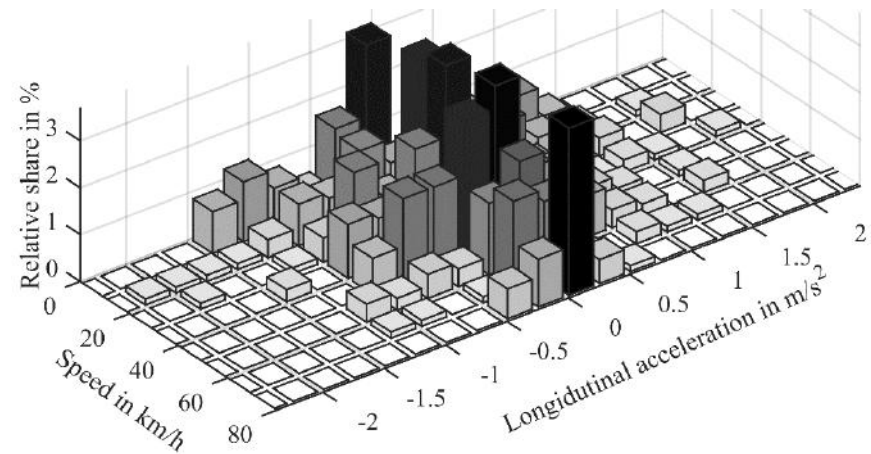
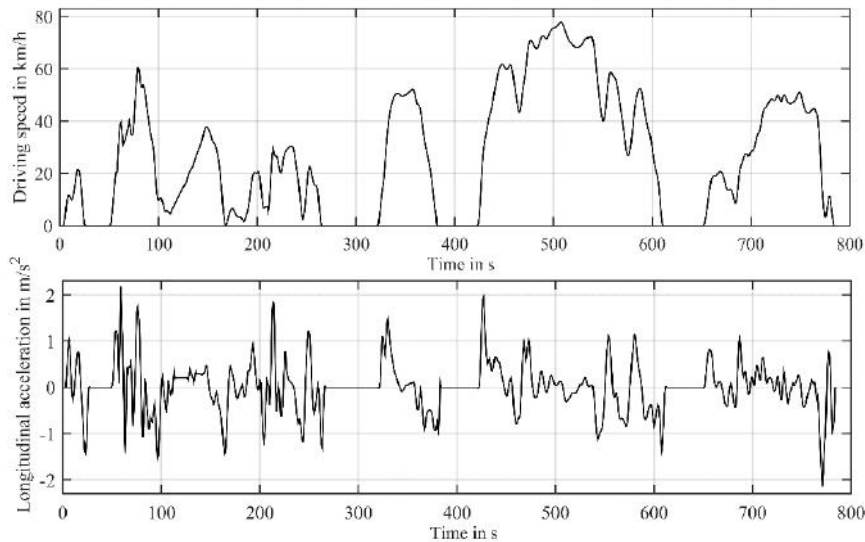


Development of real-world Driving Cycles for Battery Electric Vehicles

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Agenda

- Motivation
- Empiric Foundation
- Methodology of Cycle Generation
- Real-world Driving Cycles
- Comparison of Driving Cycles
- Conclusion and Outlook

Motivation

- Driving cycles are **important instrument** in vehicle development
- Official **evaluation of energy consumption** and emissions etc.
- **Problem: Not representative** for real-world use
- Modern vehicle **development follows test cycles**
 - ➔ **Increasing gap** between real-world consumption and cycle consumption [3]
- **Consumption** and required torque differ by more than factor 2 **depending on the cycle** [4], [5]
 - ➔ Apropriate evaluation needs **apropriate driving cycle**
- **No empirically based driving cycles** for Battery Electric Vehicles (BEV) in mixed fleets

Empiric Foundation (1)

- Data gathered within project: 

Gefördert durch:



Bundesministerium
für Wirtschaft
und Technologie

Bundesministerium
für Verkehr, Bau
und Stadtentwicklung

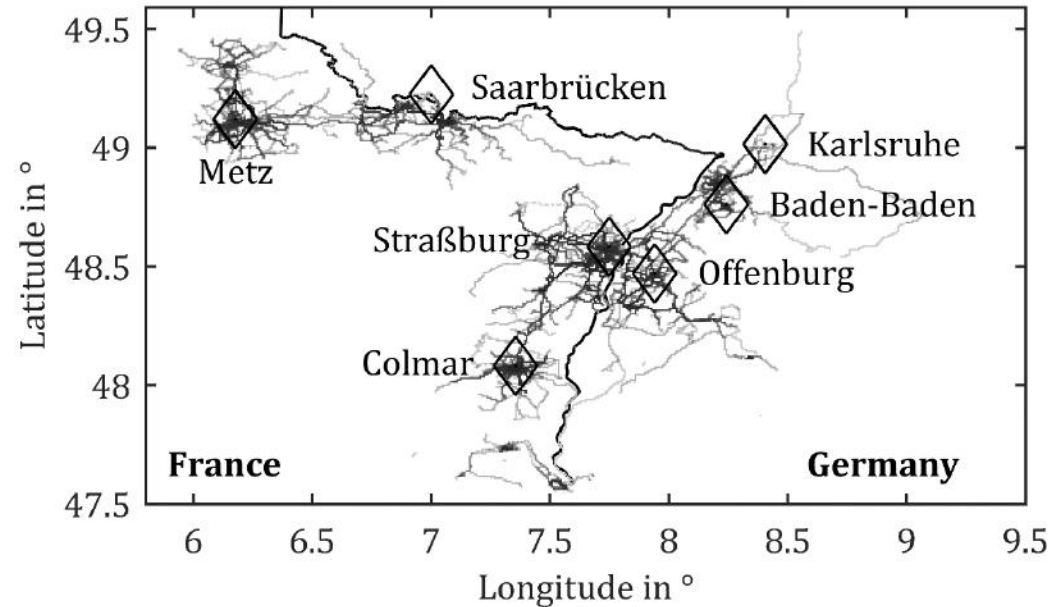
aufgrund eines Beschlusses des Deutschen Bundestages

- **Field Operational Test** with over 100 electric vehicles (EV) in Germany and France
- EV used in **mixed commercial fleets** (alternatives for long-distance travel available)
- More than **18 months** of **data collection**
- Automotive **CAN data loggers** and Smartphones as additional loggers



Empiric Foundation (2)

- EV used in area along French-German border
- Over **125.000 datasets** from trips recorded
 - ➡ More than **600.000 km**
- **Continuous monitoring** all over the year
 - ➡ No seasonal influence
- Reduction on **sub-sample** with **continuous speed signal** at 1 Hz or more



Empiric Foundation (3)

■ 74 % urban trips → rather short

■ Trip length:

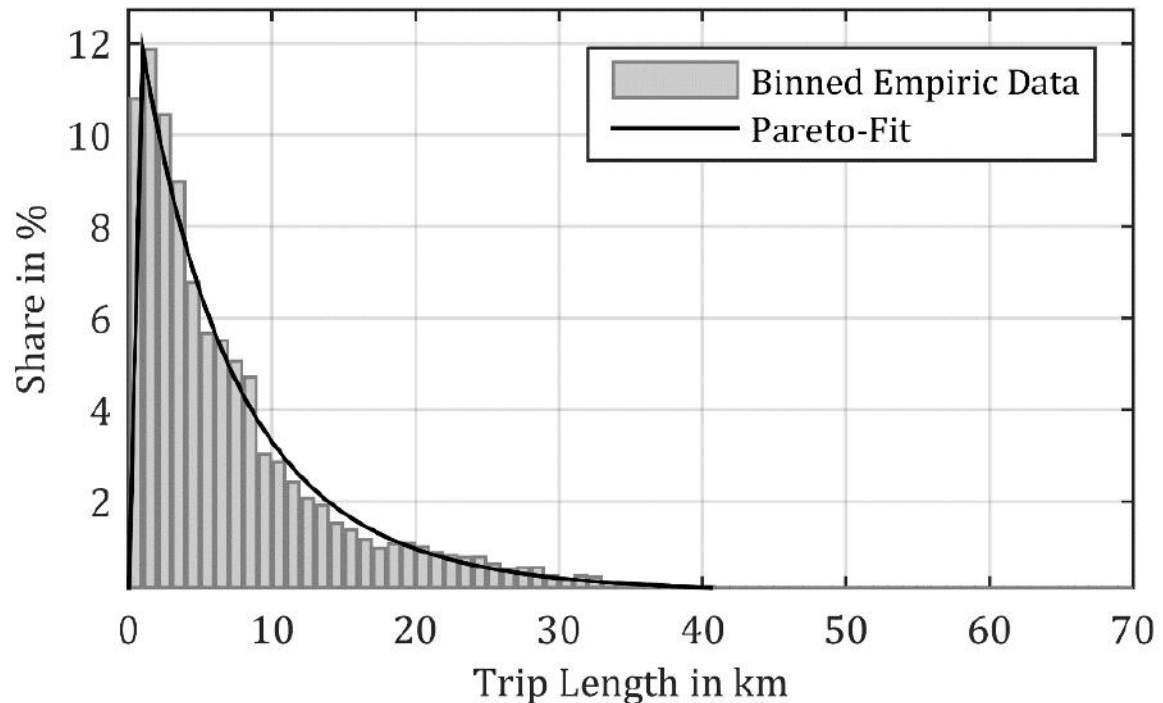
- Mean value 8.4 km
- Median 5.2 km

■ Trip duration:

- Mean value 20 min
- Median 13.3 min

■ Trip Purpose

- 77.5 % Business Trips
- 15.9 % Commuting
- 6.6 % Private Trips
(prohibited for some EV)



$$f(x|k, \sigma_p, \theta) = \left(\frac{1}{\sigma_p}\right) \left(1 + k \frac{(x - \theta)}{\sigma_p}\right)^{-1 - \frac{1}{k}}; \text{ für } \forall x \geq 0,$$

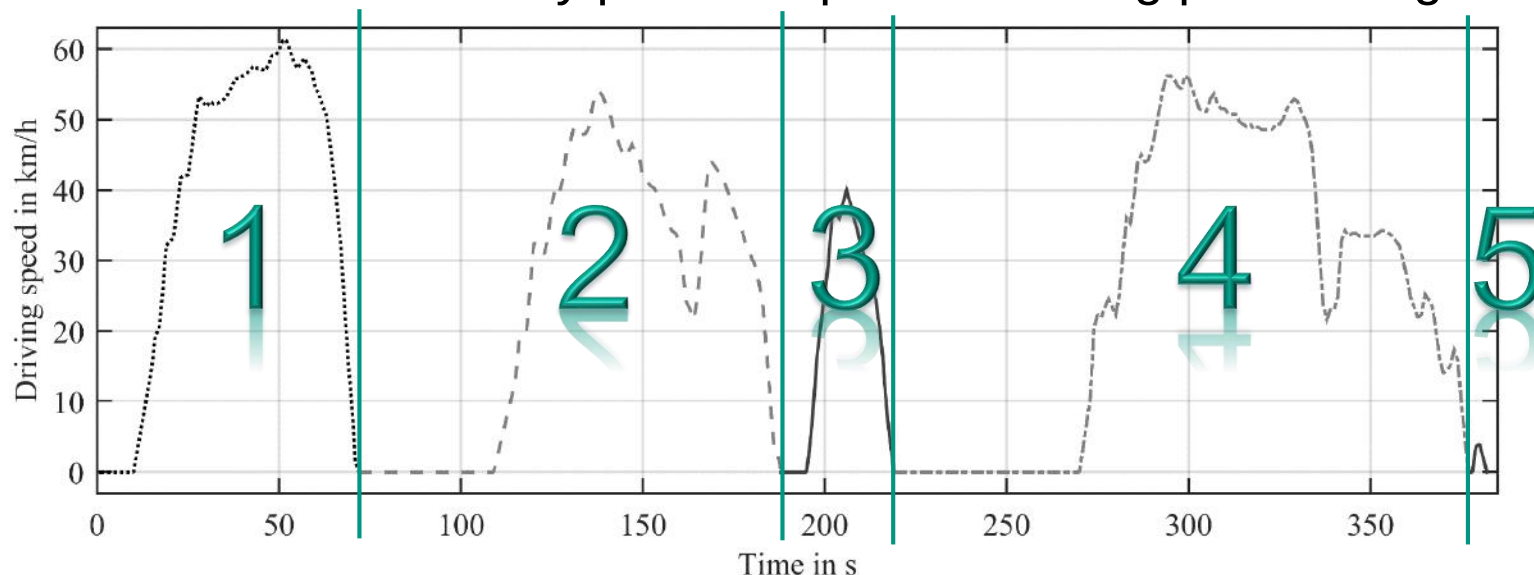
$$k = 0.13; \sigma_p = 7.28; \theta = 0.02$$

Methodology of Cycle Generation (1)

- Goal: driving cycles to **represent real-world-usage**
- **Driveability** must be ensured
- **Micro-trip methodology** [9]:
 - All trips divided into micro-trips
 - Selected micro-trips combined for driving cycle

■ Micro-trip:

Phase with constantly positive speed including preceeding idle-phase



Methodology of Cycle Generation (2)

■ Statistical **analysis** of all trips to define **target values**

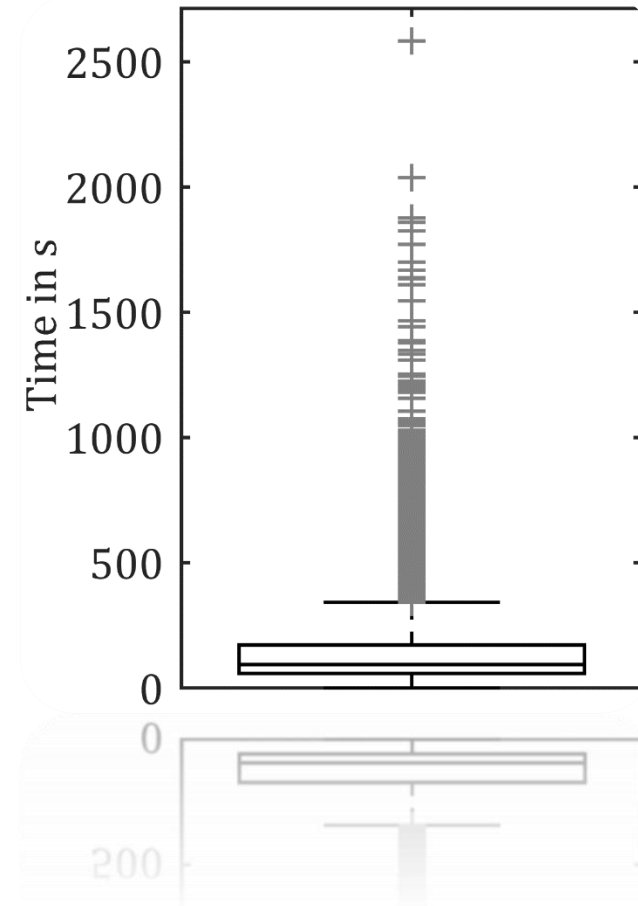
No.	Parameter	Unit
1	Average speed	km/h
2	Average speed >0	km/h
3	Average longitudinal acceleration	m/s ²
4	Average longitudinal deceleration	m/s ²
5	Average duration of driving sequences	s
6	Proportion idling	%
7	Proportion cruising	%
8	Proportion creeping	%
9	Proportion acceleration	%
10	Proportion deceleration	%
11	Number of acceleration-deceleration changes	-
12	Root mean square longitudinal acceleration	m/s ²
13	Normalised positive acceleration kinetic energy	m/s ²

Operating mode	Speed v in km/h	Longitudinal acceleration a_x in m/s ²
Idling	0	0
Cruising	> 5	$0,1 \leq a_x \leq 0,1$
Creeping	$0 < v \leq 5$	$-0,1 \leq a_x \leq 0,1$
Acceleration	> 0	> 0,1
Deceleration	> 0	< -0,1

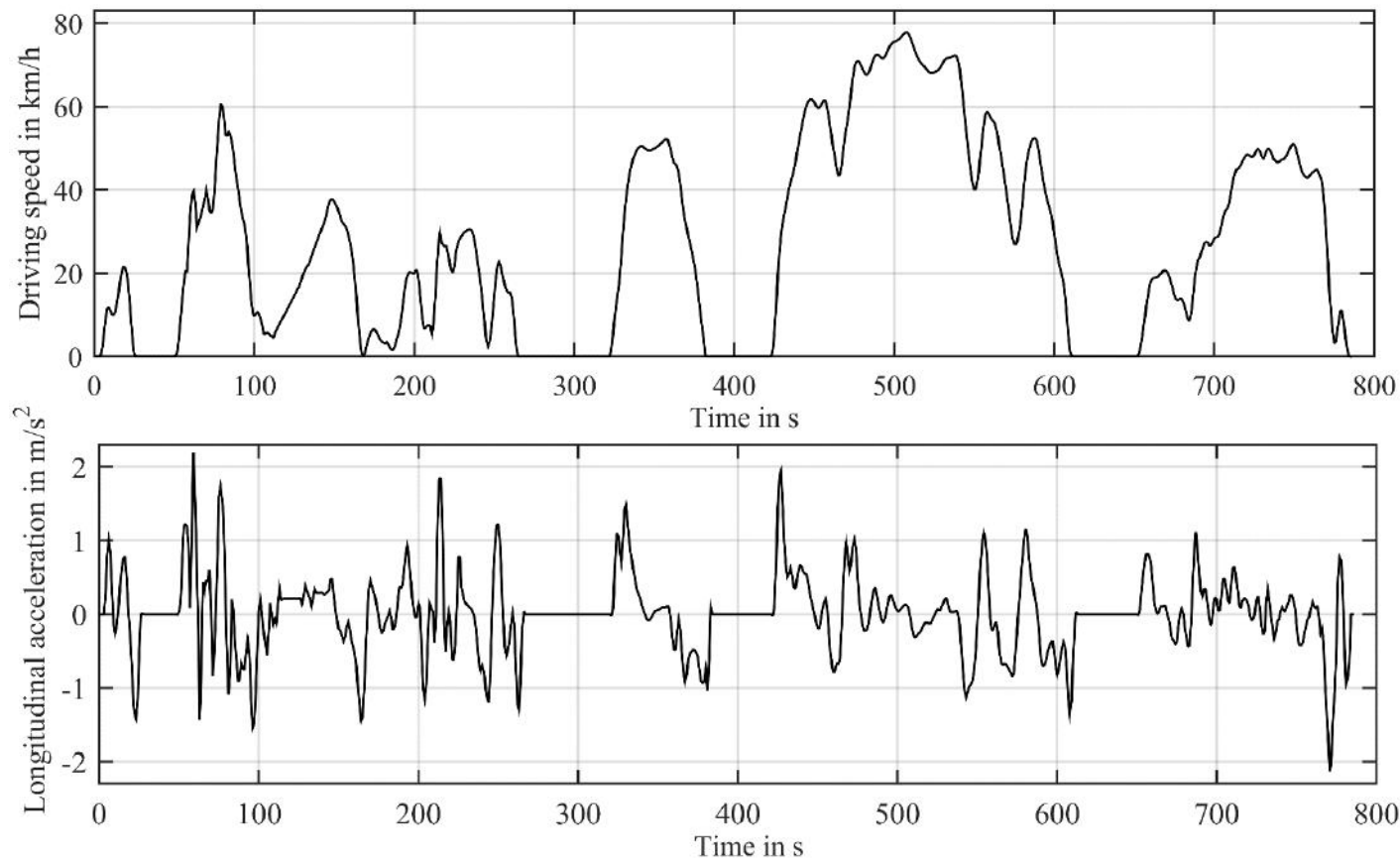
■ **Number of micro-trips** and target-window for **total duration** defined

Methodology of Cycle Generation (3)

- Database → **90.000** micro-trips
- **Removal** of strong statistical **outliers**
(e.g. duration of driving sequences
→ 7.8 % removed)
- **100 million** random sequences of micro-trips
computed as **candidate cycles**
- **Ranking** of trips following **two criteria**:
 - **Performance Value**: Sum of deviation
against 13 target parameters
 - **SSD**: Sum Square Difference of longitudinal
dynamics in 13 speed classes (0 to 130 km/h)
and 32 acceleration classes (-4 to +4 m/s²)
- Best **combined ranking** selects driving cycle



Fleet-BEV-Cycle (1)



■ Length: 5,828 m

■ Duration: 783 s

■ 5 micro-trips

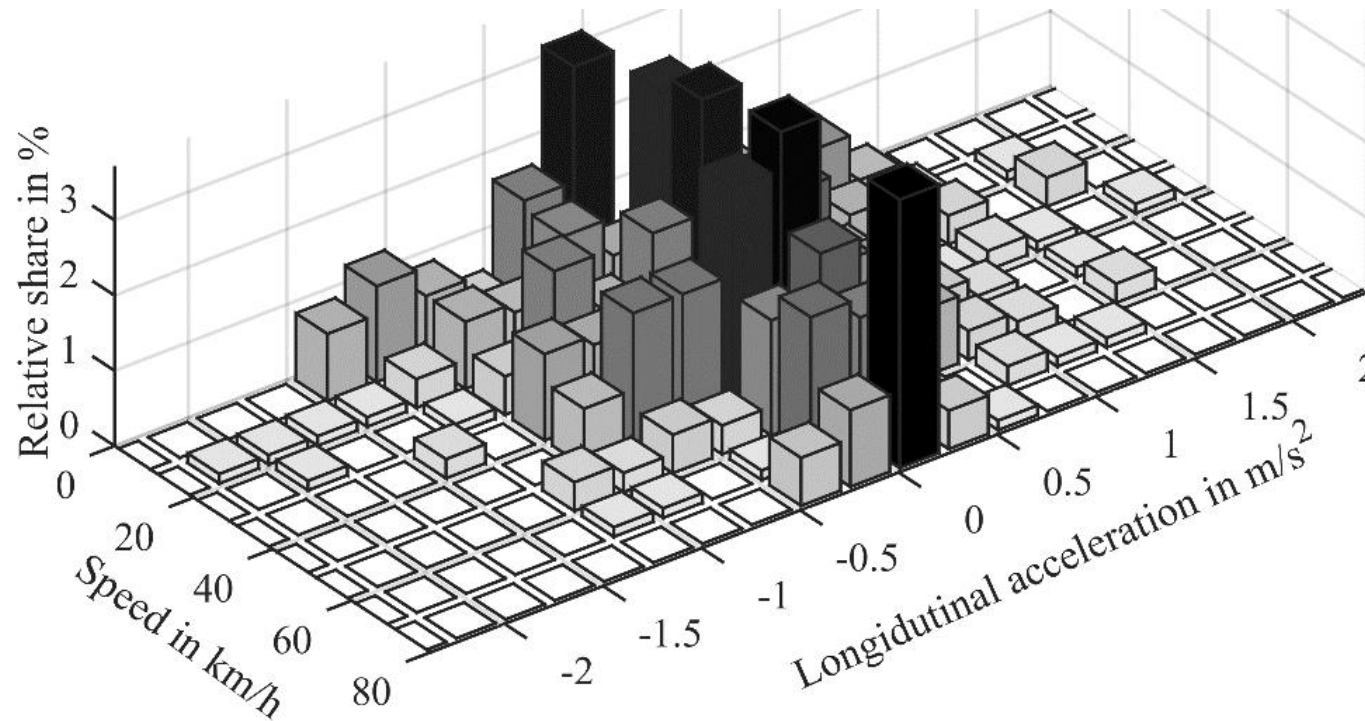
■ $\bar{v}$: 26.7 km/h

■ $\bar{v}_{v>0}$: 34.6 km/h

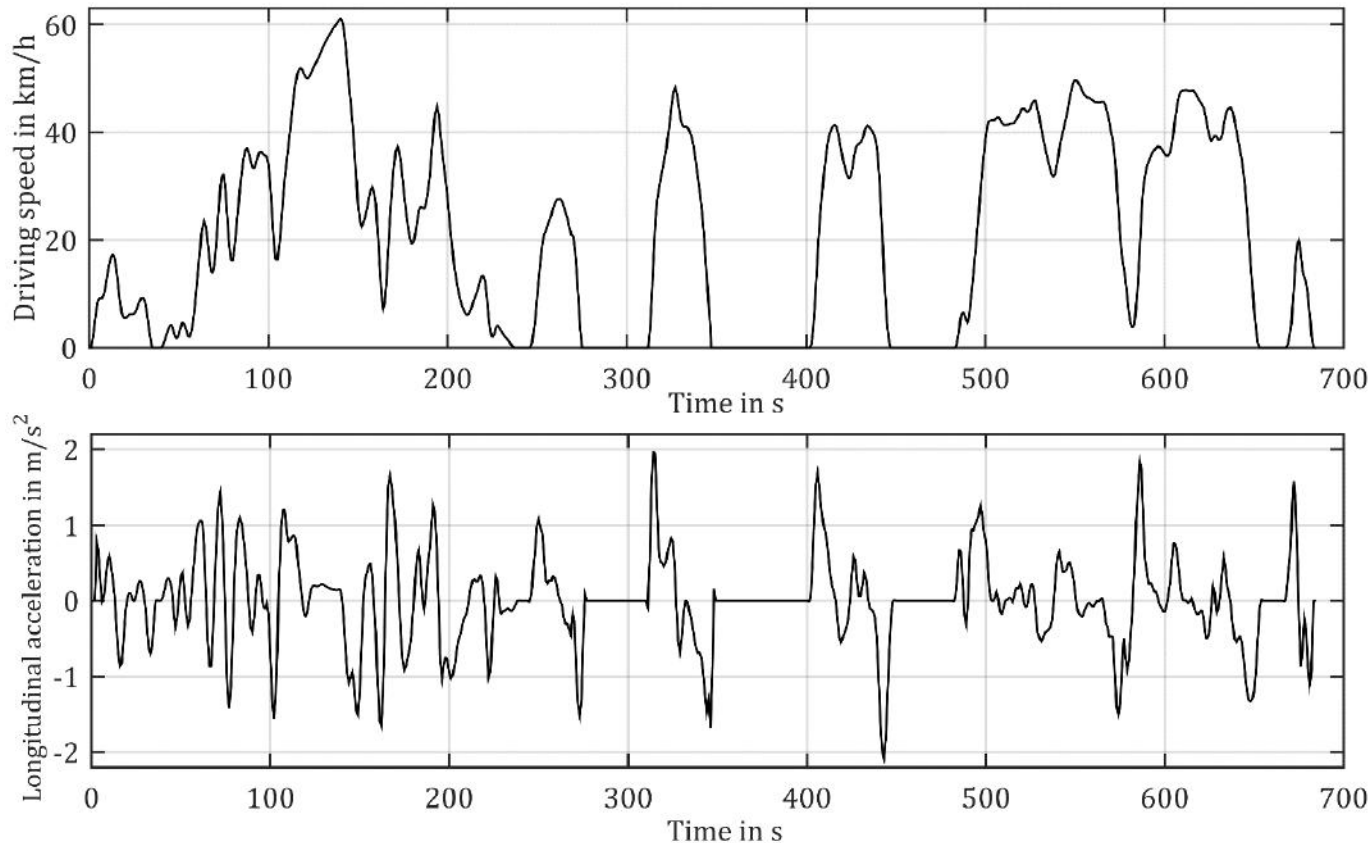
■ Idle: 22.6 %

Fleet-BEV-Cycle (2)

- Cycle represents **mixed operation**
- **Urban** as well as **rural** speeds play important role



Fleet-BEV-Urban-Cycle (1)



■ Length: 4,021 m

■ Duration: 684s

■ 7 micro-trips

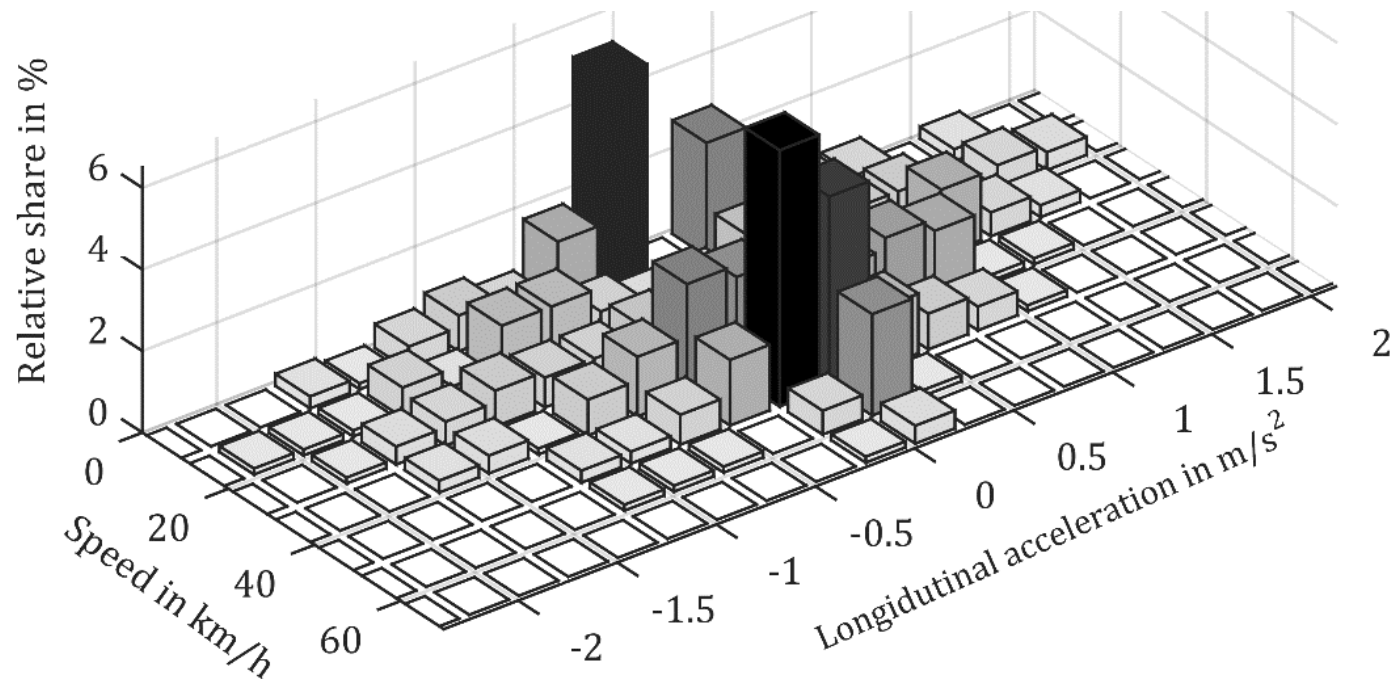
■ $\bar{v}$: 21.2 km/h

■ $\bar{v}_{v>0}$: 27.6 km/h

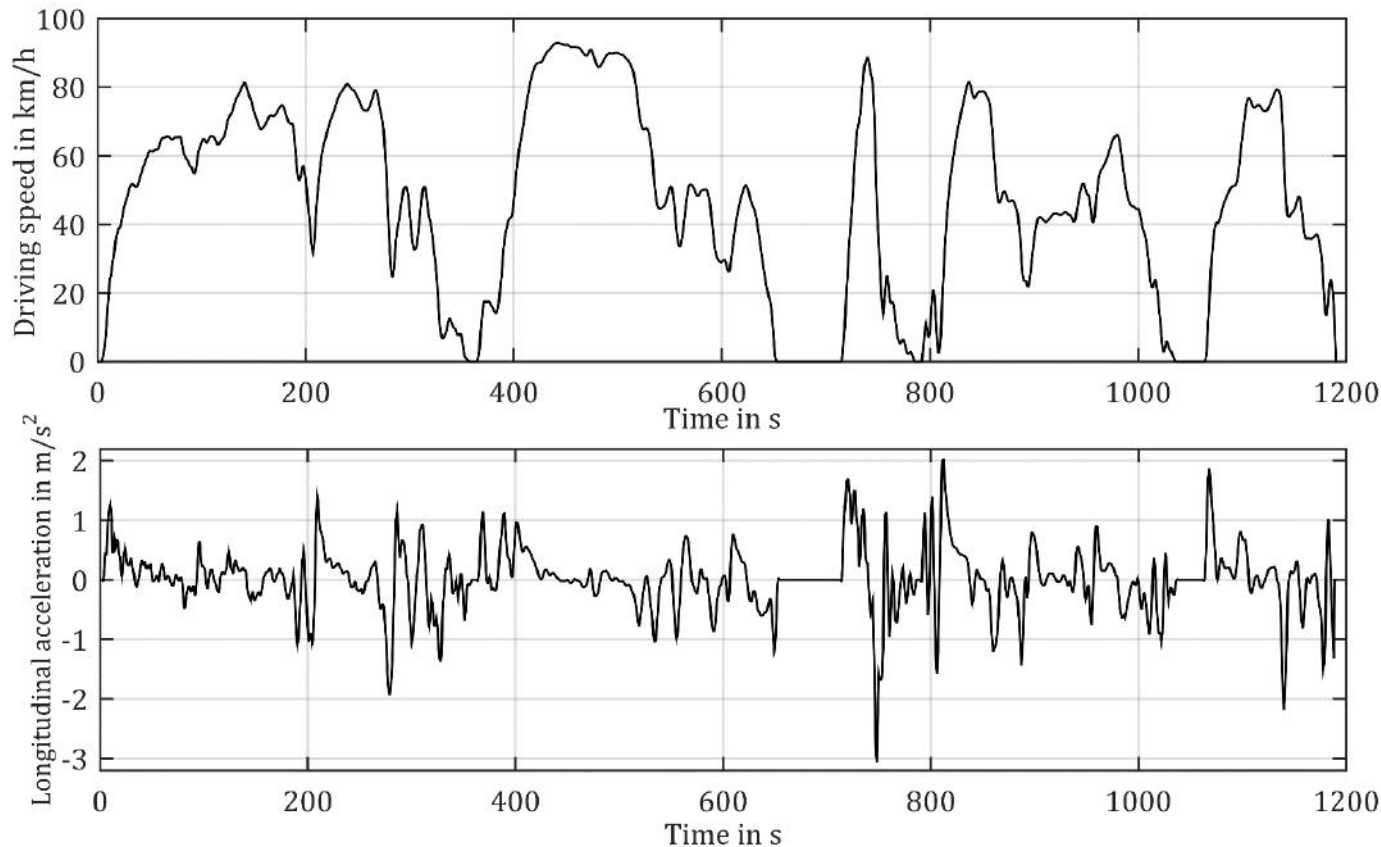
■ Idle: 23.3 %

Fleet-BEV-Urban-Cycle (2)

- Exclusively built on **urban micro-trips**
(never faster than 70 km/h, more than 80 % of time below 60 km/h)
- Dominant class is **constant driving** between 40 and 50 km/h
- **Volatile speed** profile



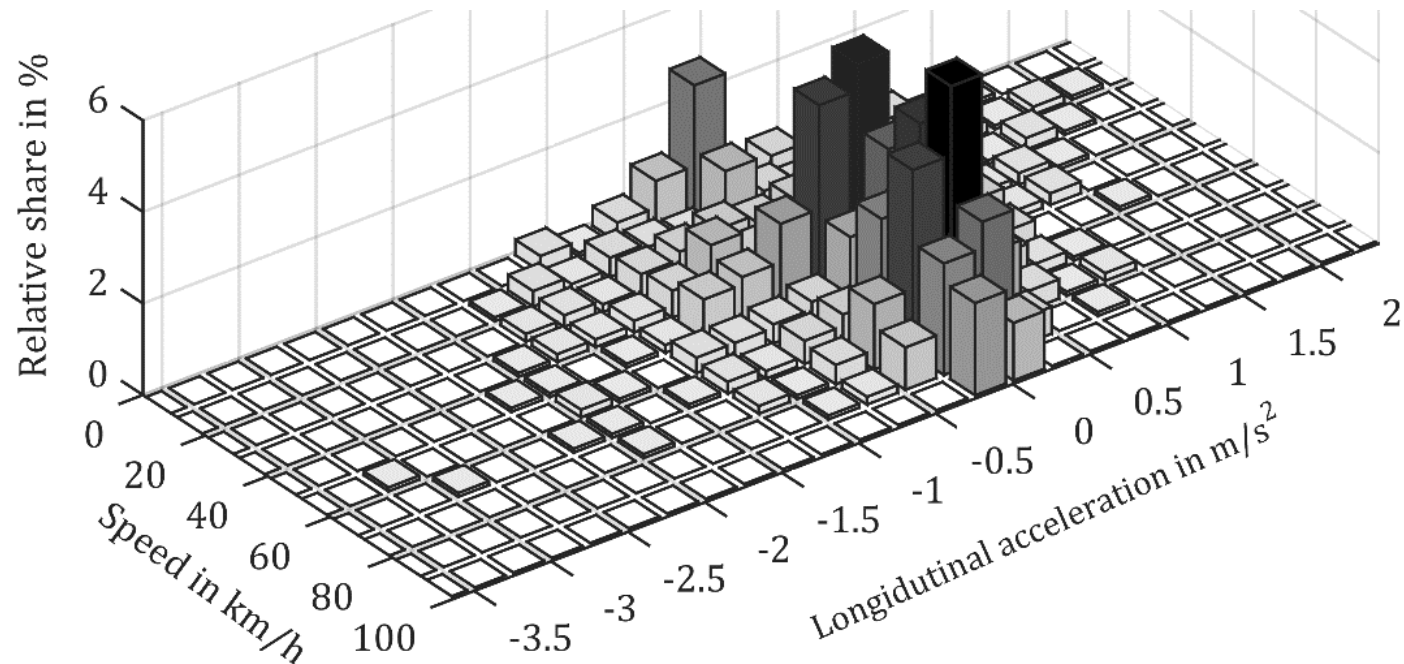
Fleet-BEV-Rural-Cycle (1)



- Length: 15,393 m
- Duration: 1,190 s
- 5 micro-trips
- $\bar{v}$: 46.6 km/h
- $\bar{v}_{v>0}$: 34.6 km/h
- Idle: 9.3 %

Fleet-BEV-Rural-Cycle (2)

- Exclusively built on **rural micro-trips**
(at least 20 % of driving time >60 km/h, at least once >70 km/h)
- Focus on **rural speed** around 70 km/h, but also **city passes**
- Higher proportion of **constant driving**



Comparison of Driving Cycles

	Length (m)	Duration (s)	Average speed (km/h)	Maximum speed (km/h)	Idle (%)	Number of Acc/Dec-changes per km	Rel. PKE in %*
Fleet-BEV-Cycle	5,828	783	26.7	78	22.6	5.3	100
Fleet-BEV-Urban-Cycle	4,021	684	21.2	61	23.3	7.2	114.6
Fleet-BEV-Rural-Cycle	15,393	1,190	46.6	92.9	9.3	2.6	83.5
NEDC	11,013	1,220	33.4	120	27.3	1.27	57.8
WLTP for class 3 Vehicles	23,000	1,800	46.5	120	13	2	79.8

*Rel. PKE = Relative normalised positive acceleration kinetic energy

■ NEDC:

- **Longer** and **faster** than two of three cycles
- **Less** accelerations and **dynamic** aspects

■ WLTP:

- 23 km: **Longer than 96.5 %** of monitored trips, similarities with rural cycle
- More dynamic aspects than NEDC, less than Fleet-BEV-Cycles

Comparison of Driving Cycles

Fleet-BEV-Cycle

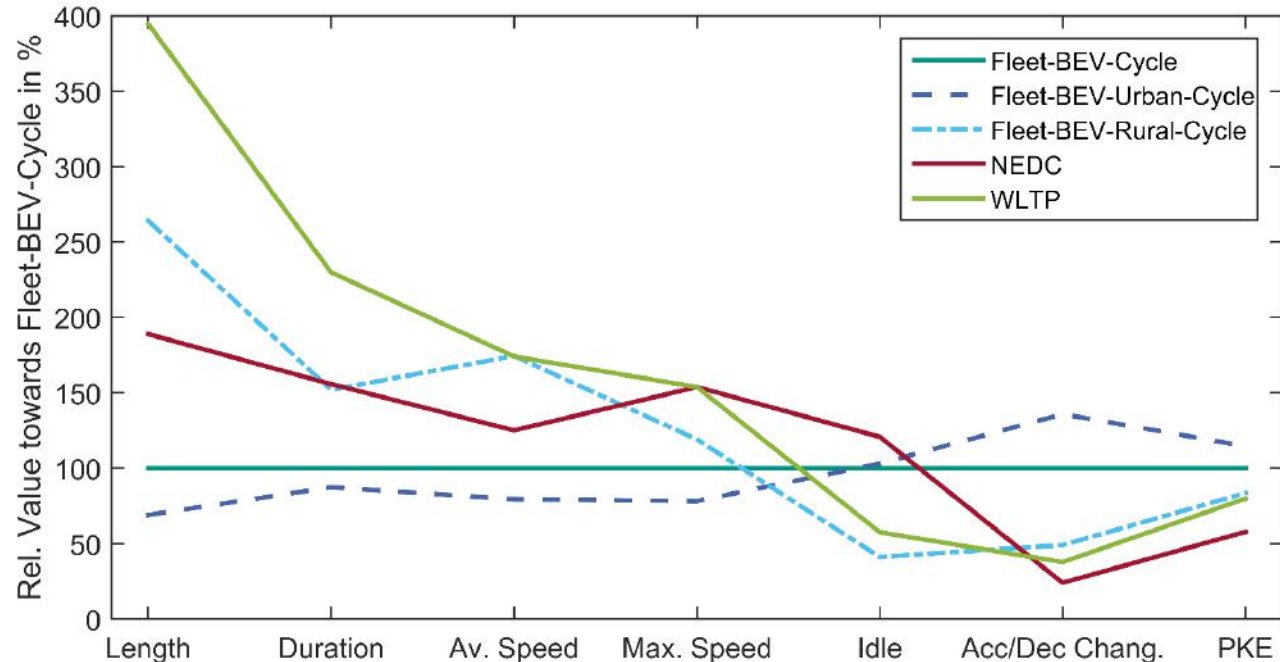
Fleet-BEV-
Urban-Cycle

Fleet-BEV-Rural-
Cycle

NEDC

WLTP for class 3
Vehicles

*Rel. PKE = Relative norm



■ NEDC:

- **Longer** and **faster** than two of three cycles
- **Less** accelerations and **dynamic** aspects

■ WLTP:

- 23 km: **Longer than 96.5 %** of monitored trips, similarities with rural cycle
- More dynamic aspects than NEDC, less than Fleet-BEV-Cycles

Conclusion and Outlook

- Driving cycles **important instrument** in vehicle development but often **improper representation** of real-world driving
- Large **data** collection with **Field Operational Test**
- Focus on **BEV** in **commercial fleets**
- **Three driving cycles** built up with micro-trip methodology
- Fleet-BEV-Cycles show significant **differences** to **NEDC** and **WLTP**
- Further **evaluation** of cycles in **simulation** and **bench test** suggested
- Maybe **adaption** necessary for usage with human drivers (smoother speed profiles)
- Tool for experiments on **energetic consumption** as well as the development of **components** and **vehicles**

Thank you very much for your attention!



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