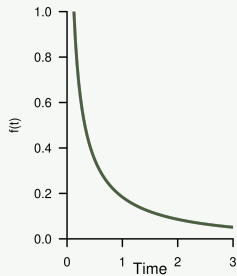
Exponential survival distribution



Weibull survival distribution (I)



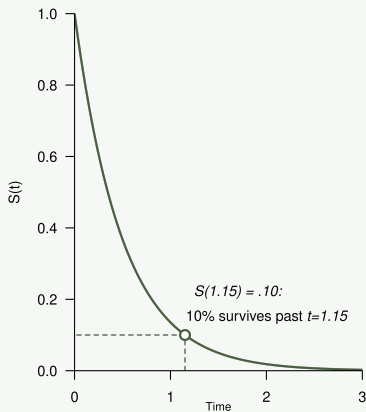
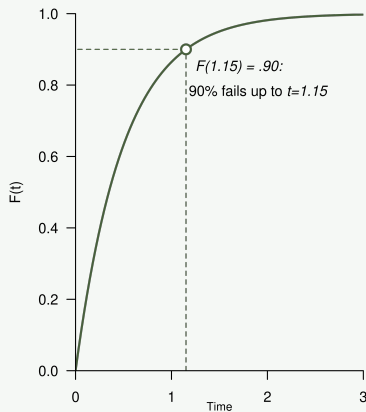
Weibull survival distribution (II)



Quantiles

Q: What is the time by which $(100q)\%$ of the population will fail?

A: Value t_q such that $F(t_q) = q$, or, equiv., $S(t_q) = 1 - q$.



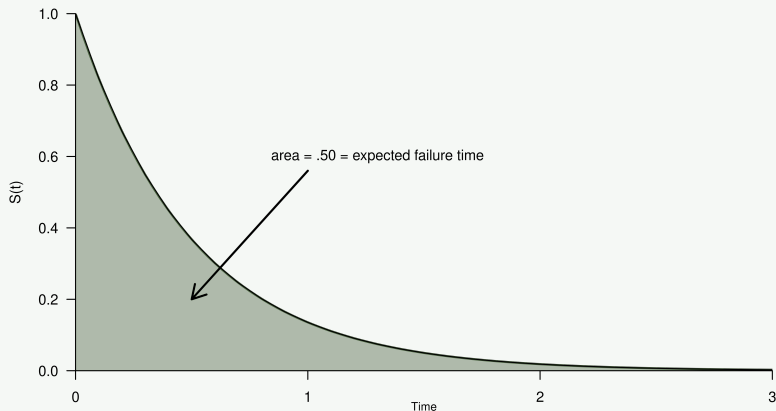
In particular, median survival time = $t_{.50}$.

Expected failure time

(Note: T is skewed, so the mean is not the best summary. Better use median.)

Q: What is the expected failure time?

A: It is the area under the survival function.



Various estimation approaches

There are several options available to estimate the survival function (and friends).

Here we will briefly go through only a few:

- ▶ Not parametric and homogeneous (i.e., without predictors):
 - ▶ Kaplan-Meier estimator
 - ▶ Altschuler-Nelson estimator
- ▶ Parametric:
 - ▶ Homogeneous (i.e., no predictors): Exponential, Weibull, normal, logistic, log-normal, log-logistic,...
 - ▶ Proportional hazards models
- ▶ Semi-parametric:
 - ▶ Cox proportional hazards regression model

After a brief intro to each, I will use them all on an empirical dataset.

Kaplan-Meier estimator

- ▶ Also known as the *product-limit* estimator.
- ▶ Non parametric, and super simple to do even manually.
- ▶ Key ingredient: *Conditional probabilities*.

Assume $t = 0, 1, 2, \dots$

We have that $S(0) = P(T > 0) = 1$. For $t \geq 1$ we then have that

$$P(T > t | T > t - 1) = \frac{P(T > t, T > t - 1)}{P(T > t - 1)} = \frac{P(T > t)}{P(T > t - 1)}$$

and so

$$P(T > t) = P(T > t - 1) \times P(T > t | T > t - 1),$$

or in terms of the survival function,

$$S(t) = S(t - 1) \times P(T > t | T > t - 1)$$

$$\boxed{S(t) = S(t - 1) \times (1 - P(T \leq t | T > t - 1))}$$

Kaplan-Meier estimator – Example

Data: Seven subjects; failure times $T = 1, 3, 3, 3+, 6+, 9, 10+$.

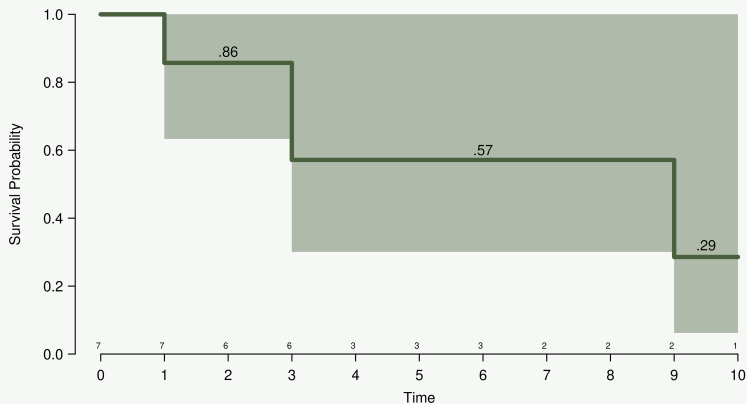
Day	No. subjects at risk	Deaths	Censored	$S(t) = S(t-1) \times$ $\times (1 - P(T \leq t T > t-1))$
1	7	1	0	$1 \times (1 - 1/7) = 6/7$
3	$7 - (1 + 0) = 6$	2	1	$6/7 \times (1 - 2/6) = 4/7$
6	$6 - (2 + 1) = 3$	0	1	$4/7 \times (1 - 0/3) = 4/7$
9	$3 - (0 + 1) = 2$	1	0	$4/7 \times (1 - 1/2) = 2/7$
10	$2 - (1 + 0) = 1$	0	1	$2/7 \times (1 - 0/1) = 2/7$

Hence:

$$S(t) = \begin{cases} 1, & 0 \leq t < 1 \\ 6/7 = .86, & 1 \leq t < 3 \\ 4/7 = .57, & 3 \leq t < 9 \\ 2/7 = .29, & 9 \leq t < 10 \\ \text{undefined}^*, & t \geq 10 \end{cases}.$$

*Not everyone failed by $t = 10$, so we cannot tell what happened after that.

Kaplan-Meier estimator – Example



Altschuler-Nelson estimator

- ▶ Non parametric, also simple.
- ▶ Similar to Kaplan-Meier, but based on $\Lambda(t)$.

Recall that $\Lambda(t)$ = accumulated risk up until time t .

Hence it makes sense to estimate $\Lambda(t)$ by

$$\hat{\Lambda}(t) = \sum_{i:t_i \leq t} \frac{\# \text{ failures at } t_i}{\# \text{ subjects at risk at } t_i}.$$

Then,

$$\hat{S}(t) = \exp(-\hat{\Lambda}(t)).$$

Interesting property: $\sum_i \hat{\Lambda}(Y_i) = \text{total number of events}$.

Altschuler-Nelson estimator – Example

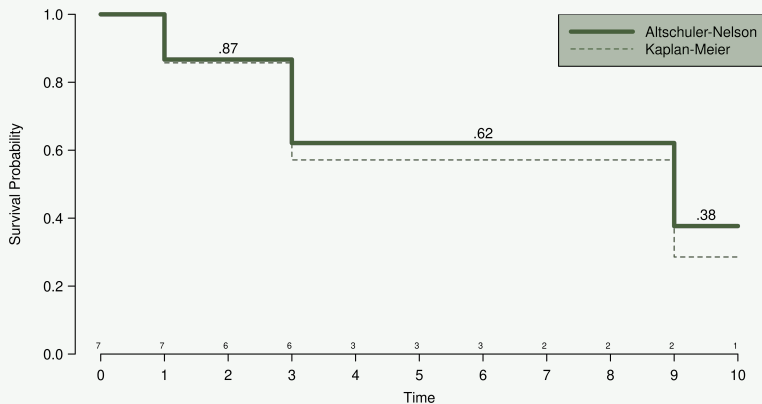
Data: Seven subjects; failure times $T = 1, 3, 3, 3+, 6+, 9, 10+$.

Day	No. subjects at risk	Deaths	Censored	$\Lambda(t)$
1	7	1	0	1/7
3	$7 - (1 + 0) = 6$	2	1	$1/7 + 2/6 = 10/21$
6	$6 - (2 + 1) = 3$	0	1	$10/21 + 0/3 = 10/21$
9	$3 - (0 + 1) = 2$	1	0	$10/21 + 1/2 = 41/42$
10	$2 - (1 + 0) = 1$	0	1	$41/42 + 0/1 = 41/42$
		$\Sigma_i = 4$	$\Sigma_i = 4$	

Hence:

$$S(t) = \exp(-\Lambda(t)) = \begin{cases} \exp(0) = 1, & 0 \leq t < 1 \\ \exp(-1/7) = .87, & 1 \leq t < 3 \\ \exp(-10/21) = .62, & 3 \leq t < 9 \\ \exp(-41/42) = .38, & 9 \leq t < 10 \\ \text{undefined}, & t \geq 10 \end{cases}.$$

Altschuler-Nelson estimator – Example



Homogeneous parametric models

Q: How about *continuous*, parametric, counterparts to KM and AN?
Still incorporating no predictors?

A: There are really *a lot* of possibilities.

Most common examples:

- ▶ Exponential
- ▶ Weibull
- ▶ Normal
- ▶ Logistic
- ▶ Log-normal
- ▶ Log-logistic
- ▶ ...

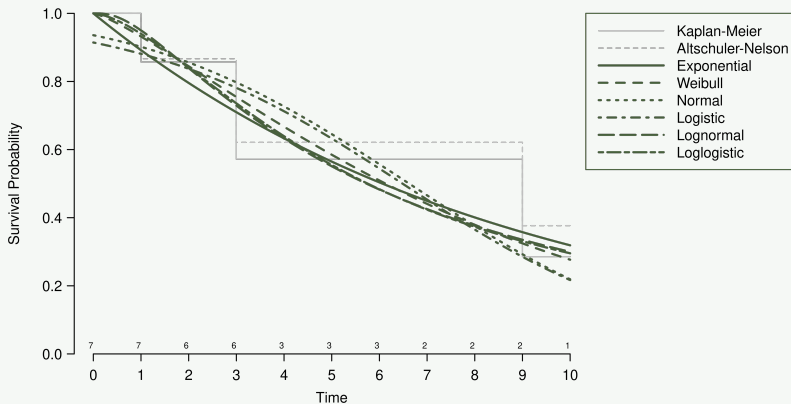
My advice:

Just fit several of these and compare.

There is no 'best' model, it depends on the data.

Homogeneous parametric models

Data: $T = 1, 3, 3, 3+, 6+, 9, 10+$.



Assessing model fit

I like Harrell's take on this:

- ▶ To assess model fit, use graphical methods.
- ▶ No significance tests at this point, great!
- ▶ But there are some test options, see e.g. Chapter 20.

We show an example:

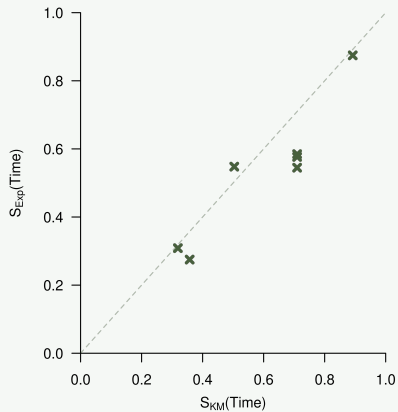
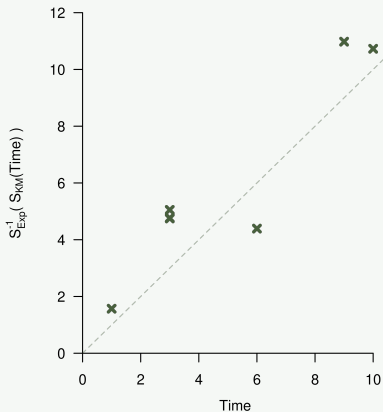
Assess the fit of the exponential model.

Two plotting options, akin to QQ-plots:

- ▶ Plot $S_{\text{Exp}}^{-1}(S_{\text{KM}}(T))$ versus T ;
- ▶ Plot $S_{\text{Exp}}(T)$ versus $S_{\text{KM}}(T)$.

Assessing model fit

Data: $T = 1, 3, 3, 3+, 6+, 9, 10+$.



Parametric proportional hazards model

First model until now that allows incorporating predictor variables

$$X = \{X_1, X_2, \dots, X_k\}.$$

- X_i can be continuous, dichotomous, polytomous, etc.

The proportional hazards (PH) model generalizes the hazard function $\lambda(t)$:

$$\lambda(t|X) = \lambda(t) \overbrace{\exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_x X_k)}^{\text{relative hazard function}} = \lambda(t) \exp(X\beta)$$

- $\lambda(t|X)$ = hazard function for T given the predictors X .
- $\lambda(t)$ = 'underlying' hazard function (for a subject with $X\beta = 0$).
- $\exp(X\beta)$ describes the *relative* effects of the predictors.

Note: The intercept β_0 may be omitted (kind of 'absorbed' into $\lambda(t)$).

Parametric proportional hazards model

$$\lambda(t|X) = \lambda(t) \exp(X\beta)$$

Here are the ‘friends’:

$$\Lambda(t|X) = \Lambda(t) \exp(X\beta)$$

$$S(t|X) = S(t)^{\exp(X\beta)}$$

- ▶ $\Lambda(t)$ = ‘underlying’ cumulative hazard function (for a subject with $X\beta = 0$).
- ▶ $S(t)$ = ‘underlying’ survival function (for a subject with $X\beta = 0$).

Parametric proportional hazards model

It is easier to consider the log-model versions:

$$\log \lambda(t|X) = \log \lambda(t) + X\beta$$

$$\log \Lambda(t|X) = \log \Lambda(t) + X\beta$$

$$\log S(t|X) = \underbrace{\log S(t)}_{\text{time}} \times \underbrace{\exp(X\beta)}_{\text{predictors}}$$

- Observe that we separated the **time** and the **predictors** components.

Important consequence due to the separability of t and X :

- The effect of X is assumed to be the same at all values of t .
- I.e.: We assume no $t \times X$ interaction effect.

Parametric proportional hazards model

How to interpret regression coefficient β_j ($j = 1, \dots, k$)?

$$\begin{aligned}\log \lambda(t|X) &= \log \lambda(t) + (\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_x X_k) \\ \log \Lambda(t|X) &= \underbrace{\log \Lambda(t)}_{\text{time}} + \underbrace{(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_x X_k)}_{\text{predictors}}\end{aligned}$$

- Additive interpretation:
- $\log \lambda(t|X)$ increases by β_j units when X_j increases by 1 unit at any time point t , holding all the other predictors constant:

$$\log \lambda(t | \dots, X_j + 1, \dots) = \log \lambda(t | \dots, X_j, \dots) + \beta_j.$$

- Same for $\log \lambda(t|X)$.

Parametric proportional hazards model

How to interpret regression coefficient β_j ($j = 1, \dots, k$)?

$$\begin{aligned}\lambda(t|X) &= \lambda(t) \times \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_x X_k) \\ \Lambda(t|X) &= \Lambda(t) \times \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_x X_k) \\ \log S(t|X) &= \underbrace{\log S(t)}_{\text{time}} \times \underbrace{\exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_x X_k)}_{\text{predictors}}\end{aligned}$$

- Multiplicative interpretation:
- $\lambda(t|X)$ is multiplied by $\exp(\beta_j)$ units when X_j increases by 1 unit at any time point t , holding all the other predictors constant:

$$\frac{\lambda(t|\dots, X_j + 1, \dots)}{\underbrace{\lambda(t|\dots, X_j, \dots)}_{\text{hazard ratio}}} = \exp(\beta_j).$$

- Same for $\Lambda(t|X)$.
- Same for $\log S(t|X)$.

Hazard ratio

$$\text{HR} = \frac{\lambda(t|\dots, X_j+1, \dots)}{\lambda(t|\dots, X_j, \dots)}$$

- ▶ $HR = 1$: No effect, i.e., X_j is unrelated to $P(\text{event})$.
- ▶ $HR < 1$: Hazard reduction, i.e., X_j is negatively associated with $P(\text{event})$. Larger survival time.
- ▶ $HR > 1$: Hazard increase, i.e., X_j is positively associated with $P(\text{event})$. Smaller survival time.

Proportional hazards assumption

The hazards ratio for any two subjects is independent of time:

$$\frac{\lambda(t|X_{Sub1})}{\lambda(t|X_{Sub2})} = \underbrace{\exp [\beta(X_{Sub1} - X_{Sub2})]}_{\text{no } t \text{ here!}}$$

In particular:

- The hazard curves for different groups (e.g., sex groups) should be proportional and thus cannot cross.

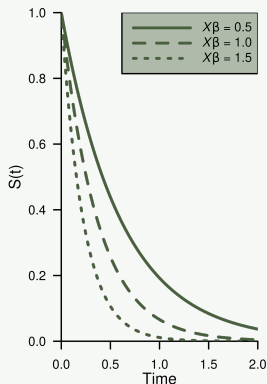
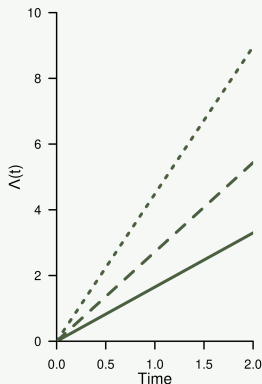
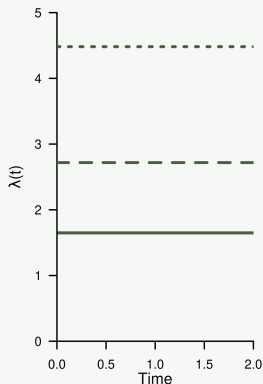
Example: Exponential PH survival model

$$X\beta = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_x X_k.$$

$$\lambda(t|X) = \exp(X\beta)$$

$$\Lambda(t|X) = t \exp(X\beta)$$

$$S(t|X) = \exp(-t)^{\exp(X\beta)}$$



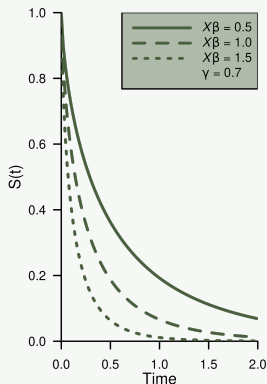
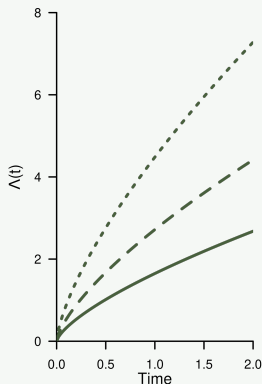
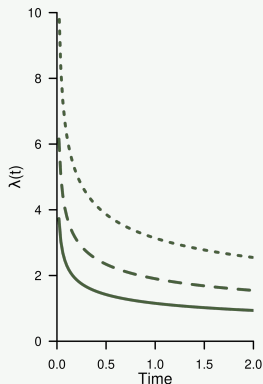
Example: Weibull PH survival model

$$X\beta = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_x X_k.$$

$$\lambda(t|X) = \gamma t^{\gamma-1} \exp(X\beta)$$

$$\Lambda(t|X) = t^\gamma \exp(X\beta)$$

$$S(t|X) = \exp(-t^\gamma \exp(X\beta))$$



Cox proportional hazards model

Seemingly the most popular survival model used.

The Cox PH model:

$$\lambda(t|X) = \lambda(t) \exp(X\beta)$$

- Looks the same as the general PH model!
- But, it is **semiparametric**:
- It makes a parametric assumption in $X\beta = \beta_1 X_1 + \dots + \beta_x X_k$.
(NB: No intercept is typical for the Cox PH model.)
- But, it assumes **no parametric model** for the hazard function $\lambda(t)$.
Actually, it won't even be estimated!

Rationale:

- The true hazard function $\lambda(t)$ may be too complex.
- The effect of the predictors is more relevant than the shape of $\lambda(t)$.

The Cox PH model allows bypassing $\lambda(t)$.

Cox proportional hazards model

But how does this *magic* work?

- Use the rank ordering of T .

Advantages:

- Better protection against outliers.
- The Cox PH model is more efficient than parametric PH models when parametric assumptions are strongly violated.
- Surprisingly, the Cox PH model is as efficient as parametric PH models even when parametric assumptions hold.

Final worked out example

I will use the *lung* dataset from the *survival* package in R.

- ▶ The data concern survival in patients with advanced lung cancer.
- ▶ These data have been analyzed *ad nauseam*, e.g.:
 - ▶ Tutorial 1
 - ▶ Tutorial 2
 - ▶ Tutorial 3
- ▶ Using Bayesian statistics and Stan!

I will just run some basics.

Want something else to play afterwards?

- ▶ Check other datasets in the *survival* R package, it has plenty (e.g., *ovarian*, *veteran*).
- ▶ Bayesian analysis on **mastectomy data** (*HSAUR* R package)
- ▶ **Recidivism** data (*carData* R package)
- ▶ ...

Lung data

Time and censoring

$Y_i = \text{time}$	$e_i = \text{status}$
306	2
455	2
1010	1
210	2
883	2
1022	1
\vdots	\vdots

Predictors

<i>age</i>	<i>sex</i>	<i>ph.ecog</i>	<i>ph.karno</i>	<i>wt.loss</i>
74	1	1	90	NA
68	1	0	90	15
56	1	0	90	15
57	1	1	90	11
60	1	0	100	0
74	1	1	50	0
\vdots	\vdots	\vdots	\vdots	\vdots

► *time*: Survival time in days

► *status*: Censoring
(1=censored, 2=dead)

► *age*: Age in years

► *sex*: Male=1, Female=2

► *ph.ecog*: ECOG performance score
(0=good, ..., 5=dead)

► *ph.karno*: 0-100 performance score (physician)

► *wt.loss*: Weight loss in last 6 months

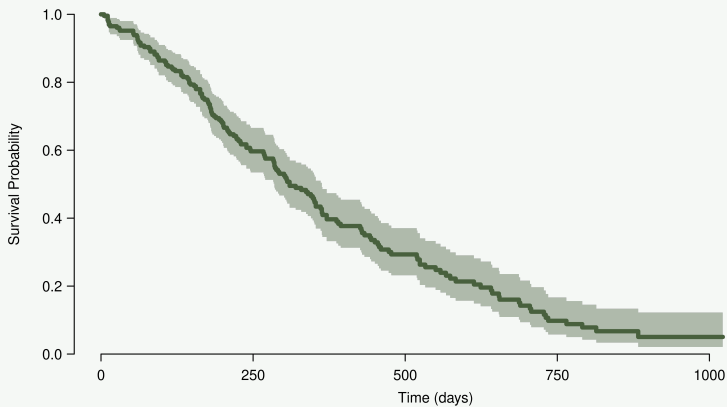
In R

There are loads of packages and options to go about:

- ▶ *rms*
- ▶ *survival*
- ▶ *survminer*
- ▶ ...

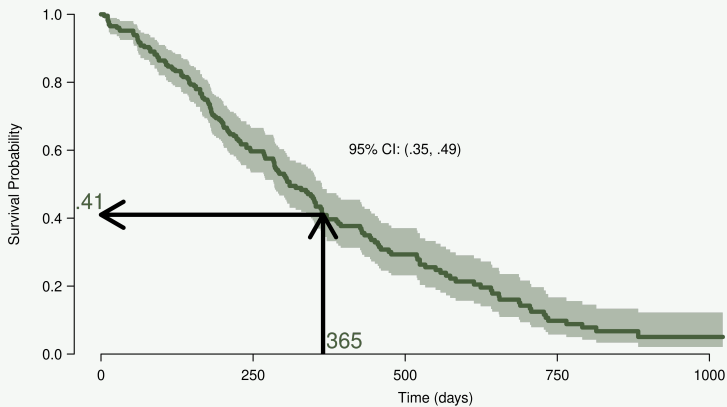
I'll use functions from various packages depending on functionality and eye-candyness.

Lung data: Kaplan-Meier



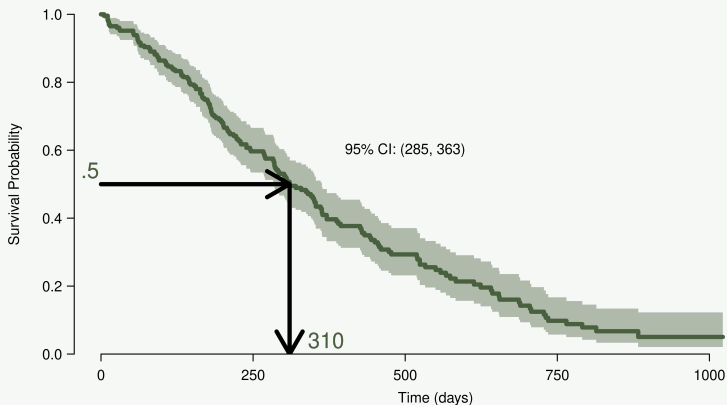
Lung data: Kaplan-Meier

What is $P(t > 365 \text{ days})$?



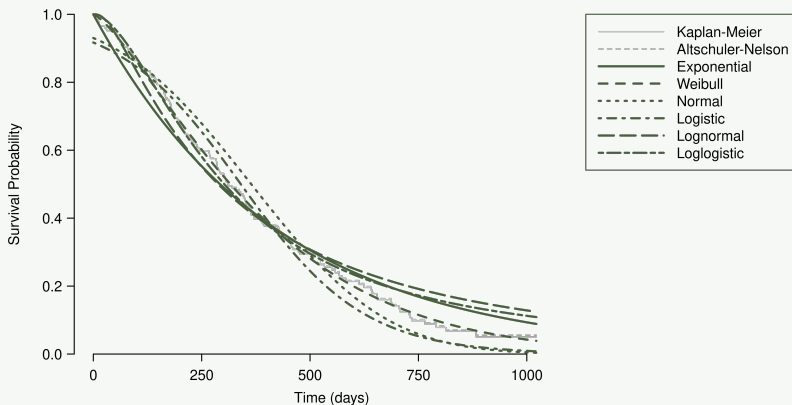
Lung data: Kaplan-Meier

What is the average (median) survival time?



Lung data: Homogeneous parametric models

With no predictors.



Lung data: Cox regression

First we regress T on sex.

term	estimate	std.error	statistic	p.value	conf.low	conf.high
sex	-0.53	0.17	-3.18	0	-0.86	-0.2

Hence

$$\lambda(t|\text{sex}) = \lambda(t) \exp(-.53\text{sex})$$

and

$$\text{hazard ratio} = \frac{\lambda(t|\text{sex} = 2)}{\lambda(t|\text{sex} = 1)} = \frac{\lambda(t|\text{Female})}{\lambda(t|\text{Male})} = \exp(-.53) \simeq .59.$$

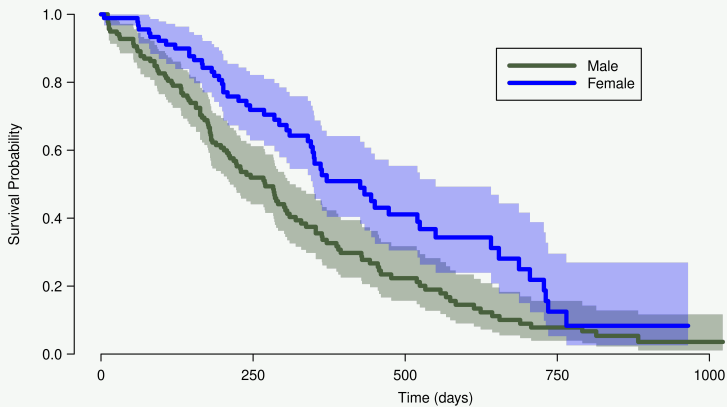
(Multiplicative) Interpretation:

- .59 times as many females are dying as males, at any time t .

or, equivalently,

- Being female reduces the hazard by $(1 - .59)100\% = 41\%$.

Lung data: Cox regression



Lung data: Cox regression

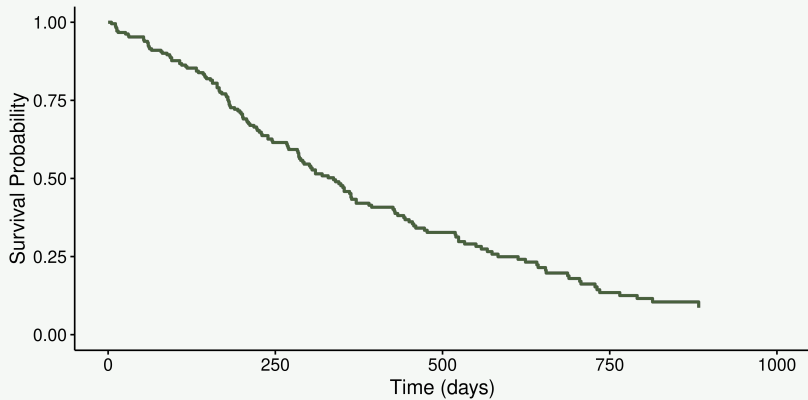
Adding more predictors.

term	estimate	std.error	statistic	p.value	conf.low	conf.high
sex	-0.63	0.18	-3.56	0.00	-0.98	-0.28
age	0.02	0.01	1.55	0.12	0.00	0.03
ph.ecog	0.74	0.19	3.87	0.00	0.37	1.12
ph.karno	0.02	0.01	1.56	0.12	0.00	0.03
wt.loss	-0.01	0.01	-1.39	0.17	-0.02	0.00

Holding the other predictors constant, ...

- ▶ $HR_{\text{sex}} = \exp(-.63) = .53$:
...being female *reduces* the hazard rate by a factor of .53 (47%), at any time t .
- ▶ $HR_{\text{age}} = \exp(.02) = 1.02$:
...each extra year *increases* the hazard rate by a factor of 1.02 (2%), at any time t .
- ▶ ...

Lung data: Cox regression



Conclusion

Survival analysis offers a plethora of statistical models suitable to analyze 'time to event' data.

Much more is to be said on this topic. For instance:

- ▶ More on assumption checking
(a lot of plotting options are available, also a few tests...).
- ▶ More plotting possibilities.
- ▶ Model comparison.
- ▶ Bayesian survival analysis!
- ▶ Accelerated failure time models.
- ▶ More complex models.
- ▶ ...