bit.ly/fable2022

Tidy Time Series & Forecasting in R

10. Forecast reconciliation

Outline

Outline

1. Hierarchical and grouped time series
2. Forecast reconciliation
3. Example: Australian tourism
4. Lab Session 20

Australian Pharmaceutical Benefits Scheme

PBS sales

```
PBS
```

```
## # A tsibble: 67,596 x 9 [1M]
## # Key:       Concession, Type, ATC1, ATC2 [336]
##       Month Concession   Type  ATC1  ATC1_~1 ATC2  ATC2_~2 Scripts  Cost
##       <mth> <chr>        <chr> <chr> <chr>   <chr> <chr>     <dbl> <dbl>
##  1 1991 Jul Concession~ Co-p~ A     Alimen~ A01   STOMAT~   18228 67877
##  2 1991 Aug Concession~ Co-p~ A     Alimen~ A01   STOMAT~   15327 57011
##  3 1991 Sep Concession~ Co-p~ A     Alimen~ A01   STOMAT~   14775 55020
##  4 1991 Oct Concession~ Co-p~ A     Alimen~ A01   STOMAT~   15380 57222
##  5 1991 Nov Concession~ Co-p~ A     Alimen~ A01   STOMAT~   14371 52120
##  6 1991 Dec Concession~ Co-p~ A     Alimen~ A01   STOMAT~   15028 54299
##  7 1992 Jan Concession~ Co-p~ A     Alimen~ A01   STOMAT~   11040 39753
##  8 1992 Feb Concession~ Co-p~ A     Alimen~ A01   STOMAT~   15165 54405
##  9 1992 Mar Concession~ Co-p~ A     Alimen~ A01   STOMAT~   16898 61108
## 10 1992 Apr Concession~ Co-p~ A     Alimen~ A01   STOMAT~   18141 65356
## # ... with 67,586 more rows, and abbreviated variable names
## #   1: ATC1_desc, 2: ATC2_desc
```

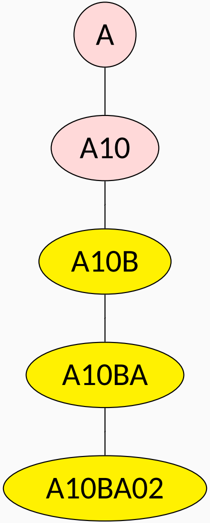
ATC drug classification

A	Alimentary tract and metabolism
B	Blood and blood forming organs
C	Cardiovascular system
D	Dermatologicals
G	Genito-urinary system and sex hormones
H	Systemic hormonal preparations, excluding sex hormones and insulins
J	Anti-infectives for systemic use
L	Antineoplastic and immunomodulating agents
M	Musculo-skeletal system
N	Nervous system
P	Antiparasitic products, insecticides and repellents
R	Respiratory system
S	Sensory organs

ATC drug classification

ATC1: 14 classes

ATC2: 84 classes



Alimentary tract and metabolism

Drugs used in diabetes

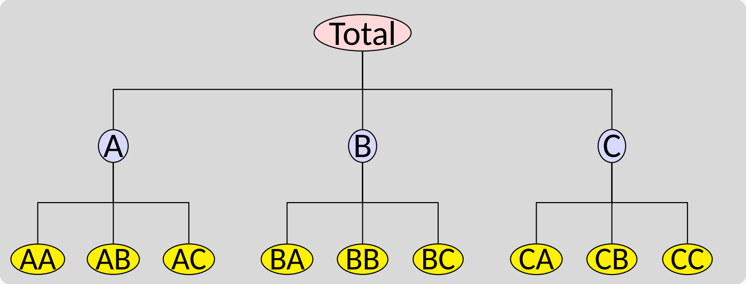
Blood glucose lowering drugs

Biguanides

Metformin

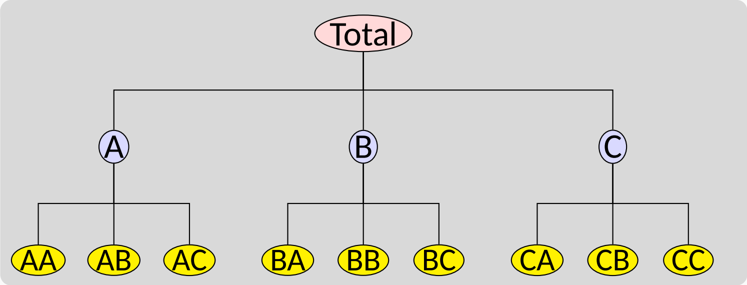
Hierarchical time series

A **hierarchical time series** is a collection of several time series that are linked together in a hierarchical structure.



Hierarchical time series

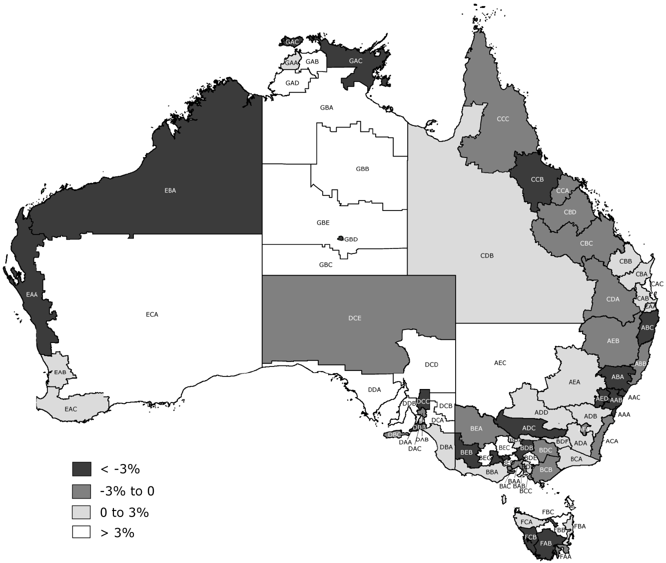
A **hierarchical time series** is a collection of several time series that are linked together in a hierarchical structure.



Examples

- PBS sales by ATC groups
- Tourism demand by states, zones, regions

Australian tourism



Australian tourism

```
tourism
```

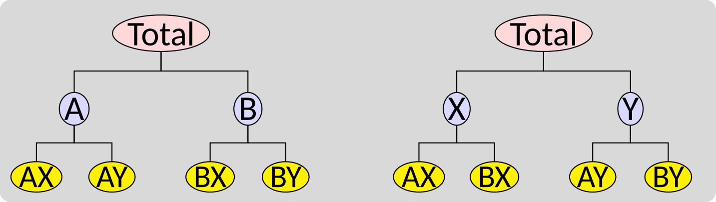
```
## # A tsibble: 24,320 x 5 [1Q]
## # Key:       Region, State, Purpose [304]
##    Quarter Region   State           Purpose  Trips
##      <qtr> <chr>    <chr>           <chr>    <dbl>
##  1 1998 Q1 Adelaide South Australia Business  135.
##  2 1998 Q2 Adelaide South Australia Business  110.
##  3 1998 Q3 Adelaide South Australia Business  166.
##  4 1998 Q4 Adelaide South Australia Business  127.
##  5 1999 Q1 Adelaide South Australia Business  137.
##  6 1999 Q2 Adelaide South Australia Business  200.
##  7 1999 Q3 Adelaide South Australia Business  169.
##  8 1999 Q4 Adelaide South Australia Business  134.
##  9 2000 Q1 Adelaide South Australia Business  154.
```

Australian tourism

- Quarterly data on visitor night from 1998:Q1 – 2013:Q4
- From: *National Visitor Survey*, based on annual interviews of 120,000 Australians aged 15+, collected by Tourism Research Australia.
- Split by 7 states, 27 zones and 76 regions (a geographical hierarchy)
- Also split by purpose of travel
  - Holiday
  - Visiting friends and relatives (VFR)
  - Business
  - Other
- 204 bottom-level series

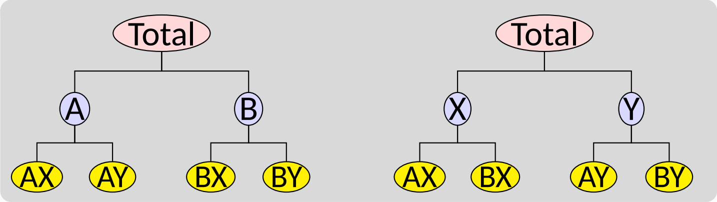
Grouped time series

A **grouped time series** is a collection of time series that can be grouped together in a number of non-hierarchical ways.



Grouped time series

A **grouped time series** is a collection of time series that can be grouped together in a number of non-hierarchical ways.



Examples

- Tourism by state and purpose of travel
- Retail sales by product groups/sub groups, and by countries/regions

Creating aggregates

```
PBS %>%
  aggregate_key(ATC1 / ATC2, Scripts = sum(Scripts)) %>%
  filter(Month == yearmonth("1991 Jul")) %>%
  print(n = 18)
```

```
## # A tsibble: 98 x 4 [1M]
## # Key:       ATC1, ATC2 [98]
##       Month ATC1         ATC2         Scripts
##       <mth> <chr*>       <chr*>         <dbl>
##  1 1991 Jul <aggregated> <aggregated> 8090395
##  2 1991 Jul A            <aggregated>  799025
##  3 1991 Jul B            <aggregated>  109227
##  4 1991 Jul C            <aggregated> 1794995
##  5 1991 Jul D            <aggregated>  299779
##  6 1991 Jul G            <aggregated>  300931
##  7 1991 Jul H            <aggregated>  112114
##  8 1991 Jul J            <aggregated> 1151681
##  9 1991 Jul L            <aggregated>   24580
## 10 1991 Jul M            <aggregated>  562956
## 11 1991 Jul N            <aggregated> 1546023
## 12 1991 Jul P            <aggregated>   47661
## 13 1991 Jul R            <aggregated>  859273
## 14 1991 Jul S            <aggregated>  391639
```

Creating aggregates

```
tourism %>%
  aggregate_key(Purpose * (State / Region), Trips = sum(Trips)) %>%
  filter(Quarter == yearquarter("1998 Q1")) %>%
  print(n = 15)
```

```
## # A tsibble: 425 x 5 [1Q]
## # Key:       Purpose, State, Region [425]
##    Quarter Purpose      State              Region       Trips
##      <qtr> <chr*>       <chr*>             <chr*>       <dbl>
##  1 1998 Q1 <aggregated> <aggregated>       <aggregat~ 23182.
##  2 1998 Q1 Business     <aggregated>       <aggregat~  3599.
##  3 1998 Q1 Holiday      <aggregated>       <aggregat~ 11806.
##  4 1998 Q1 Other        <aggregated>       <aggregat~   680.
##  5 1998 Q1 Visiting     <aggregated>       <aggregat~  7098.
##  6 1998 Q1 <aggregated> ACT                <aggregat~   551.
##  7 1998 Q1 <aggregated> New South Wales    <aggregat~  8040.
##  8 1998 Q1 <aggregated> Northern Territory <aggregat~   181.
##  9 1998 Q1 <aggregated> Queensland         <aggregat~  4041.
## 10 1998 Q1 <aggregated> South Australia    <aggregat~  1735.
## 11 1998 Q1 <aggregated> Tasmania           <aggregat~   982.
## 12 1998 Q1 <aggregated> Victoria           <aggregat~  6010.
```

Creating aggregates

- Similar to `summarise()` but using the key structure
- A grouped structure is specified using `grp1 * grp2`
- A nested structure is specified via `parent / child`.
- Groups and nesting can be mixed:

```
(country/region/city) * (brand/product)
```

- All possible aggregates are produced.
- These are useful when forecasting at different levels of aggregation.

Outline

The problem

1. How to forecast time series at all nodes such that the forecasts add up in the same way as the original data?
2. Can we exploit relationships between the series to improve the forecasts?

The problem

1. How to forecast time series at all nodes such that the forecasts add up in the same way as the original data?
2. Can we exploit relationships between the series to improve the forecasts?

The solution

1. Forecast all series at all levels of aggregation using an automatic forecasting algorithm.
   (e.g., `ETS`, `ARIMA`, ...)
2. Reconcile the resulting forecasts so they add up correctly using least squares optimization (i.e., find closest reconciled forecasts to the original forecasts).
3. This is available using `reconcile()`.

Forecast reconciliation

```
tourism %>%
  aggregate_key(Purpose * (State / Region), Trips = sum(Trips)) %>%
  model(ets = ETS(Trips)) %>%
  reconcile(ets_adjusted = min_trace(ets)) %>%
  forecast(h = 2)
```

```
## # A fable: 1,700 x 7 [1Q]
## # Key:     Purpose, State, Region, .model [850]
##    Purpose  State           Region        .model    Quarter
##    <chr*>   <chr*>          <chr*>        <chr>       <qtr>
##  1 Business ACT             Canberra      ets       2018 Q1
##  2 Business ACT             Canberra      ets       2018 Q2
##  3 Business ACT             Canberra      ets_adju~ 2018 Q1
##  4 Business ACT             Canberra      ets_adju~ 2018 Q2
##  5 Business ACT             <aggregated>  ets       2018 Q1
##  6 Business ACT             <aggregated>  ets       2018 Q2
##  7 Business ACT             <aggregated>  ets_adju~ 2018 Q1
##  8 Business ACT             <aggregated>  ets_adju~ 2018 Q2
```

Hierarchical and grouped time series

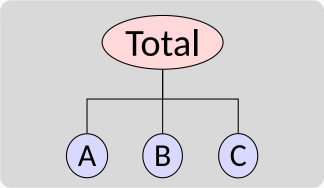
Every collection of time series with aggregation constraints can be written as

$$\boldsymbol{y}_t = \boldsymbol{S}\boldsymbol{b}_t$$

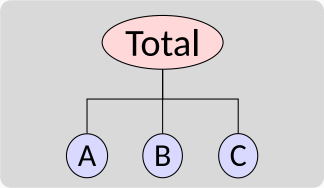
where

- $\boldsymbol{y}_t$ is a vector of all series at time t
- $\boldsymbol{b}_t$ is a vector of the most disaggregated series at time t
- $\boldsymbol{S}$ is a “summing matrix’ ’ containing the aggregation constraints.

Hierarchical time series



Hierarchical time series

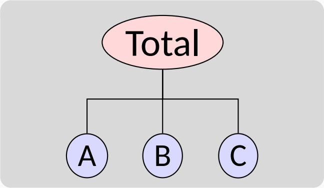


y_t : observed aggregate of all series at time t.

$y_{X,t}$: observation on series X at time t.

$\boldsymbol{b}_t$: vector of all series at bottom level in time t.

Hierarchical time series



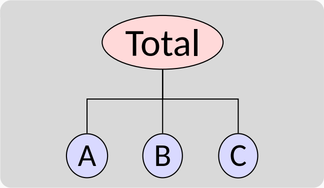
y_t : observed aggregate of all series at time t.

$y_{X,t}$: observation on series X at time t.

$\boldsymbol{b}_t$: vector of all series at bottom level in time t.

$$\boldsymbol{y}_t = \begin{pmatrix} y_t \\ y_{A,t} \\ y_{B,t} \\ y_{C,t} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} y_{A,t} \\ y_{B,t} \\ y_{C,t} \end{pmatrix}$$

Hierarchical time series



y_t : observed aggregate of all series at time t.

$y_{X,t}$: observation on series X at time t.

$\boldsymbol{b}_t$: vector of all series at bottom level in time t.

$$\boldsymbol{y}_t = \begin{pmatrix} y_t \\ y_{A,t} \\ y_{B,t} \\ y_{C,t} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\boldsymbol{S}} \underbrace{\begin{pmatrix} y_{A,t} \\ y_{B,t} \\ y_{C,t} \end{pmatrix}}_{\boldsymbol{b}_t}$$

$$\boldsymbol{y}_t = \boldsymbol{S}\boldsymbol{b}_t$$

Forecasting notation

Let $\hat{\boldsymbol{y}}_n(h)$ be vector of initial h-step forecasts, made at time n, stacked in same order as $\boldsymbol{y}_t$.

Forecasting notation

Let $\hat{\boldsymbol{y}}_n(h)$ be vector of initial h-step forecasts, made at time n, stacked in same order as $\boldsymbol{y}_t$.
(In general, they will not "add up".)

Forecasting notation

Let $\hat{\boldsymbol{y}}_n(h)$ be vector of initial h-step forecasts, made at time n, stacked in same order as $\boldsymbol{y}_t$.
(In general, they will not "add up".)

Reconciled forecasts must be of the form:

$$\tilde{\boldsymbol{y}}_n(h) = \boldsymbol{S}\boldsymbol{G}\hat{\boldsymbol{y}}_n(h)$$

for some matrix $\boldsymbol{G}$.

Forecasting notation

Let $\hat{\boldsymbol{y}}_n(h)$ be vector of initial h-step forecasts, made at time n, stacked in same order as $\boldsymbol{y}_t$.
(In general, they will not "add up".)

Reconciled forecasts must be of the form:

$$\tilde{\boldsymbol{y}}_n(h) = \boldsymbol{S}\boldsymbol{G}\hat{\boldsymbol{y}}_n(h)$$

for some matrix $\boldsymbol{G}$.

- $\boldsymbol{G}$ extracts and combines base forecasts $\hat{\boldsymbol{y}}_n(h)$ to get bottom-level forecasts.
- $\boldsymbol{S}$ adds them up

Optimal combination forecasts

Main result

The best (minimum sum of variances) unbiased forecasts are obtained when $\boldsymbol{G} = (\boldsymbol{S}'\Sigma_h^{-1}\boldsymbol{S})^{-1}\boldsymbol{S}'\Sigma_h^{-1}$, where Σ_h is the h-step base forecast error covariance matrix.

Optimal combination forecasts

Main result

The best (minimum sum of variances) unbiased forecasts are obtained when $\boldsymbol{G} = (\boldsymbol{S}'\Sigma_h^{-1}\boldsymbol{S})^{-1}\boldsymbol{S}'\Sigma_h^{-1}$, where Σ_h is the h-step base forecast error covariance matrix.

$$\tilde{\boldsymbol{y}}_n(h) = \boldsymbol{S}(\boldsymbol{S}'\Sigma_h^{-1}\boldsymbol{S})^{-1}\boldsymbol{S}'\Sigma_h^{-1}\hat{\boldsymbol{y}}_n(h)$$

Problem: Σ_h hard to estimate, especially for $h > 1$.

Solutions:

- Ignore Σ_h (OLS) [`min_trace(method='ols')`]
- Assume $\Sigma_h = k_h\Sigma_1$ is diagonal (WLS) [`min_trace(method='wls')`]
- Assume $\Sigma_h = k_h\Sigma_1$ and estimate it (GLS)

Features

- Covariates can be included in initial forecasts.
- Adjustments can be made to initial forecasts at any level.
- Very simple and flexible method. Can work with *any* hierarchical or grouped time series.
- Conceptually easy to implement: regression of base forecasts on structure matrix.

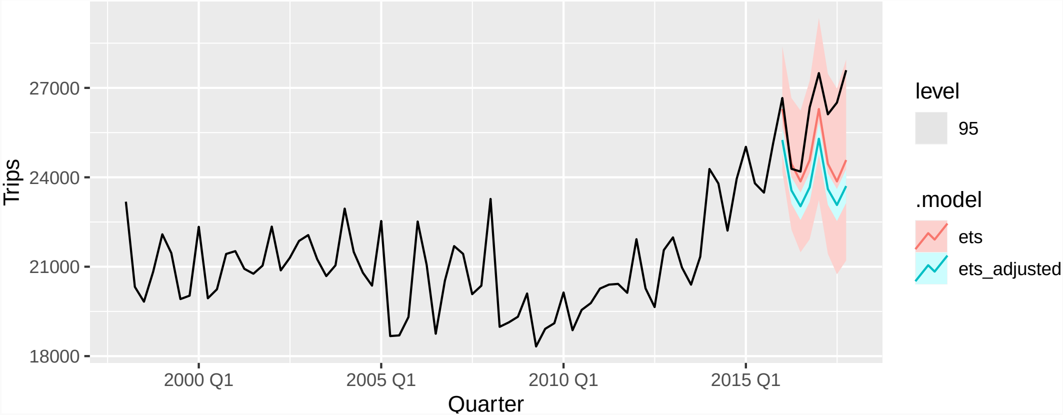
Outline

Example: Australian tourism

```r
tourism_agg <- tourism %>%
  aggregate_key(Purpose * (State / Region),
    Trips = sum(Trips)
  )
fc <- tourism_agg %>%
  filter_index(. ~ "2015 Q4") %>%
  model(ets = ETS(Trips)) %>%
  reconcile(ets_adjusted = min_trace(ets)) %>%
  forecast(h = "2 years")
```

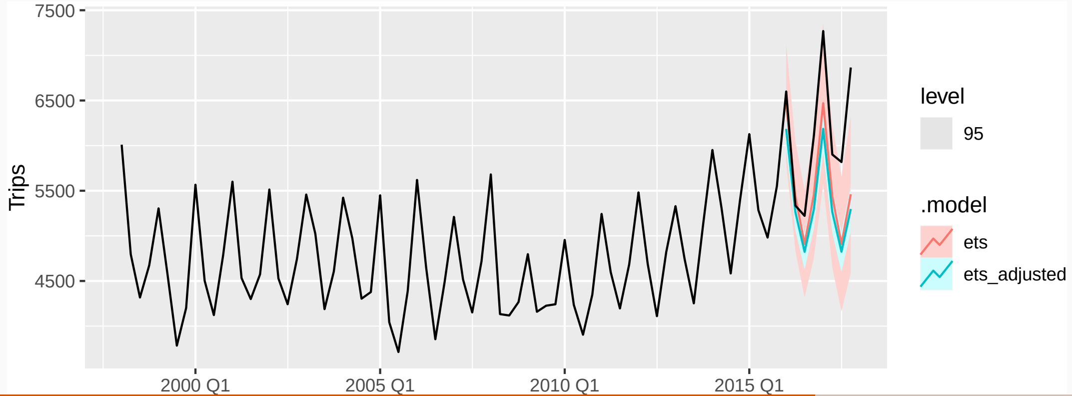
Example: Australian tourism

```
fc %>%
  filter(is_aggregated(Purpose) & is_aggregated(State)) %>%
  autoplot(tourism_agg, level = 95)
```



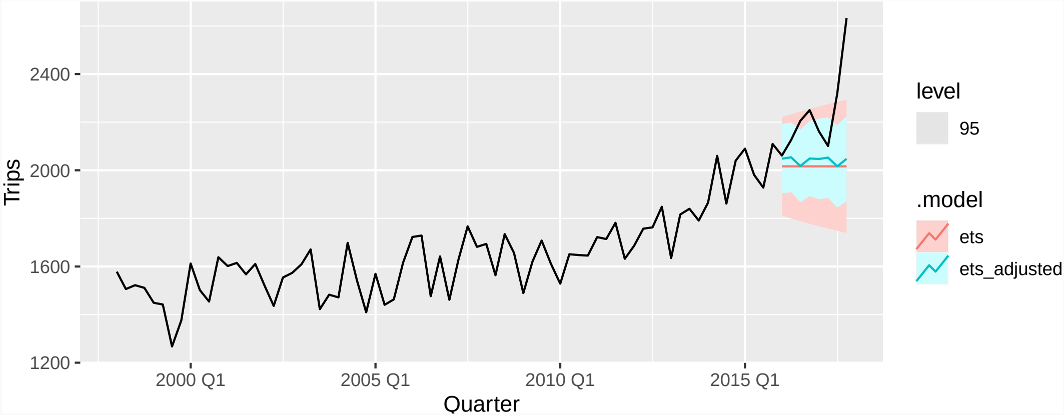
Example: Australian tourism

```
fc %>%
  filter(is_aggregated(Purpose) & State == "Victoria" &
    is_aggregated(Region)) %>%
  autoplot(tourism_agg, level = 95)
```



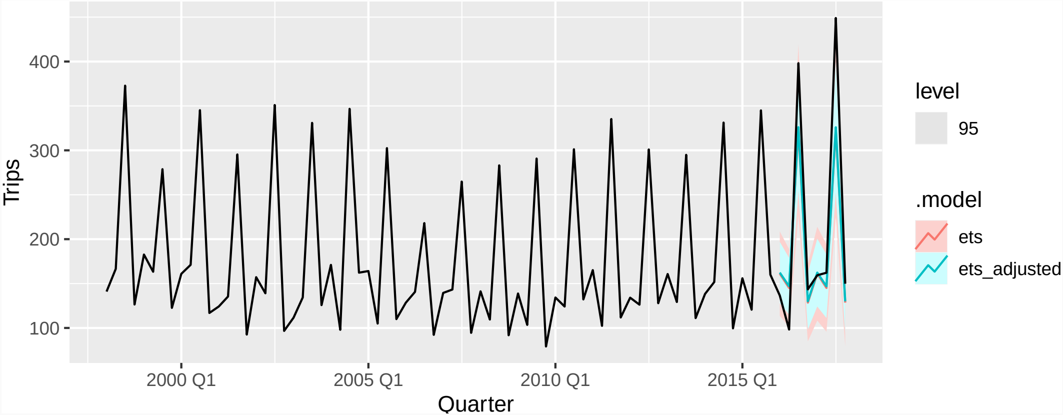
Example: Australian tourism

```
fc %>%
  filter(is_aggregated(Purpose) & Region == "Melbourne") %>%
  autoplot(tourism_agg, level = 95)
```



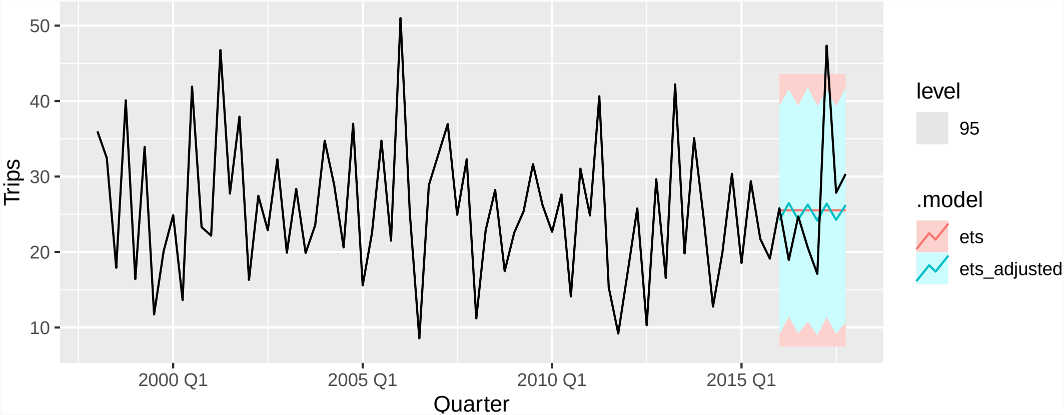
Example: Australian tourism

```
fc %>%
  filter(is_aggregated(Purpose) & Region == "Snowy Mountains") %>%
  autoplot(tourism_agg, level = 95)
```



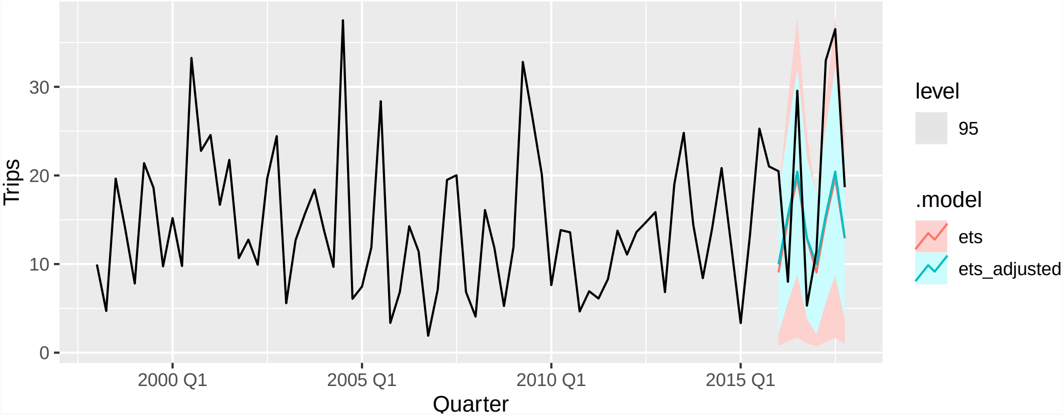
Example: Australian tourism

```
fc %>%
  filter(Purpose == "Holiday" & Region == "Barossa") %>%
  autoplot(tourism_agg, level = 95)
```



Example: Australian tourism

```r
fc %>%
  filter(is_aggregated(Purpose) & Region == "MacDonnell") %>%
  autoplot(tourism_agg, level = 95)
```



Example: Australian tourism

```
fc <- tourism_agg %>%
  filter_index(. ~ "2015 Q4") %>%
  model(
    ets = ETS(Trips),
    arima = ARIMA(Trips)
  ) %>%
  mutate(
    comb = (ets + arima) / 2
  ) %>%
  reconcile(
    ets_adj = min_trace(ets),
    arima_adj = min_trace(arima),
    comb_adj = min_trace(comb)
  ) %>%
  forecast(h = "2 years")
```

Forecast evaluation

```
fc %>% accuracy(tourism_agg)
```

```
## # A tibble: 2,550 x 13
##    .model Purpose  State          Region      .type    ME  RMSE
##    <chr>  <chr*>   <chr*>         <chr*>      <chr> <dbl> <dbl>
##  1 arima  Business ACT          ~ Canberra ~ Test  35.9   45.7
##  2 arima  Business ACT          ~ <aggregat~ Test  35.9   45.7
##  3 arima  Business New South W~ Blue Moun~ Test   1.93  10.6
##  4 arima  Business New South W~ Capital C~ Test   8.08  15.6
##  5 arima  Business New South W~ Central C~ Test  10.0   14.5
##  6 arima  Business New South W~ Central N~ Test  17.7   31.9
##  7 arima  Business New South W~ Hunter   ~ Test  35.3   43.9
##  8 arima  Business New South W~ New Engla~ Test  23.1   31.8
##  9 arima  Business New South W~ North Coa~ Test  24.8   40.1
## 10 arima  Business New South W~ Outback N~ Test   6.87  11.0
## # ... with 2,540 more rows, and 6 more variables:
```

Forecast evaluation

```
fc %>%
  accuracy(tourism_agg) %>%
  group_by(.model) %>%
  summarise(MASE = mean(MASE)) %>%
  arrange(MASE)
```

```
## # A tibble: 6 x 2
##   .model      MASE
##   <chr>      <dbl>
## 1 ets_adj     1.02
## 2 comb_adj    1.02
## 3 ets         1.04
## 4 comb        1.04
## 5 arima_adj   1.07
## 6 arima       1.09
```

Outline

Lab Session 20

- Prepare aggregations of the PBS data by Concession, Type, and ATC1.
- Use forecast reconciliation with the PBS data, using ETS, ARIMA and SNAIVE models, applied to all but the last 3 years of data.
- Which type of model works best?
- Does the reconciliation improve the forecast accuracy?
- Why doesn’t the reconcililation make any difference to the SNAIVE forecasts?

Survey

rstd.io/ws-survey