

## **KULI software supported adaption of vehicle thermal management road tests for wind tunnel usage**

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# Introduction and Outline

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## **Introduction**

Development process | Driving cycles | Why change?

02

## **Trailer towing and mountain pass driving**

Difference of road testing and wind tunnel | Possibilities to adapt driving cycle

03

## **Variation of boundary conditions**

KULI model | Wind speed | Driving resistance

04

## **What else?**

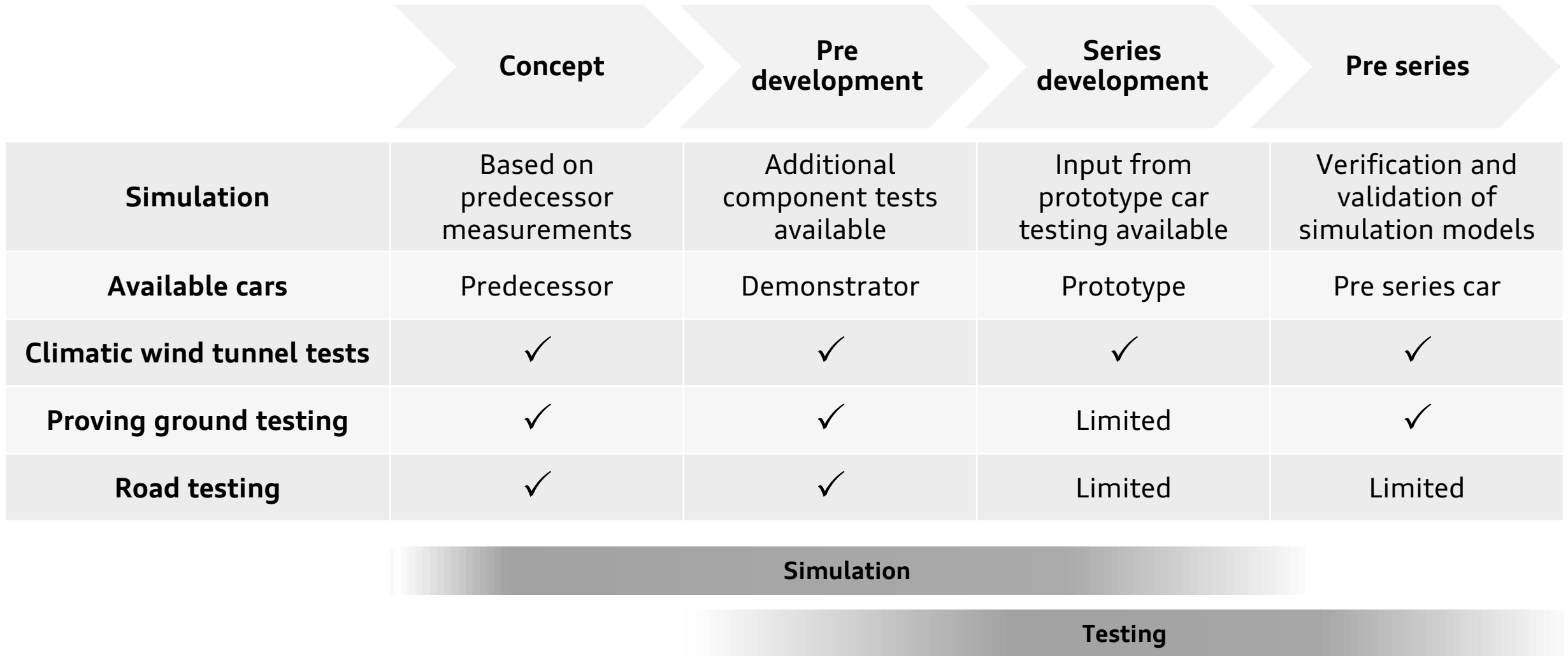
Why we still need testing and other possibilities to reduce road testing?

05

## **Conclusion**

# Development process

- › Simplified development process of a cooling system for car



## Common critical operating points of a cars cooling system for combustion engines and hybrid powertrains

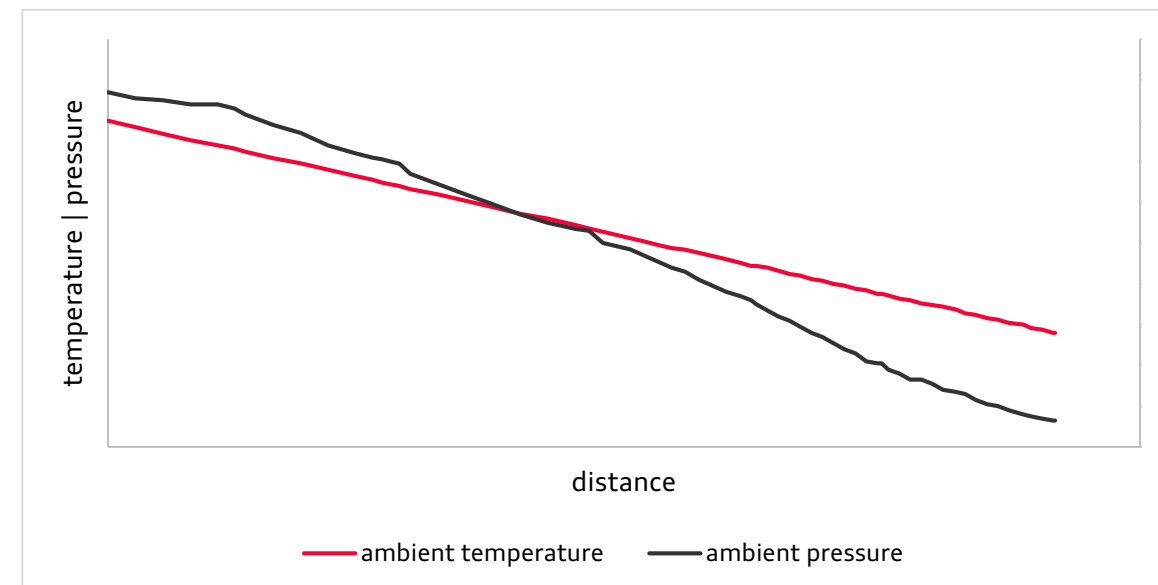
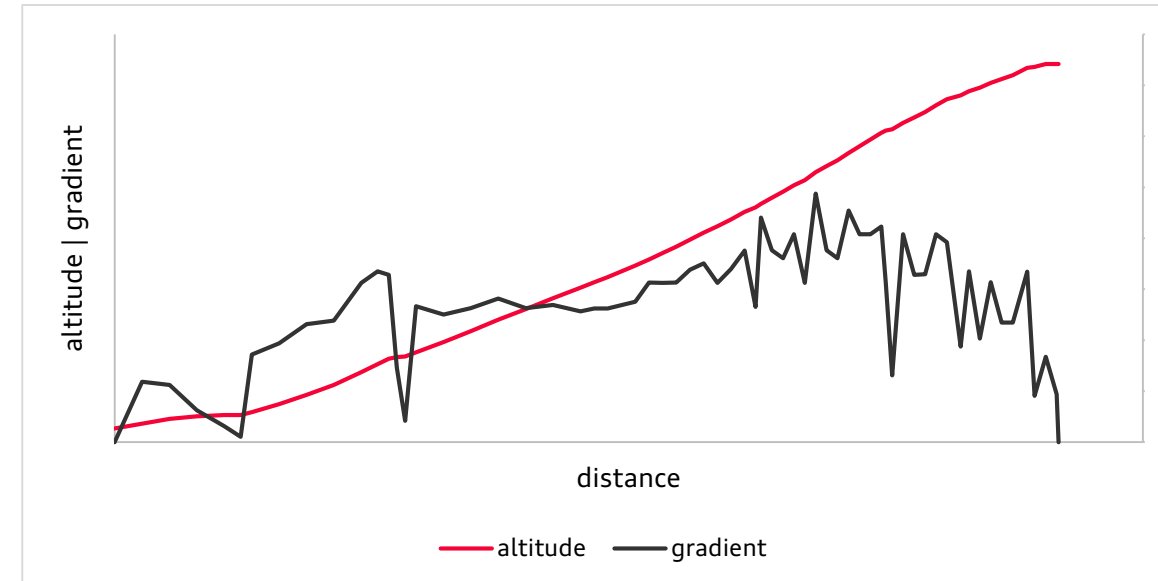
- › Steady state at high loads (highway driving)
  - › On road testing possible
  - › Climatic wind tunnel testing possible
  
- › Transient uphill driving (with trailer)
  - › On road testing
  - › Climatic wind tunnel testing with limitations
    - › Variable load and velocity possible
    - › Variable ambient temperature and solar load possible
    - › Variable ambient pressure usually not possible
  
- › Transient dynamic (race track)
  - › Race track required



# Customer expectations

- › Sport Utility Vehicles customers expectations
  - › Off road driving
  - › High comfort long range driving
  - › Towing of heavy trailers
  
- › Trailer weights up to 3500kg for global sale require a effective cooling system
  - › Safe operation with no limitation on any mountain pass worldwide
  - › Ambient temperatures up to 50°C at beginning of the mountain pass
  - › Height difference up to 1500m
  - › Driving speeds over 70km/h

Idealized profile of a real mountain pass

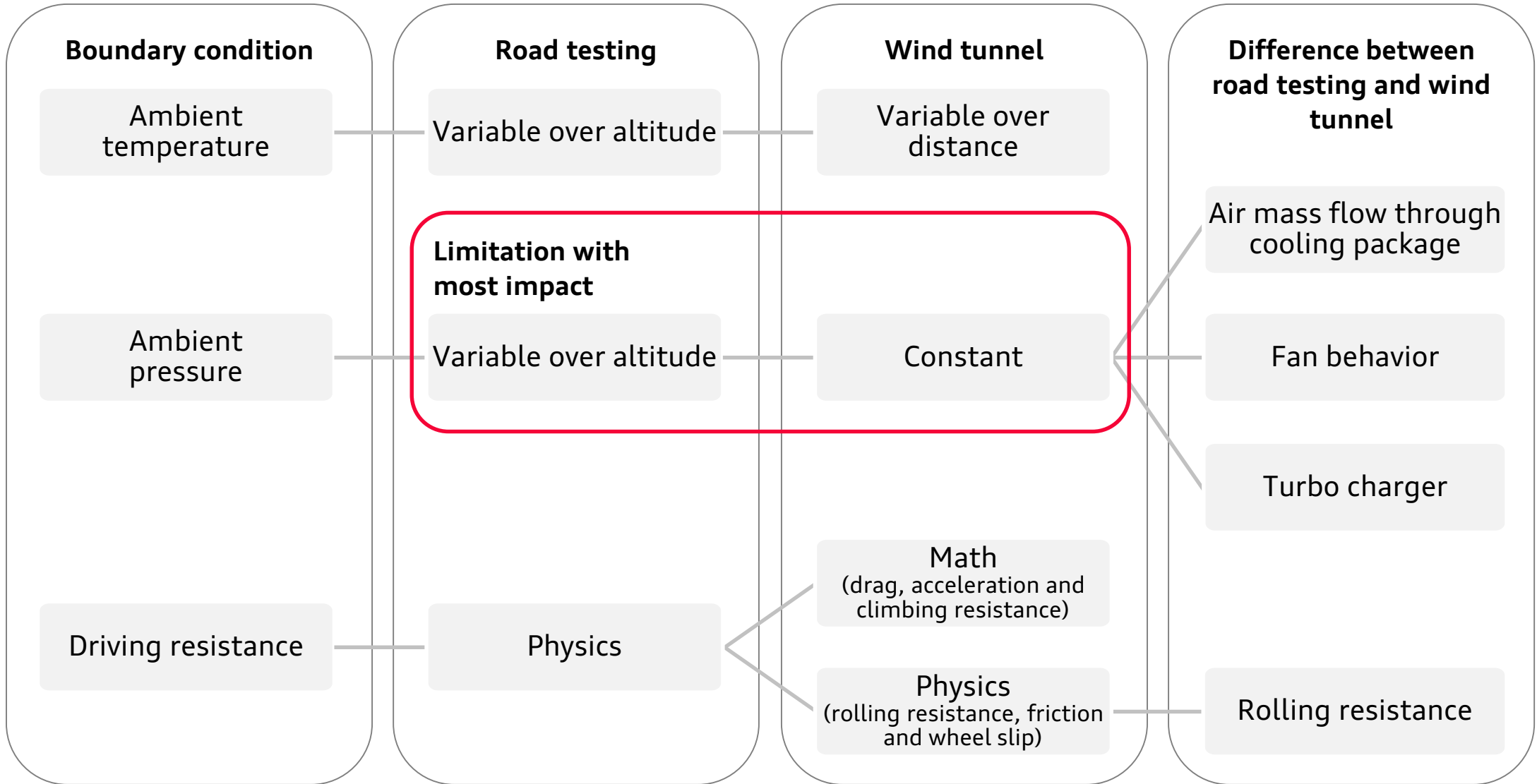


## Why change the development process?

- › Why do we want to find an equivalent cycle for a real mountain pass?
- › Restrictions in traveling due to Covid-19 since 2020
- › Save shipping time and increase car availability – share the car with other departments
- › Reduce traveling and shipping costs
- › Better repair and part changing possibility in a permanent workshop with all experts directly at the car
- › Prototypes of any stages can be measured undisguised in wind tunnels
  - › Air intakes of prototypes are design relevant and also essential for cooling system measurements
  - › Camouflage of air intakes has often an impact on cooling air mass flow
- › Idealized and repeatable ambient conditions and no traffic in wind tunnel
  - › Temperature
  - › Driving resistance
  - › Solar load
  - › Wind conditions



# Differences between road testing and wind tunnel tests focused on uphill driving



# What can be done to reduce the influence of those differences?

## Possibilities to adapt wind tunnel measurements

### > Influence of different input parameters

|                           | <b>Air mass flow through cooling package</b> | <b>Engine and drivetrain waste heat</b> | <b>Turbo Charger</b> | <b>Air conditioning</b> |
|---------------------------|--|---|----------------------|-------------------------|
| <b>Air temperature</b>    | yes  | negligible                              | yes                  | yes                     |
| <b>Driving Speed</b>      | yes  | yes                                     | yes                  | negligible              |
| <b>Wind speed</b>         | yes  | negligible                              | no                   | negligible              |
| <b>Driving resistance</b> | no   | yes                                     | yes                  | no                      |



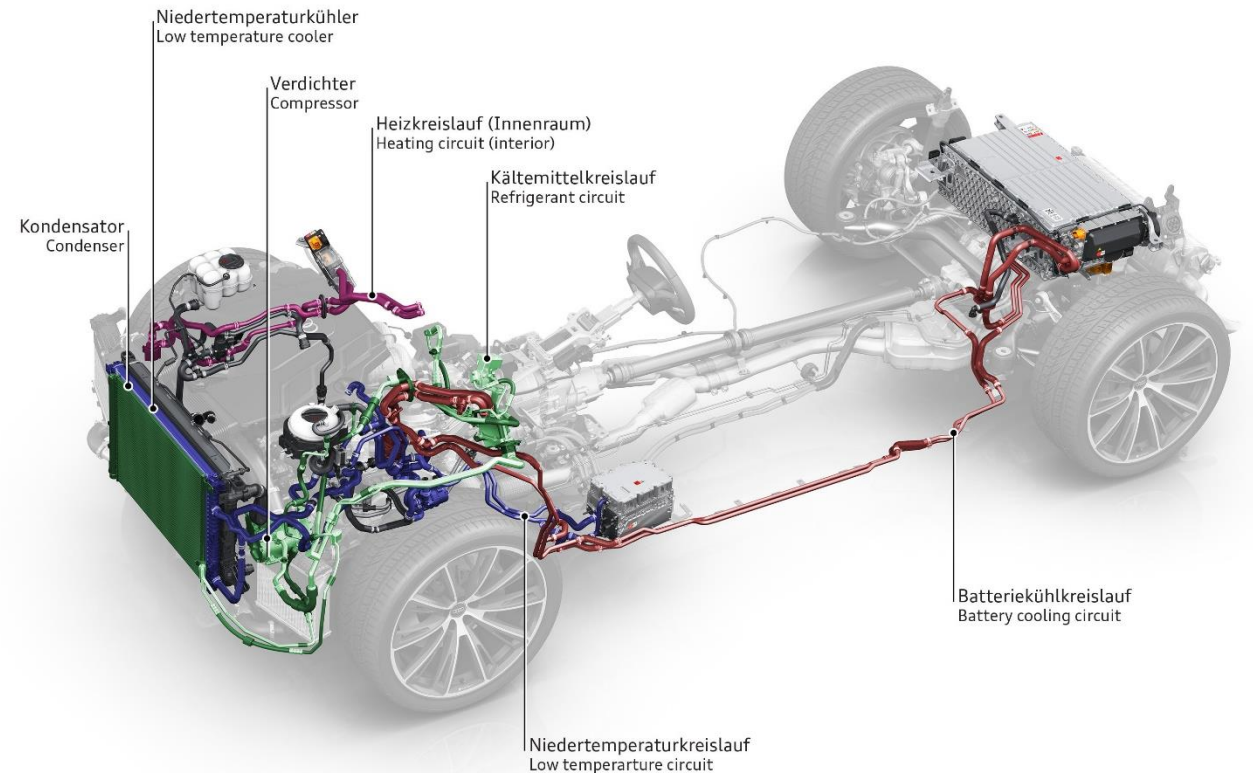
# KULI model

- › Requirements to the KULI model
  - › Proper modeled air path and fans
  - › Hydraulic model of the cooling system
  - › Thermal point mass system of engine and gearbox
  - › Model of engine waste heat dissipation
  - › Model of gearbox waste heat dissipation
  - › Simplified turbo charger model reacting on ambient pressure
  - › Simplified air conditioning and refrigerant circuit to model the condenser heat dissipation
  - › Longitudinal driving performance model



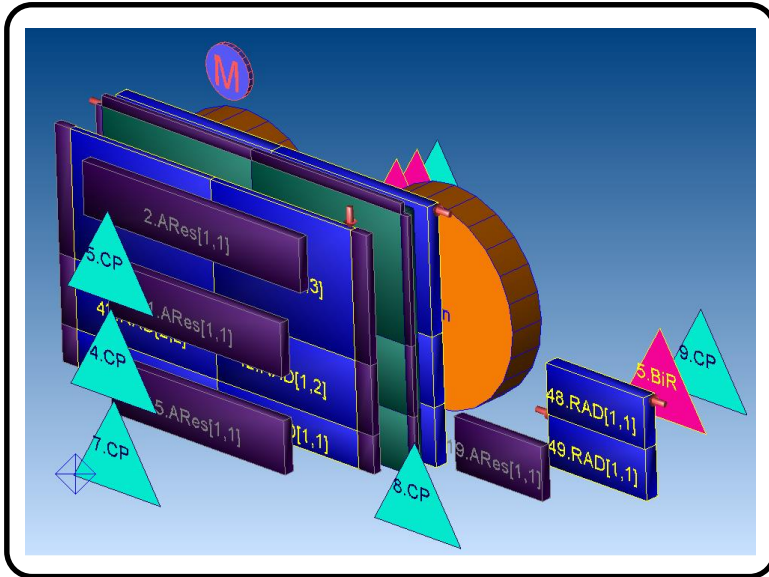
## Audi Q8 60 TFSI e

Kühlung  
Cooling  
12/20

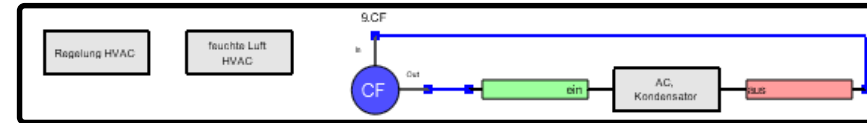


# KULI model

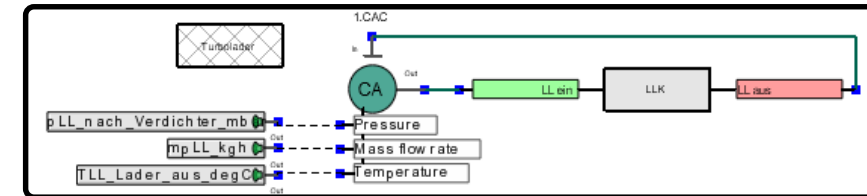
## Air path



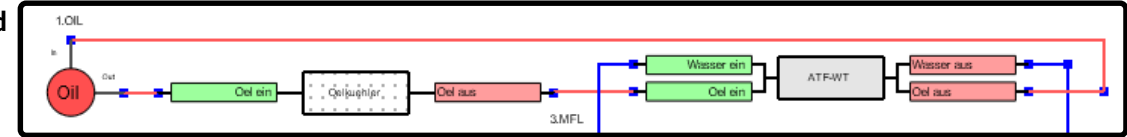
## Simplified HVAC and refrigerant circuit



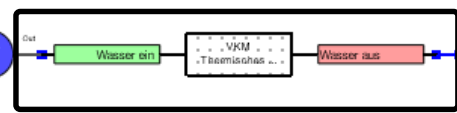
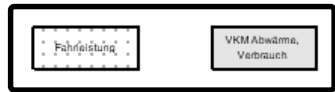
## Simplified turbo charger model



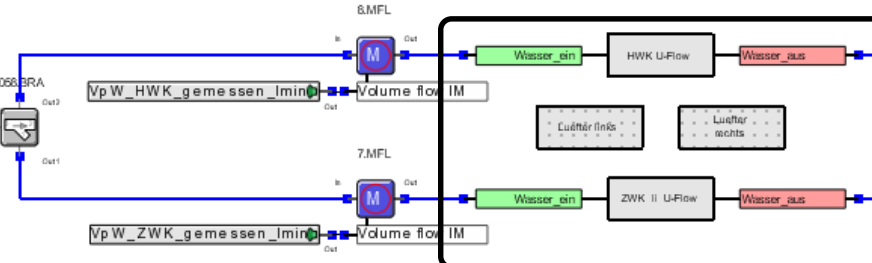
## Transmission fluid



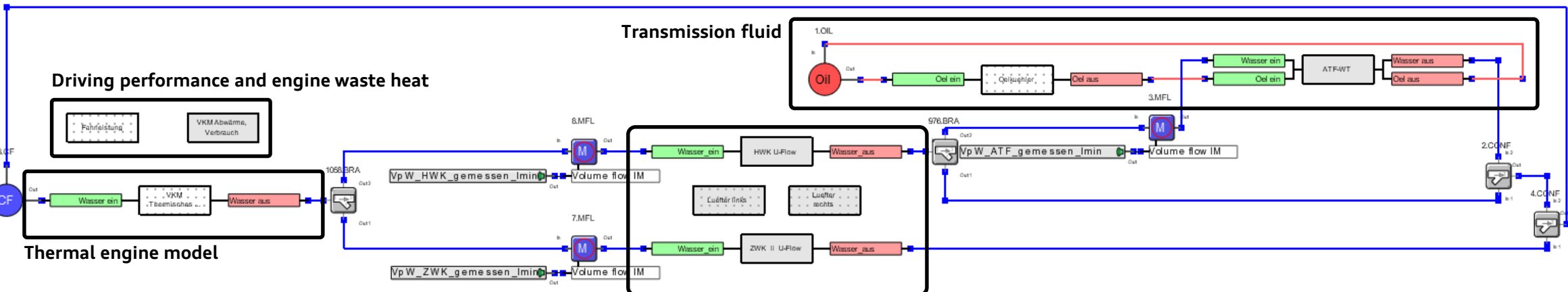
## Driving performance and engine waste heat



## Thermal engine model



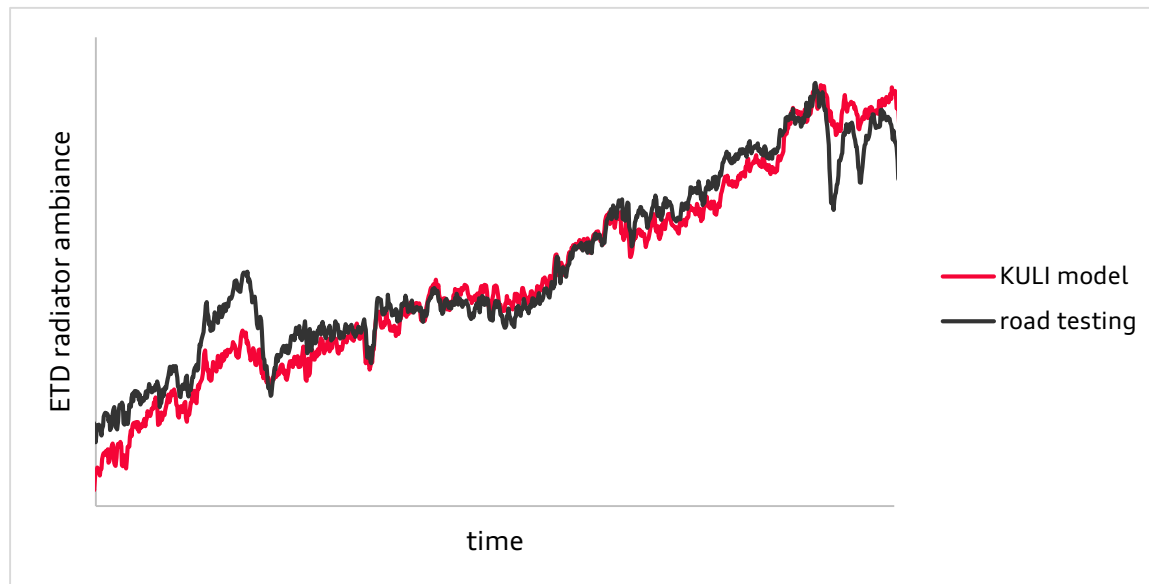
## Radiators and fans



# Verification of the model

- › Verifying the KULI model with the mountain pass measurement

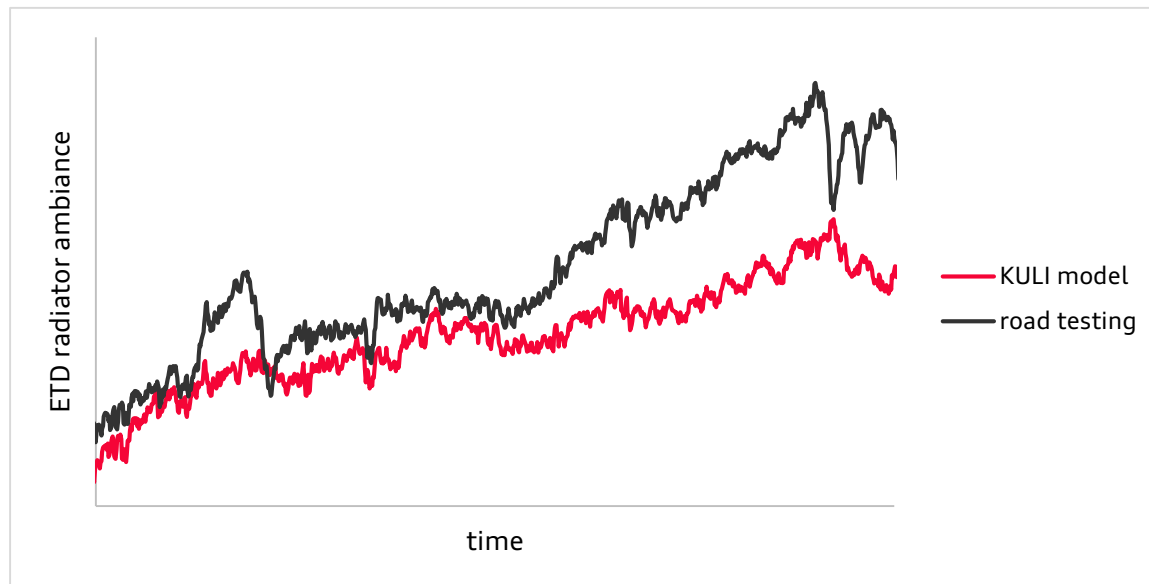
|                     | Air Temperature | Ambient pressure | Driving speed | Wind speed  | Driving resistance |
|---------------------|-----------------|------------------|---------------|-------------|--------------------|
| <b>KULI model</b>   | as measured     | as measured      | as measured   | as measured | modeled            |
| <b>road testing</b> | as measured     | as measured      | as measured   | as measured | car                |
|                     |                 |                  |               |             |                    |



# Virtual wind tunnel

## > Difference of road measurement and wind tunnel

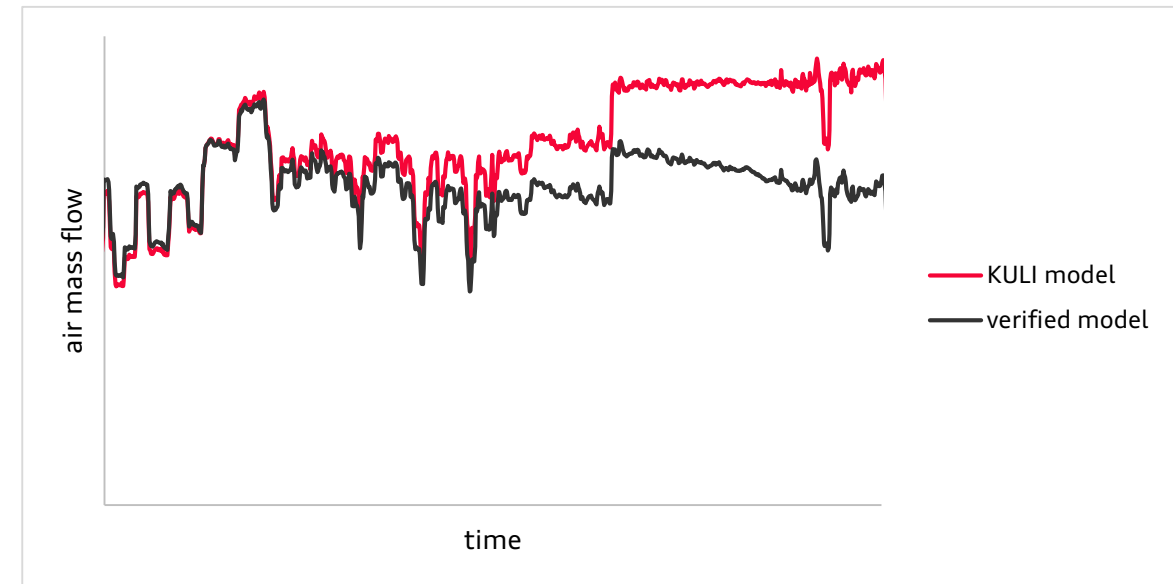
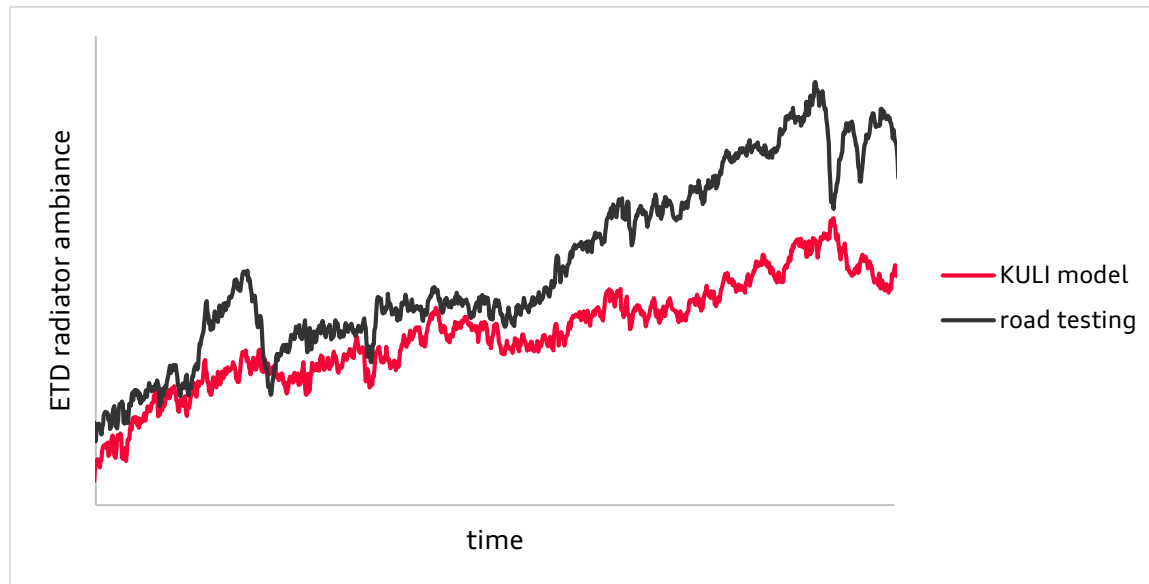
|                     | Air Temperature | Ambient pressure | Driving speed | Wind speed  | Driving resistance |
|---------------------|-----------------|------------------|---------------|-------------|--------------------|
| <b>KULI model</b>   | as measured     | constant         | as measured   | as measured | wind tunnel        |
| <b>road testing</b> | as measured     | as measured      | as measured   | as measured | car                |
|                     |                 |                  |               |             |                    |



# Virtual wind tunnel

## > Difference of road measurement and wind tunnel

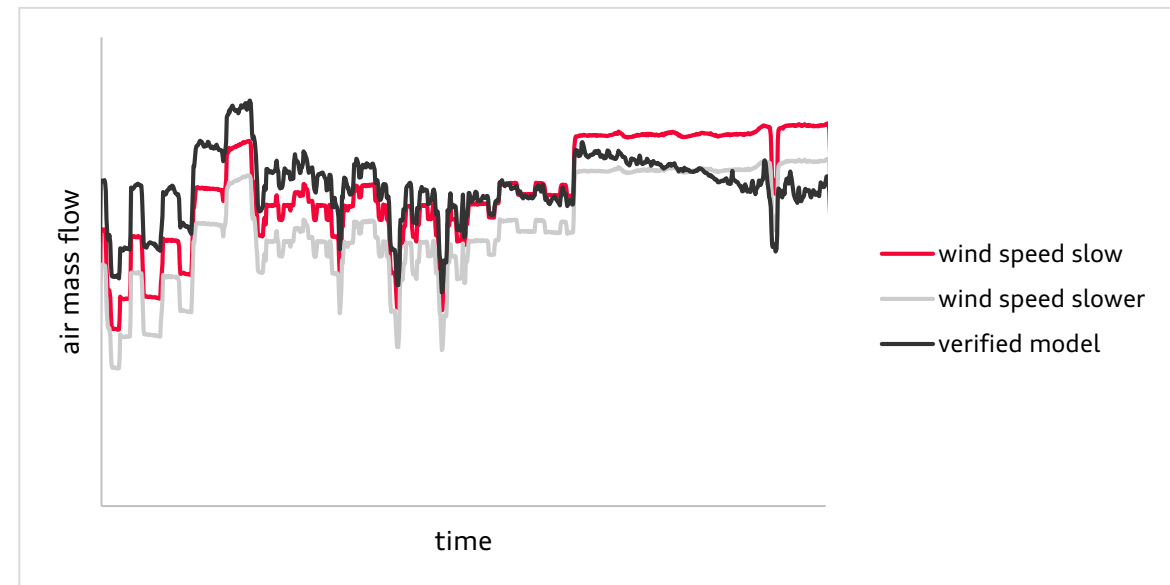
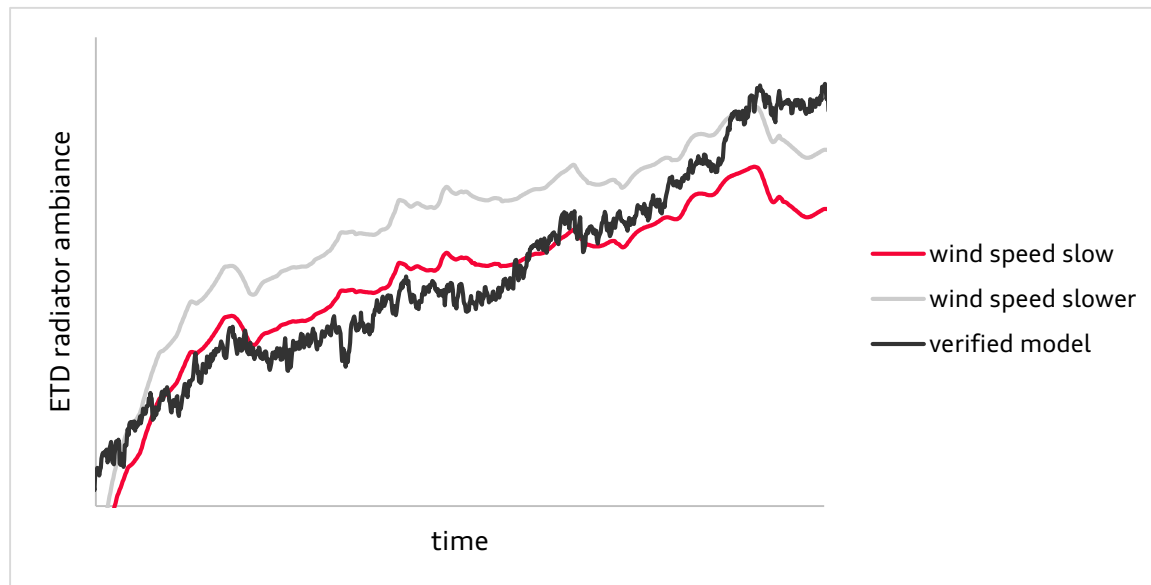
|                       | Air Temperature | Ambient pressure | Driving speed | Wind speed  | Driving resistance |
|-----------------------|-----------------|------------------|---------------|-------------|--------------------|
| <b>KULI model</b>     | as measured     | constant         | as measured   | as measured | wind tunnel        |
| <b>road testing</b>   | as measured     | as measured      | as measured   | as measured | car                |
| <b>verified model</b> | as measured     | as measured      | as measured   | as measured | modeled            |



# Virtual wind tunnel

## > Constant wind speed reduction

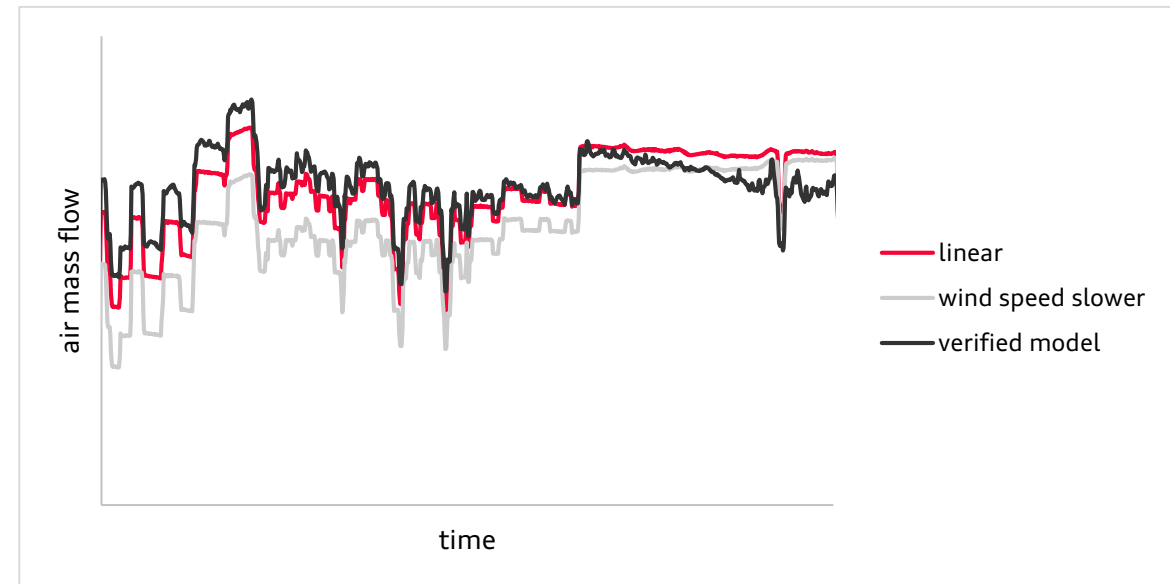
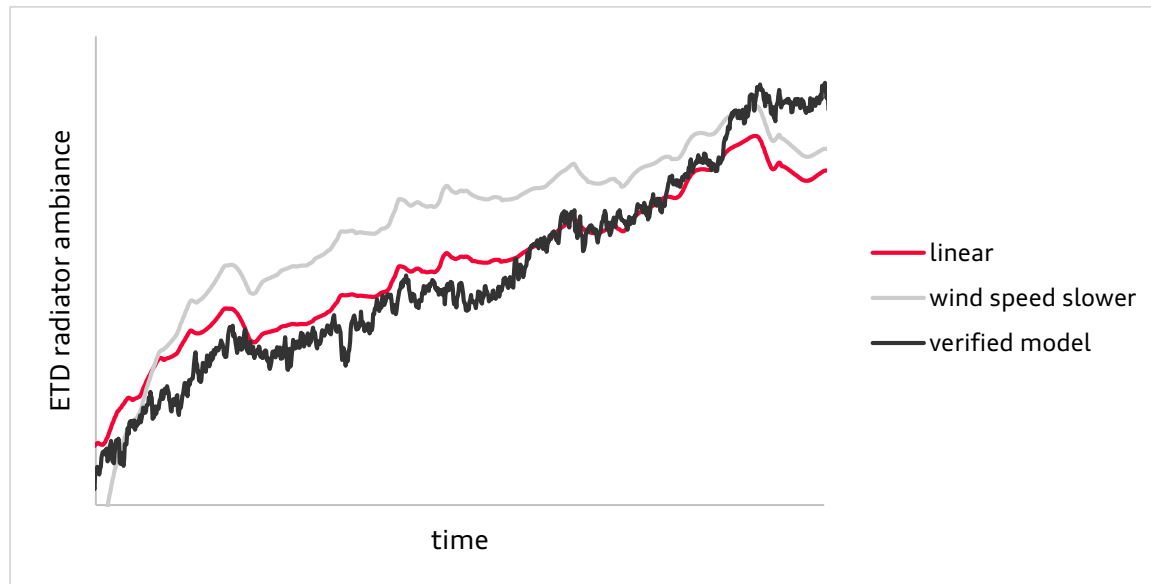
|                       | Air Temperature | Ambient pressure | Driving speed | Wind speed  | Driving resistance |
|-----------------------|-----------------|------------------|---------------|-------------|--------------------|
| <b>slow</b>           | idealized       | constant         | idealized     | slow        | wind tunnel        |
| <b>slower</b>         | idealized       | constant         | idealized     | slower      | wind tunnel        |
| <b>verified model</b> | as measured     | as measured      | as measured   | as measured | modeled            |



# Virtual wind tunnel

› Wind speed reduction as a function of time

|                       | Air Temperature | Ambient pressure | Driving speed | Wind speed   | Driving resistance |
|-----------------------|-----------------|------------------|---------------|--------------|--------------------|
| <b>linear</b>         | idealized       | constant         | idealized     | FUNC of time | wind tunnel        |
| <b>slower</b>         | idealized       | constant         | idealized     | slower       | wind tunnel        |
| <b>verified model</b> | as measured     | as measured      | as measured   | as measured  | modeled            |

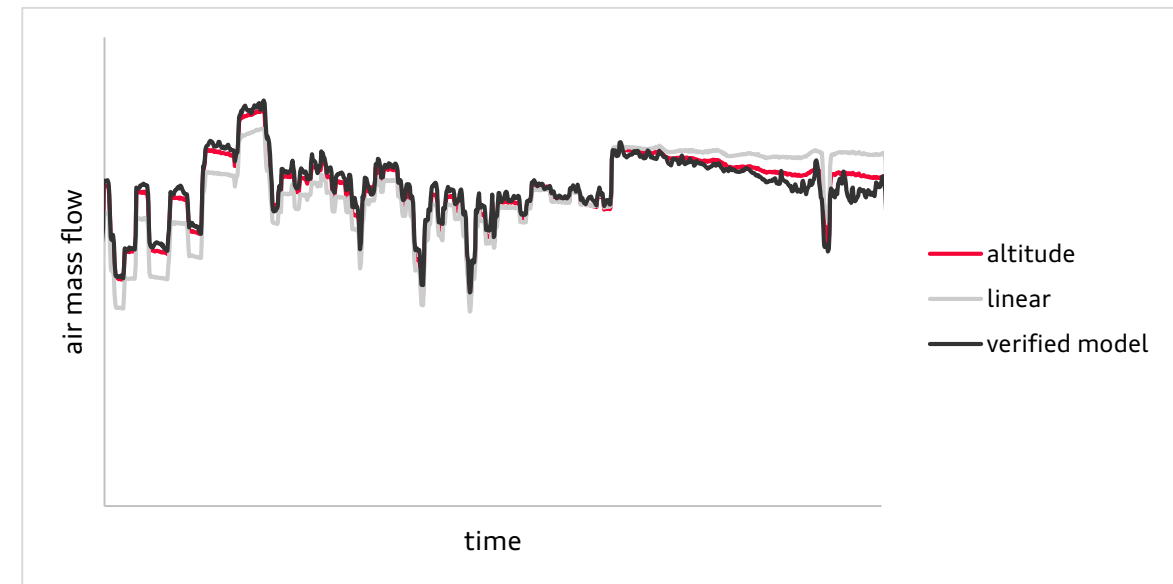
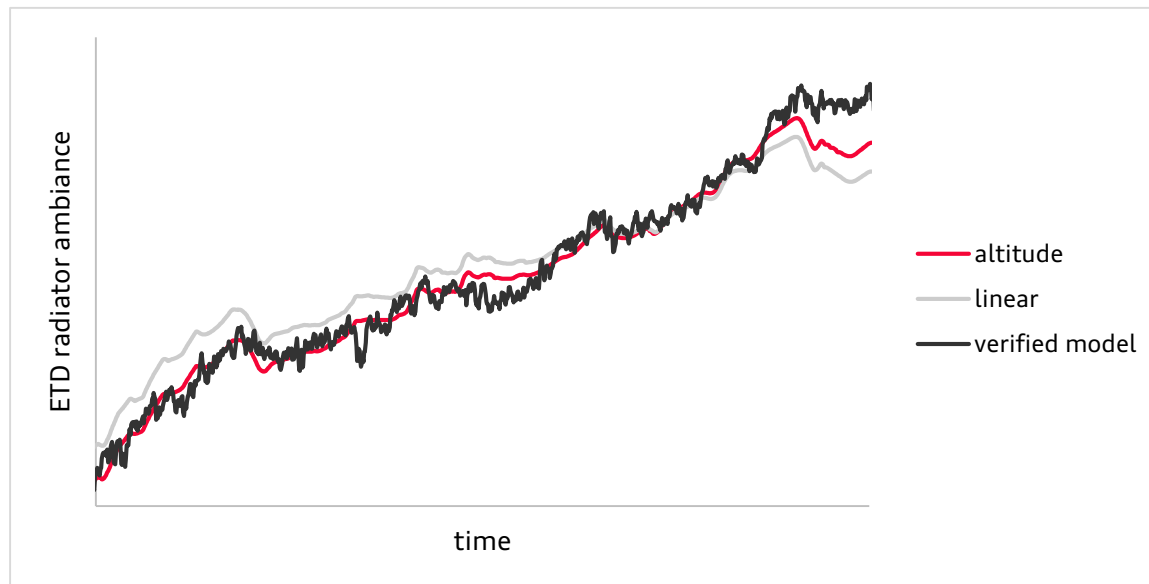




# Virtual wind tunnel

## › Wind speed reduction as a function of altitude

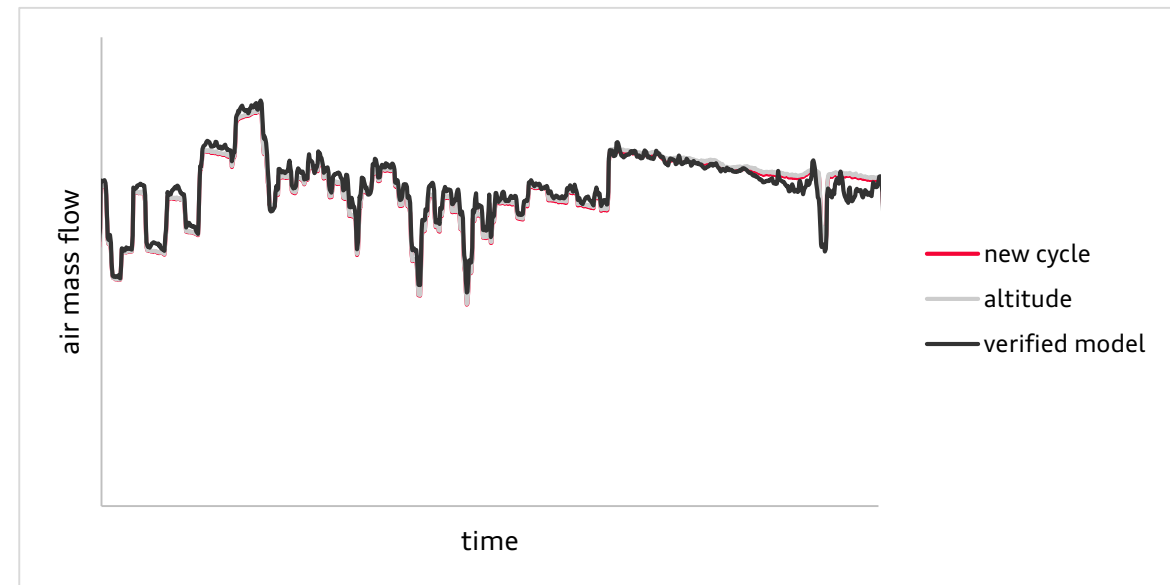
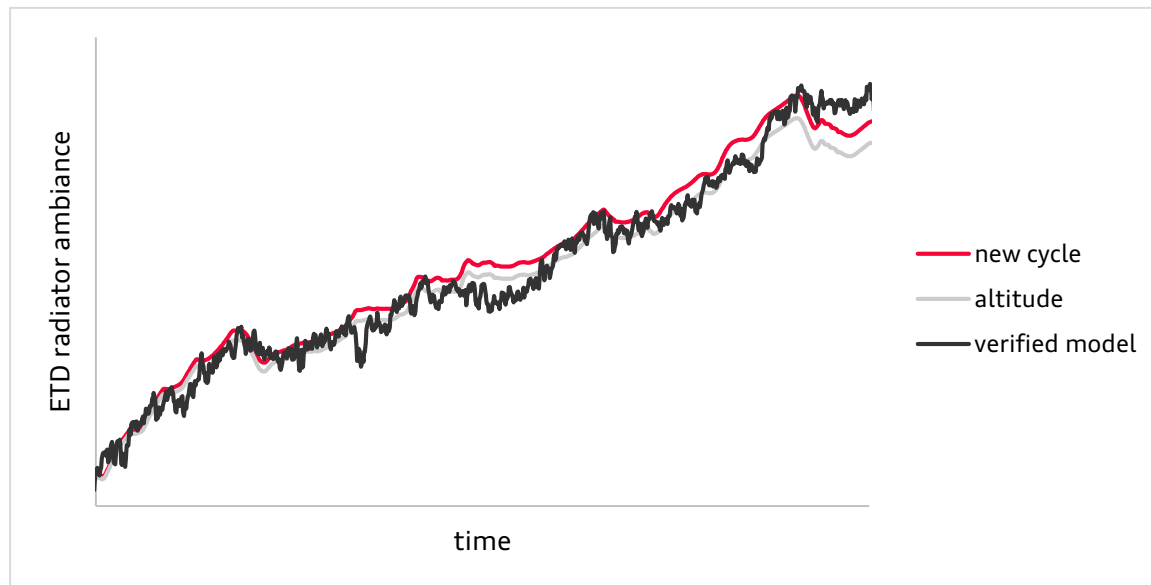
|                       | Air Temperature | Ambient pressure | Driving speed | Wind speed       | Driving resistance |
|-----------------------|-----------------|------------------|---------------|------------------|--------------------|
| <b>altitude</b>       | idealized       | constant         | idealized     | FUNC of altitude | wind tunnel        |
| <b>linear</b>         | idealized       | constant         | idealized     | FUNC of time     | wind tunnel        |
| <b>verified model</b> | as measured     | as measured      | as measured   | as measured      | modeled            |



# Virtual wind tunnel

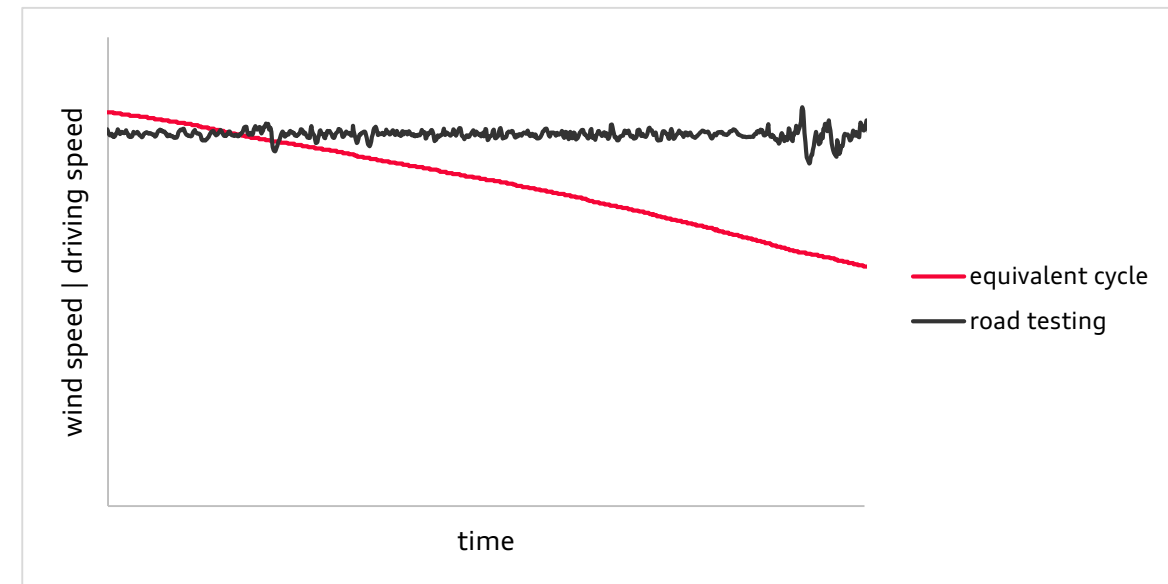
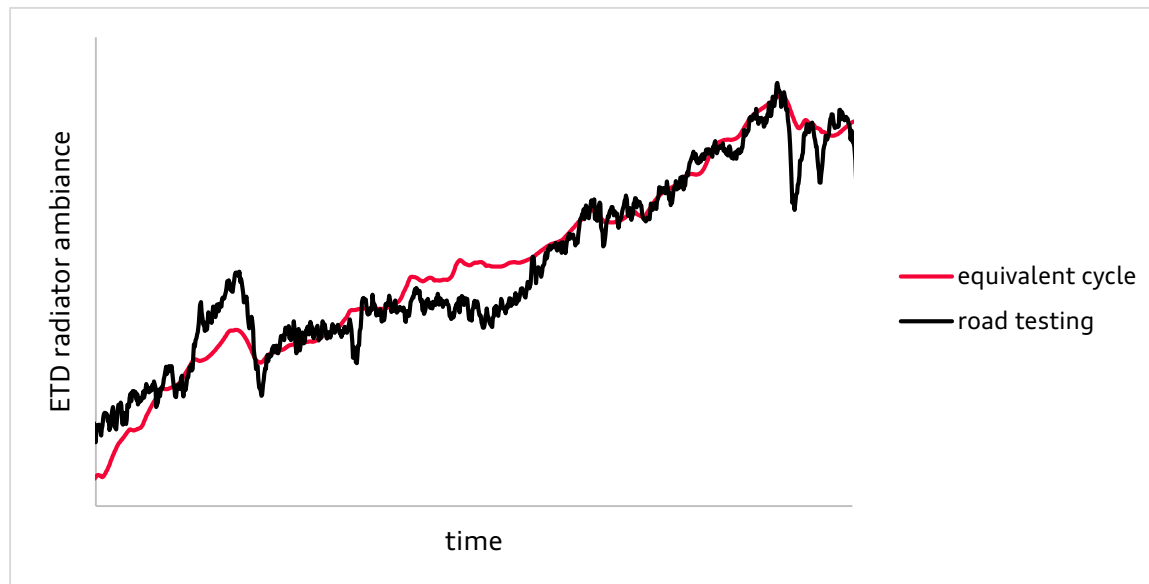
› Adjust the wind tunnel driving resistance

|                       | Air Temperature | Ambient pressure | Driving speed | Wind speed       | Driving resistance |
|-----------------------|-----------------|------------------|---------------|------------------|--------------------|
| <b>new cycle</b>      | idealized       | constant         | idealized     | FUNC of altitude | adjusted           |
| <b>altitude</b>       | idealized       | constant         | idealized     | FUNC of altitude | wind tunnel        |
| <b>verified model</b> | as measured     | as measured      | as measured   | as measured      | modeled            |



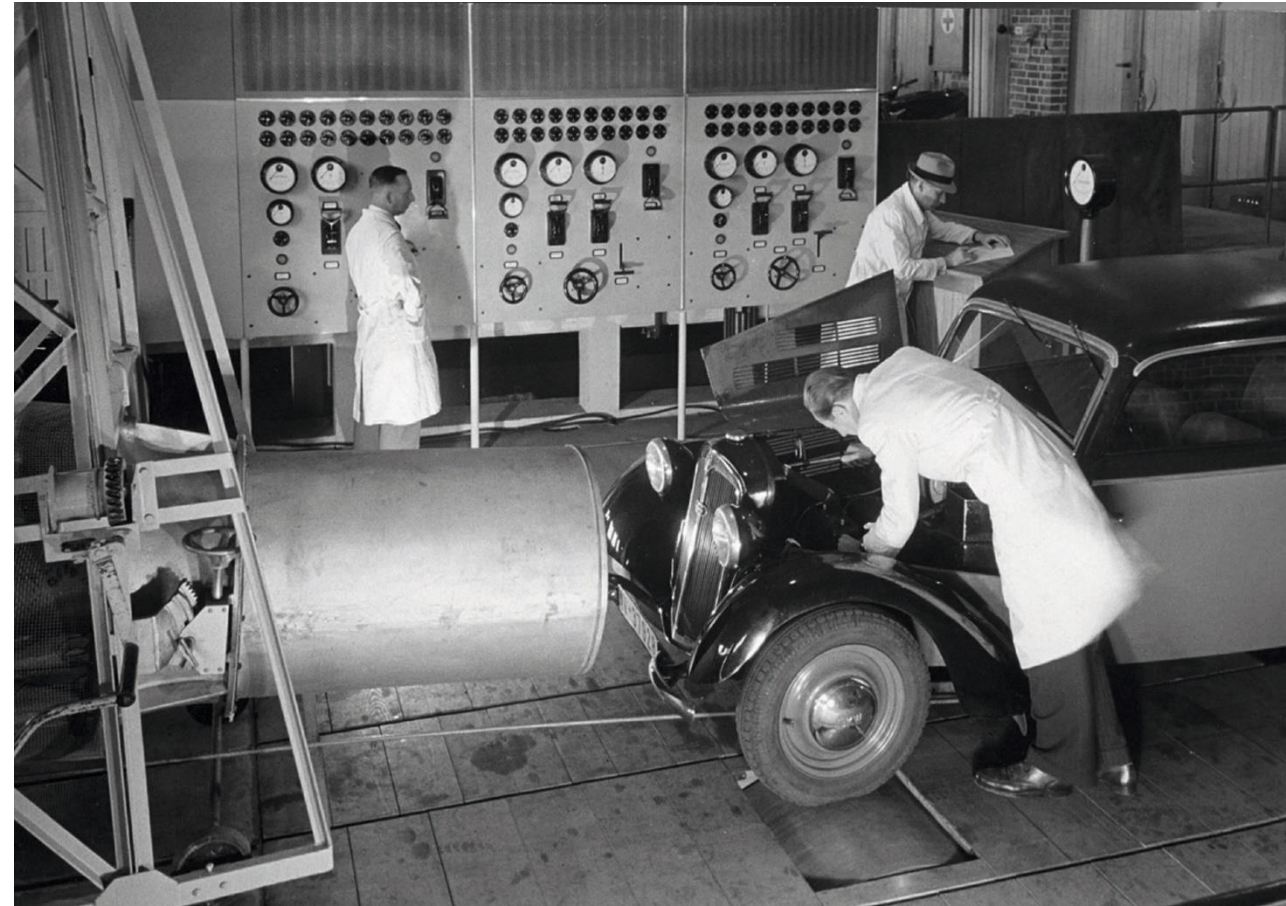
# Equivalent load cycle for climatic wind tunnel test

- › Equivalent load cycle for climatic wind tunnel tests show good results when you...
  - › ...adapt the wind speed as a function of altitude
  - › ...do a correction of rolling resistance difference



## What else?

- › Why not only do simulations?
  - › Simulation is based on simplified models
  - › Not every part of the model is up to date
  - › Thermal management software can change fast in the development process
  
- › When does it not work?
  - › Some systems change their behavior if limits are exceeded
  
- › Wind tunnel with adjustable air pressure exist
  - › Higher costs
  - › Travelling required



## Conclusion

- › The virtual car can be used to support the whole development process
- › Help to find equivalent load cycles for wind tunnel tests
- › The proper modeling of the main systems is important
- › Simulation model is just as good as it's input parameters and component tests
- › Verification has to be done at different relevant operating points
  
- › The main differences of mountain pass testing and wind tunnel testing have been identified
- › An equivalent load cycle has been defined
  
- › Further steps
  - › Verification of the model with climatic wind tunnel tests
  - › Verification of the equivalent load cycle with different car models
  - › Substitute the mountain pass testing with wind tunnel tests

Thank

**Thank you!**

you!