DELIVERABLE 2.1, DRIVING CYCLE AS FINGERPRINT OF BRAKING FOR SELECTED CITY NETWORKS AND PROCESS FOR TRANSFER TO OTHER CITIES

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Work Package Lead	M+H
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DoA	Driving cycle as fingerprint of braking for selected city networks and process for transfer to other cities. This deliverable refers to task 2.1.

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DATE	VERSION	AUTHOR	COMMENT
31/01/2023	1	Niemann	First draft of deliverable
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30/10/2023	3	Niemann	Final Report – Revised Version after internal quality check
30/11/2023	4	Niemann	Final Report – Revised Version after review of PO

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LIST OF ABBREVIATIONS

ACRONYM	DESCRIPTION
VMAX	LINK Vehicle Measurement and Data Acquisiton System
CDF	Cumulative Density Function
AUVASA	**Autobuses Urbanos de Valladolid, S. A.**
IUTA	Institut für Umwelt & Energie, Technik & Analytik e.V.
M+H	**Mann + Hummel International GmbH & Co. KG**
ZF	**ZF Friedrichshafen AG**

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
a	Acceleration in m/s²
t	Time in s
T	Temperature in °C
v	Velocity in km/h

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SUMMARY

Based on the current state of the art a method for driving cycle generation was chosen and applied to city bus cycles for brake emissions. Measurements in two European cities (Valladolid, Spain and Ancona, Italy) were performed to collect data as a database. In Valladolid three representative bus lines were measured and in Ancona two bus lines were measured. The measured database was analysed regarding its statistical properties, such as speed distribution, velocity distribution and acceleration distribution. Especially the two-dimensional speed-acceleration distribution was analyzed as this is a state of the art criteria for the evaluation of driving cycles.

Different methodologies for the development of a driving cycle were compared and the short trip methodology was chosen as adequate for this task. The short trip method was adopted to generate an adequate driving cycle for each bus line in each partner city. Part of the adoption was the extension of the short trip definition. In the original method a short trip is defined as phase between one stop brake event and another stop brake event. For the application of city busses, this would lead to very short cycle times (1-2 minutes). Therefore, extended short trips were defined as the time between one stop brake event and the n-th stop brake event in a row. With that parameter n the cycle time can be controlled individually. These cycles can be used in the following tasks in dynamometer measurements and have to be evaluated regarding their suitability as an emission cycle.

1. INTRODUCTION

Brake Wear Particles have a significant contribution to traffic related particulate mass emissions in urban environments. Particulate mass in the ambient air is related to several health issues, and therefore a reduction of particulate mass in the ambient air is of interest. Retrofit Brake Emission Filters for city buses are a possible solution to address this issue. The contribution of city buses to brake wear particulate matter in the ambient air is not quantified yet. Emission measurements on a dynamometer are the state-of-the-art method to quantify emission factors. A measurement method for passenger cars is available but a measurement method for commercial vehicles needs to be developed, including a driving cycle. The development of a representative driving cycle for city buses is required. The above-mentioned point is the subject of Task 2.1. The results are of interest to make a measurement procedure for commercial vehicle's brake wear emissions available, and also to understand the contribution of city buses to brake wear particulate matter in ambient air.

1.1. CONTRIBUTIONS OF PARTNERS

Table 1 Contributions of Partners

PARTNER SHORT NAME	CONTRIBUTIONS
AUVASA	Infrastructure and buses for on road measurements in Valladolid
CARTIF	Scientific / Technical Advice
Conerobus	Infrastructure and buses for on road measurements in Ancona
CSIC	Quality Control Partner
IUTA e.V.	Scientific / Technical Advice
LINK Engineering	Vehicle Measurements, Data Analysis, Driving Cycle Generation, Report
M + H	Scientific / Technical Advice
ZF	Scientific / Technical Advice

2. OBJECTIVES AND EXPECTED IMPACT

The braking pattern of city buses was monitored at partner cities Valladolid and Ancona. For this purpose, the minimal viable instrumentation recorded total deceleration and friction brake activity, for Internal Combustion Engine and hybrid buses. Braking and driving events of monitored city driving were condensed into a WLTP-style driving cycle to be run on the dynamometer as a short but representative sequence for the respective partner city. Emissions of the transport network of the city were estimated (in a later phase of the project) based on such dynamometer runs. The process of cycle development was documented to be applicable to other cities.

3. STATE OF THE ART ON DRIVING CYCLE GENERATION

In literature [1] different methods for the generation of driving cycles are known. Each one has certain fields of applications and its own advantages and disadvantages. In general, four main classes of methods are known:

- Micro-Trip based method
- Segment based method
- Pattern Classification
- Modal Cycle Construction / Markov Chains

An important step of the cycle generation is the assessment of the cycle in comparison to the measured database. Both cycle generation and assessment are described in the following sections.

3.1.CYCLE CONSTRUCTION METHODS

3.1.1. MICRO-TRIP AND SEGMENT-BASED CYCLE CONSTRUCTION

A micro trip is defined as velocity time series between two stops. Multiple micro trips are assembled in a way that they meet the statistical characteristics of the measured database with minimum deviations. The assembly can be done randomly or by choice of certain trip characteristics. In addition to zero velocity as a criterion for the end of a micro trip, the segment-based method uses changes in road-type to split the velocity time series into pieces. This approach was also used by Steven et al. [2] for the development of the WLTP exhaust and the WLTP brake.

3.1.2. CYCLE CONSTRUCTION WITH PATTERN CLASSIFICATION

Cycle construction with pattern classification uses kinematic sequences / trips. In this method a classification of those kinematic sequences according to statistical criteria is performed and transition probabilities between different classes of consecutive sequences is calculated to address this probability in the cycle development.

3.1.3. MODAL CYCLE CONSTRUCTION

The modal cycle construction method uses Markov Chains, a statistical tool that give the possibility to summarize the statistical properties of the measured database in a matrix, the so-called transition matrix. For this purpose, the measured data is separated in velocity classes / velocity bins e.g., 1 km/h bins. The transition matrix describes the change of speed from second to second (or from sample point to sample point). After summarizing the transition probabilities from one speed class to another speed class in the transition matrix, the transition matrix is used to generate a driving cycle that has the same overall transition probabilities from one speed class to another speed class.

3.2.CYCLE ASSESSMENT CRITERIA

To assess driving cycles and to compare them to the measured reference several cycle assessment criteria are used. Commonly used criteria are:

- average speed
- maximum speed
- minimum speed
- average acceleration
- average deceleration
- Speed-Acceleration Frequency Distribution (SAFD)

4. METHODOLOGY FOR AEROSOLFD DRIVING CYCLE

4.1.DATA COLLECTION

Measurements were performed in Valladolid (3 bus lines) and Ancona (2 bus lines):

- Valladolid Line C1: 26 hours measurement
- Valladolid Line 2: 25 hours measurement
- Valladolid Line 3: 25 hours measurement
- Ancona Line 286 18 m bus: 8 hours measurement
- Ancona Line 418: 12 hours measurement

To measure the necessary data, buses were equipped with LINK VMAX data acquisition systems, acceleration sensors (LINK Model 4067-DCX-X5), GPS system for speed and position, as well as thermocouples (Type K) for brake disc temperatures. The installation took place in the workshop of AUVASA and Conerobus with personal from AUVASA, Conerobus, and Link. Link personnel were on site during the whole data collection period. Additionally, wear mass particle measurements of the brake pads were performed in Valladolid. Pictures of the experimental setup are shown in Figures 1-7. The selected bus routes were the most frequently used based on the statement of the bus companies and are shown in Figures 8-12.

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Figure 1: Solaris Bus from AUVASA's Bus Line C1 and Line 3 in Valladolid

Figure 2: LINK VMAX Data Acquisition System

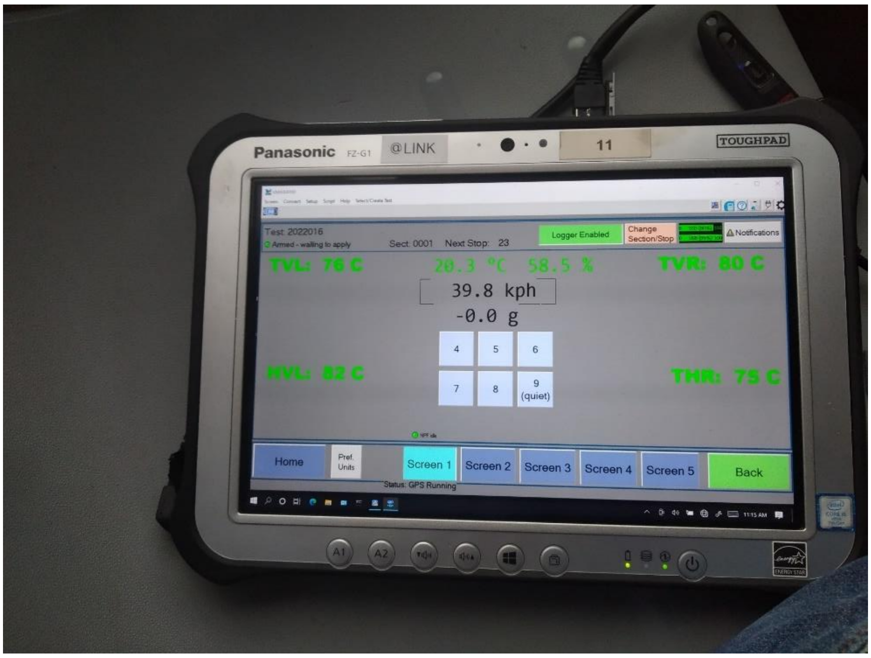

Figure 3: Control Screen for LINK VMAX

Figure 4: LINK VMAX fixed in longitudinal direction to the bus (left) and Control Screen (right)

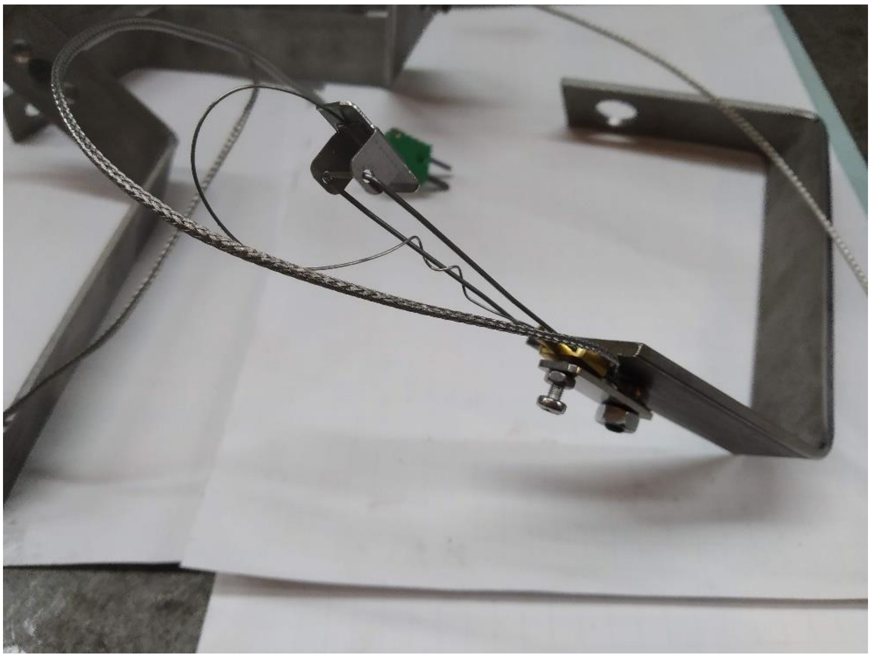

Figure 5: Sliding Thermocouple for temperature measurement at the brake disc's surface

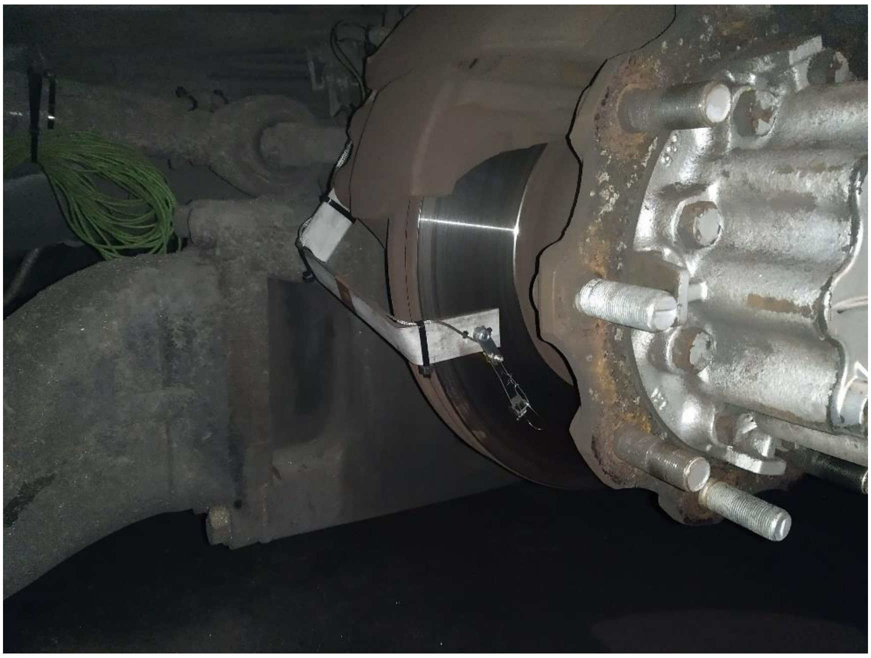

Figure 6: Thermocouple installed at the brake

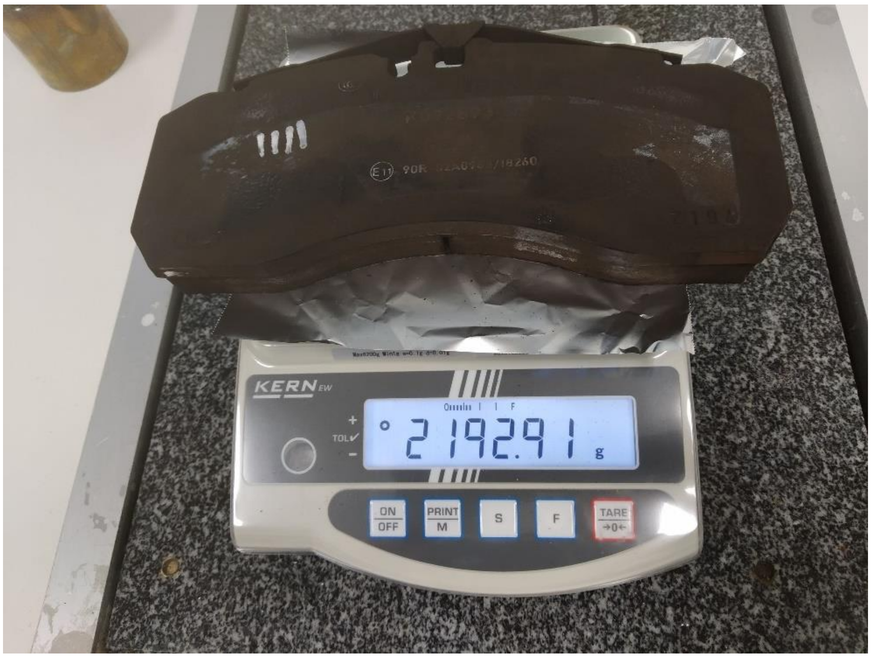

Figure 7: Wear mass measurement of the brake pads

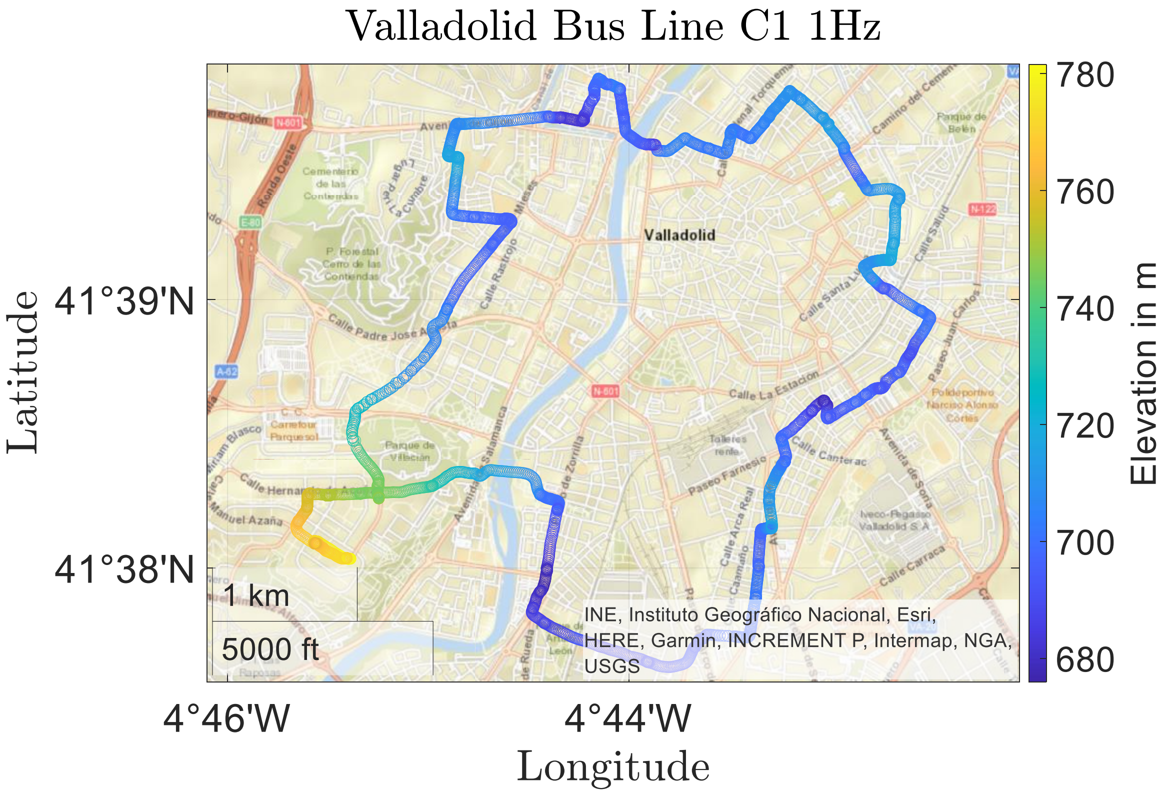

Figure 8: Route of Line C1 in Valladolid including GPS height information

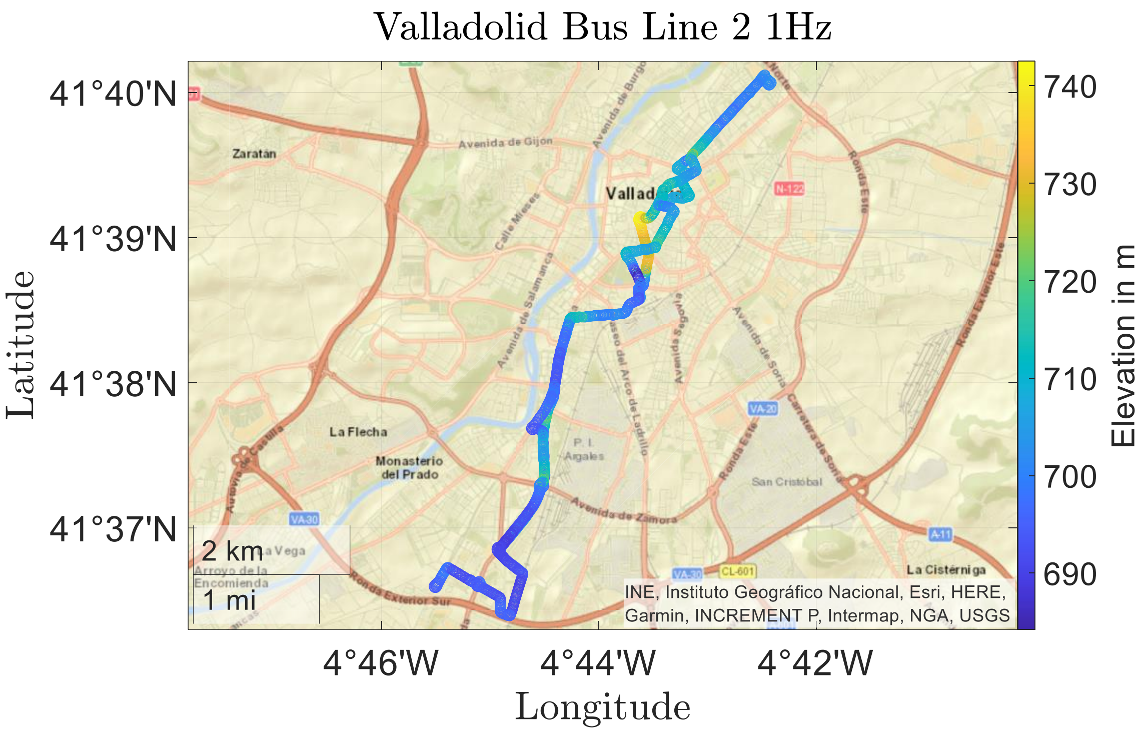

Figure 9: Route of Line 2 in Valladolid including GPS height information

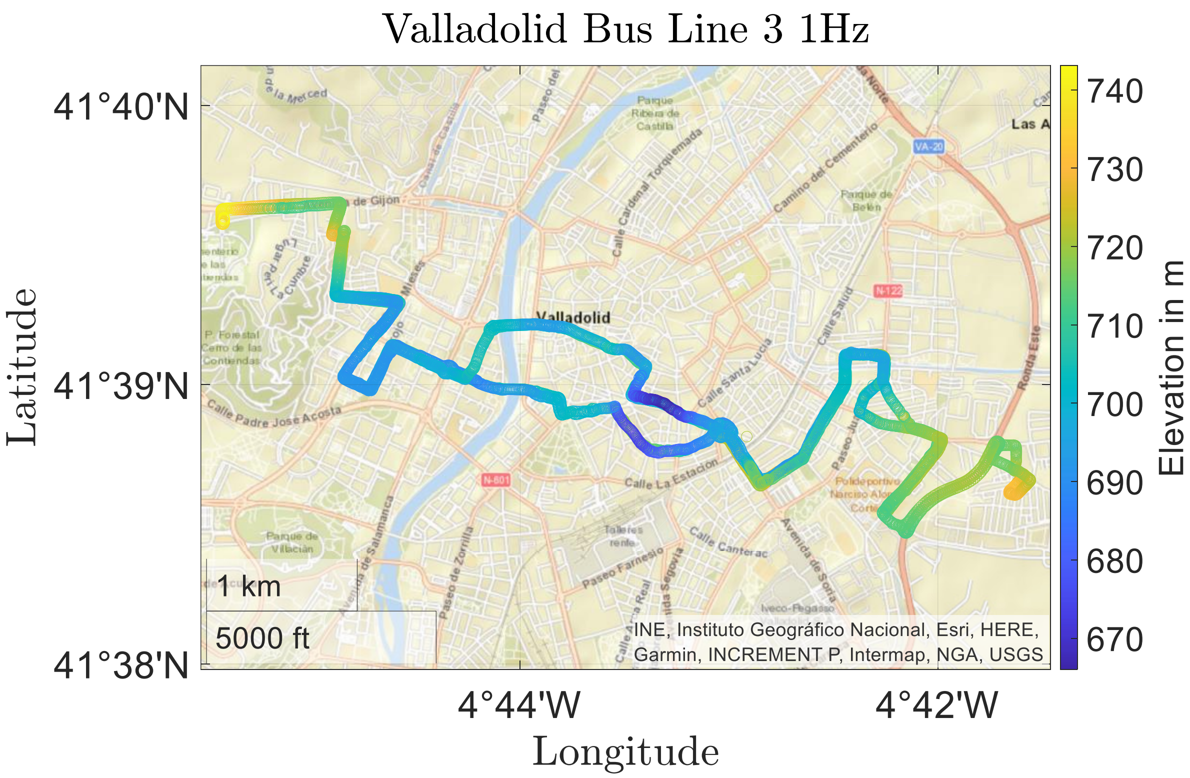

Figure 10: Route of Line 3 in Valladolid including GPS height information

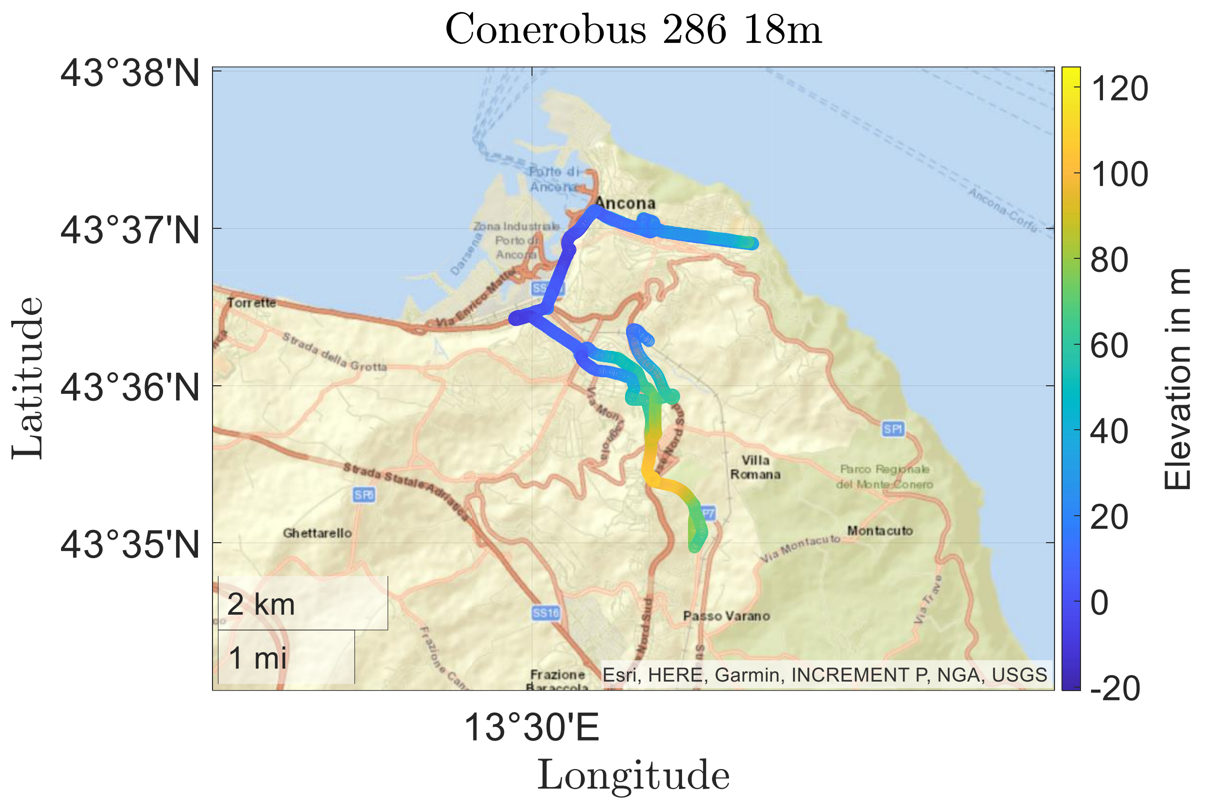

Figure 11: Route of Line 286 in Ancona with the 18 m Bus including GPS height information

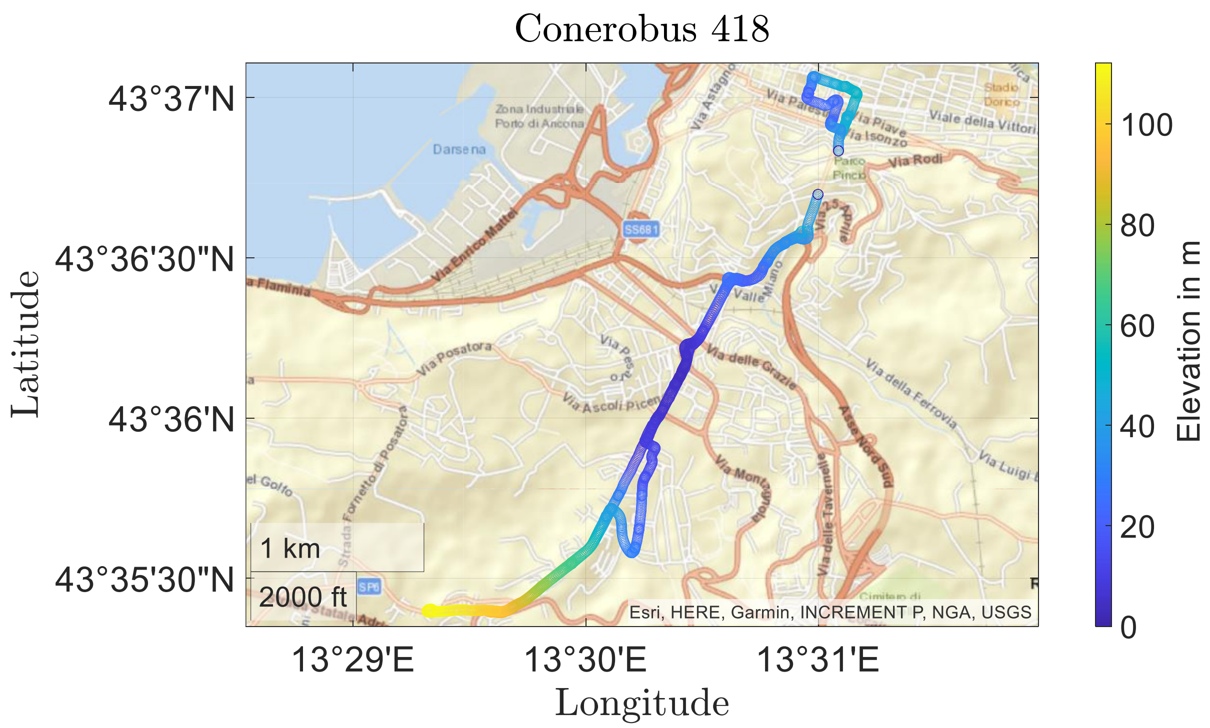

Figure 12: Route of Line 418 in Ancona including GPS height information

4.2. CYCLE CONSTRUCTION METHOD AND CYCLE ASSESSMENT CRITERIA

The driving cycle generation method used in Aerosolfd is a micro trip method (see 3.1.1), that was adopted by Steven et al. [2] and was also used for the development of the WLTP exhaust [2] and the WLTP Brake [3]. It was chosen as it is a state-of-the-art method. In comparison to cycle generation with Markov Chains it has the advantage that it can also deal with less data, as Markov Chains requirefilled-out transition matrix, which cannot be guaranteed with the available data sets. Cumulative Density Functions (CDF) of speed and acceleration will be used as assessment criteria.

5. RESULTS

Figure 13 shows the time series of velocity and brake disc temperatures (left blue axis). Standstill phases are marked with blue circles and Numbers (St 14, St 15 etc.). The start and end points of the stop phases are also used to determine the beginning and the end of short trips. Accelerations (measured with inertial measurement unit, calculated from GPS velocity and calculated from GPS velocity with filtering) are plotted on the right orange axes as well as the signal from the brake switch which indicates the drivers input on the brake pedal as binary signal. Brake events are extracted from the filtered velocity signal by applying a threshold of 0.16 m/s² which indicates the beginning of a deceleration phase that is not just caused by driving resistances [4]. The same data is plotted in Figure 14 in an enlarged view.

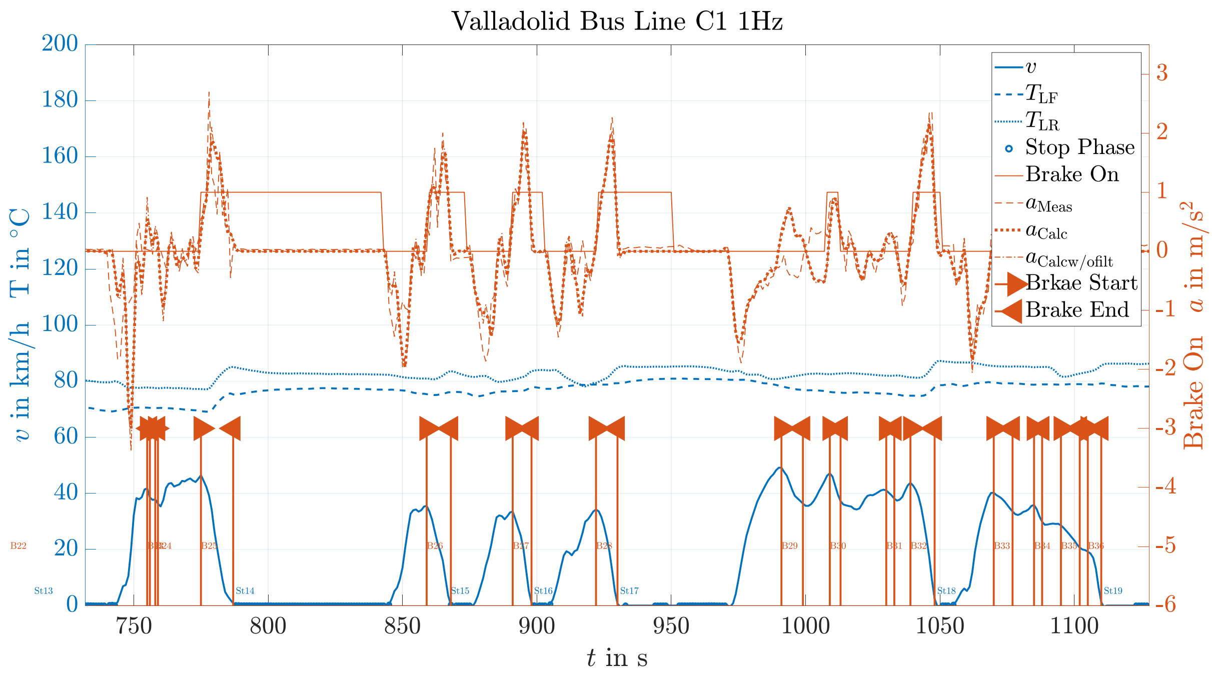

Figure 13: Time series of velocity, brake disc temperatures, 'brake on' signal, accelerations (measured, calculated, calculated and filtered with Savitzky-Golay-filter), numbered stop phases, numbered brake start and end points.

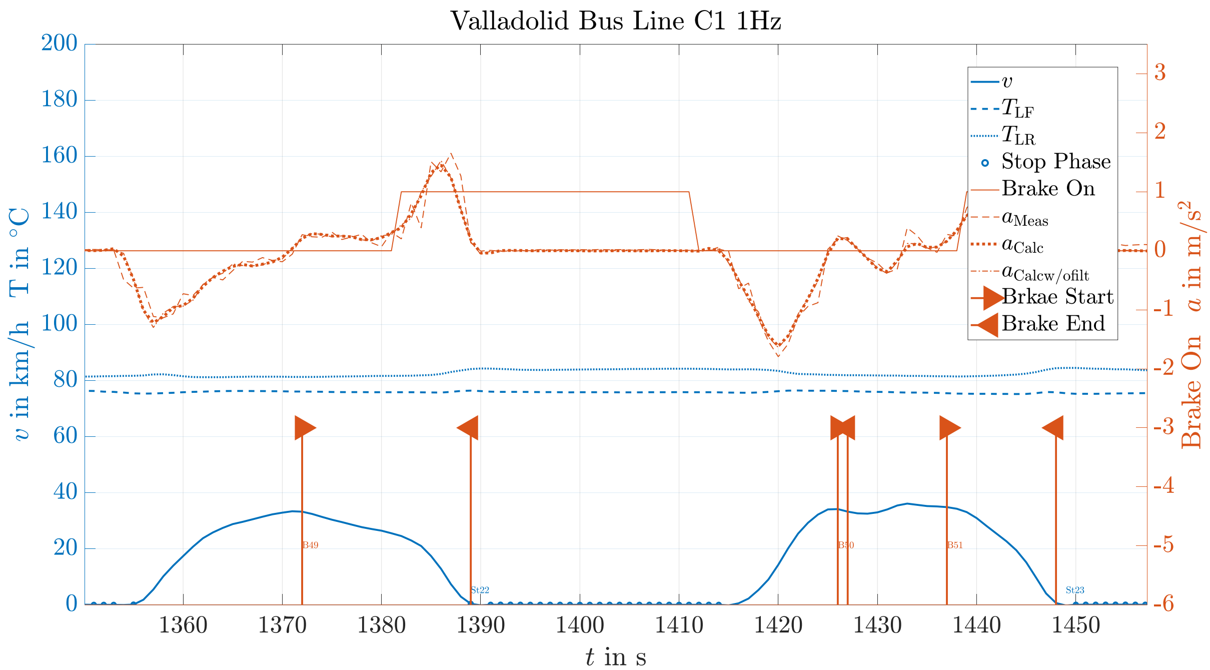

Figure 14: Detailed view of time series of velocity, brake disc temperatures, 'brake on' signal, accelerations (measured, calculated, calculated and filtered with Savitzky-Golay-filter), numbered stop phases, numbered brake start and end points.

5.1.STATISTICAL ASSESSMENT OF THE MEASURED COLLECTIVE

As baseline for the development of the driving cycle, the statistical characteristics of the measured data are analysed. In this section data from Valladolid Bus Line C1 is used as an example to explain the process of cycle generation in detail and to explain the modifications that were made / the parameters that were changed in order to adjust the original short-trip method. All calculations were performed with a dataset sampled at 1 Hz. Figure 15 shows the distribution of acceleration and deceleration, which is characterised by a nearly symmetric behaviour. A maximum acceleration of approximately 2 m/s² occurred. Approximately 40 % of the time was standstill time. The temperatures at the rear axle higher than at front axle, probably due to use of a retarder and wheel load distribution. The average disc temperature at the front axle is approximately 70 °C and at the rear axle 75 (right side) to 85 °C (left side).

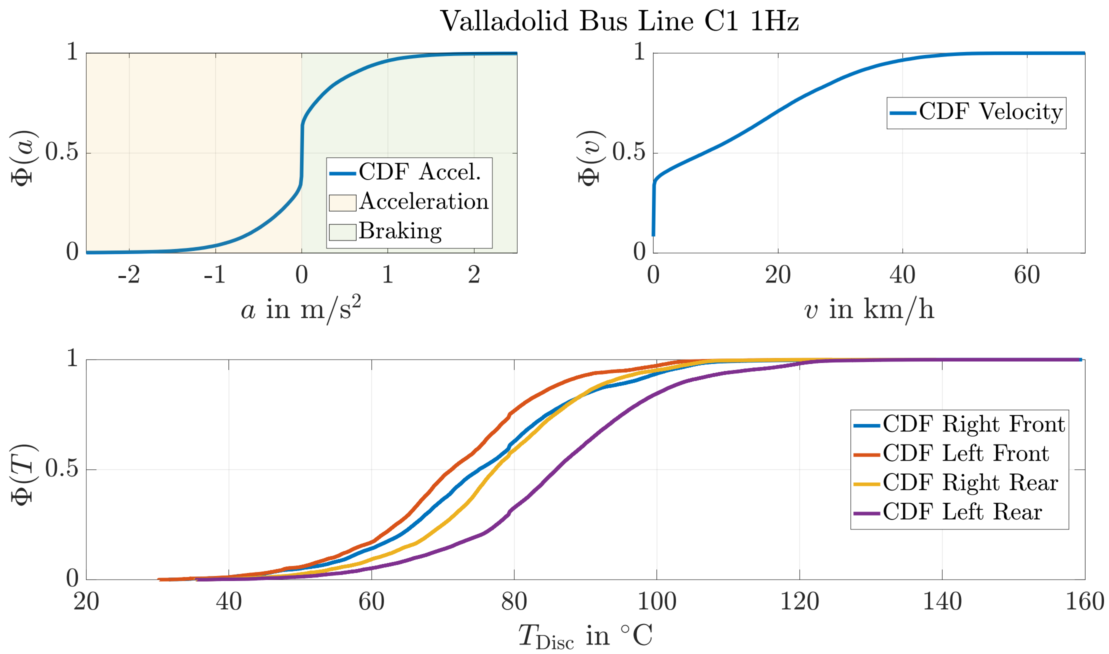

Figure 15: Cumulative density function of acceleration (top left), velocity (top right) and disc temperatures (bottom) for Valladolid Bus Line C1

Figure 16 shows the distribution of acceleration and velocity in a two-dimensional graphical representation. An advantage compared to one dimensional graph in Figure 15 is that it is possible to see at which velocities which accelerations occurred. This information is important at the end of the development process, when the measured database is compared to the developed driving cycle, so the generated driving cycle has to meet the velocity-acceleration distribution of the database as close as possible.

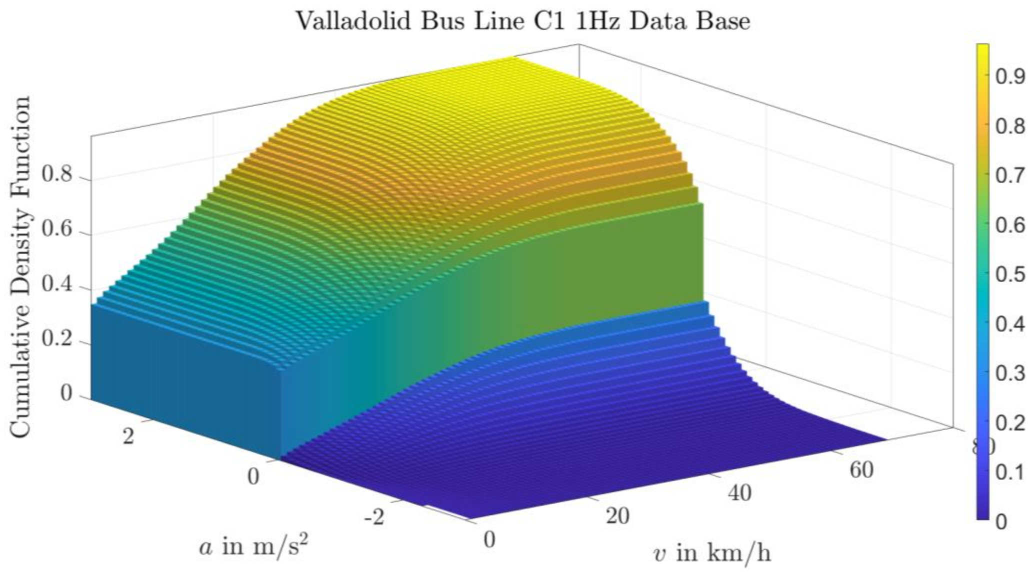

Figure 16: Two-Dimensional Cumulative Density Function of velocity and acceleration for Valladolid Bus Line C1

5.2. DRIVING CYCLE GENERATION ACCORDING TO ORIGINAL METHOD

The methodology used for the development of WLTP exhaust analysed the data for multiple speeds (low, medium, high, extra high). The advantage of this methodology is that the speed characteristics of different countries can be separated and additionally the computation effort for the cycle development is lower. Figure 17 shows the distributions of short trip time in the measurements of Valladolid Bus line C1. This distribution is used in the original short trip method to reduce the computation effort for driving cycle generation by choosing *n* short trip times, that will be used for the later driving cycle. To ensure that these short trip times are representative compared to the database, they are chosen from *n*=4 intervals of the short trip durations of the database. These intervals can be found in Figure 17 on the right orange y-axis as black dotted lines of the cumulative distribution. Short Trips with this short trip duration are used in the next step by combining them in all possible combinations to multiple cycle candidates. A selection of those candidate cycles are plotted in Figure 18.

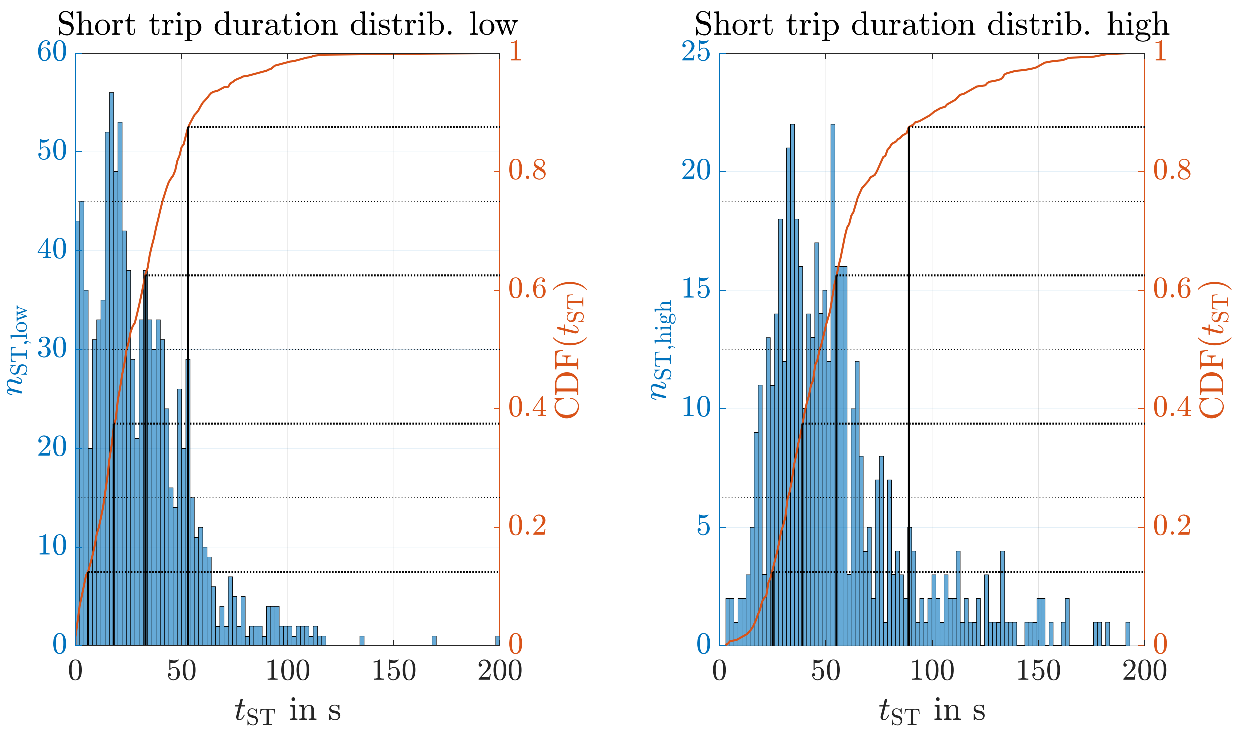

Figure 17: Distribution of short trip durations for low and highspeed section: histogram (left blue axes) and cumulative density function (right orange axes) for Valladolid Bus Line C1

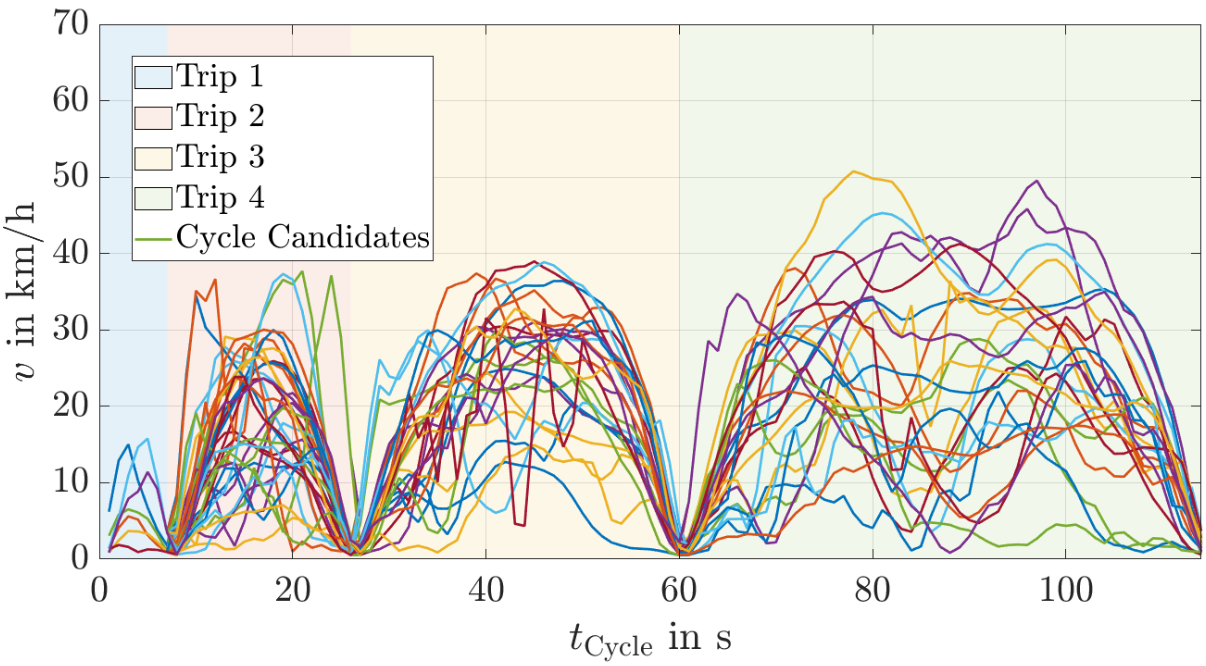

Figure 18: Candidate cycles generated from short trips for Valladolid Bus Line C1

In Figure 19 and Figure 20 two exemplary cycles are shown as velocity time profile (left diagrams) and as cumulative distribution (right diagrams). In these figures two problems can be seen:

1. The cycle time is very short (120 s), which would be not appropriate for gravimetric filter measurements.
2. Due to the short cycle time only a very limited number of speed-acceleration data points are available for the calculation of the frequency distribution / cumulative distribution. A higher number of data points would be desirable for a precise comparison of the statistical properties of the measured database and the newly generated driving cycle. Therefore, the original method was adopted, which is described in the next section.

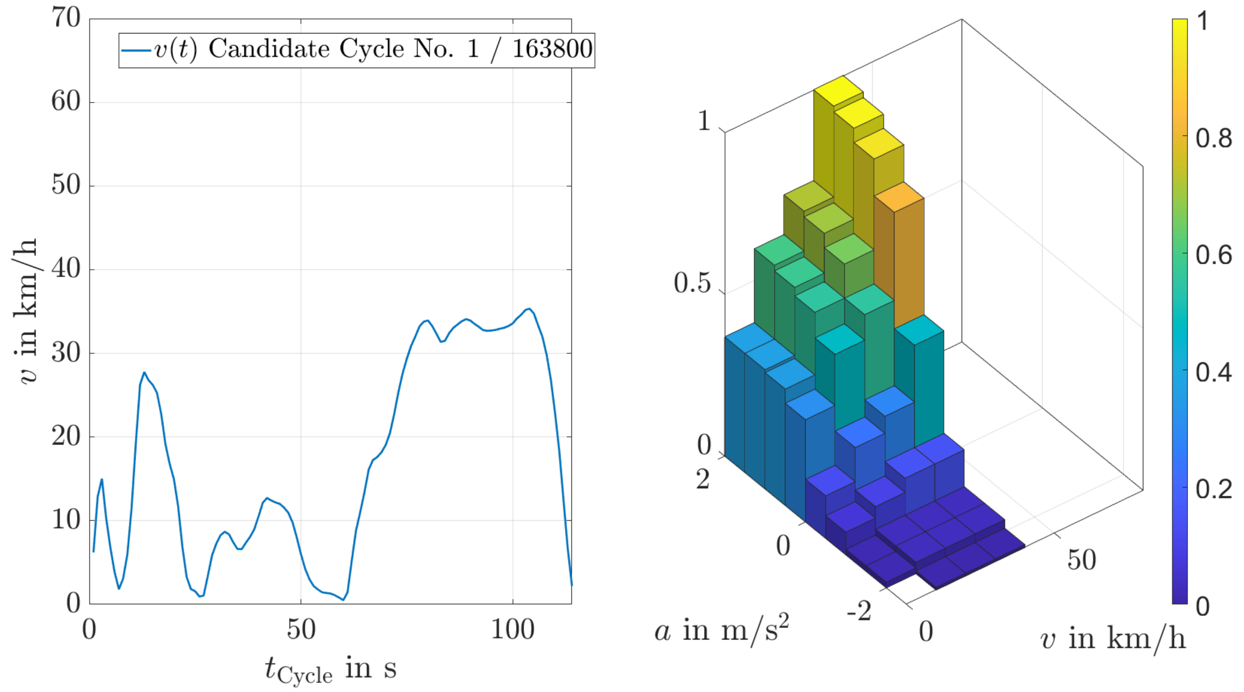

Figure 19: Velocity time series for candidate cycle 1 from 163800 cycles for Valladolid Bus Line C1 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right)

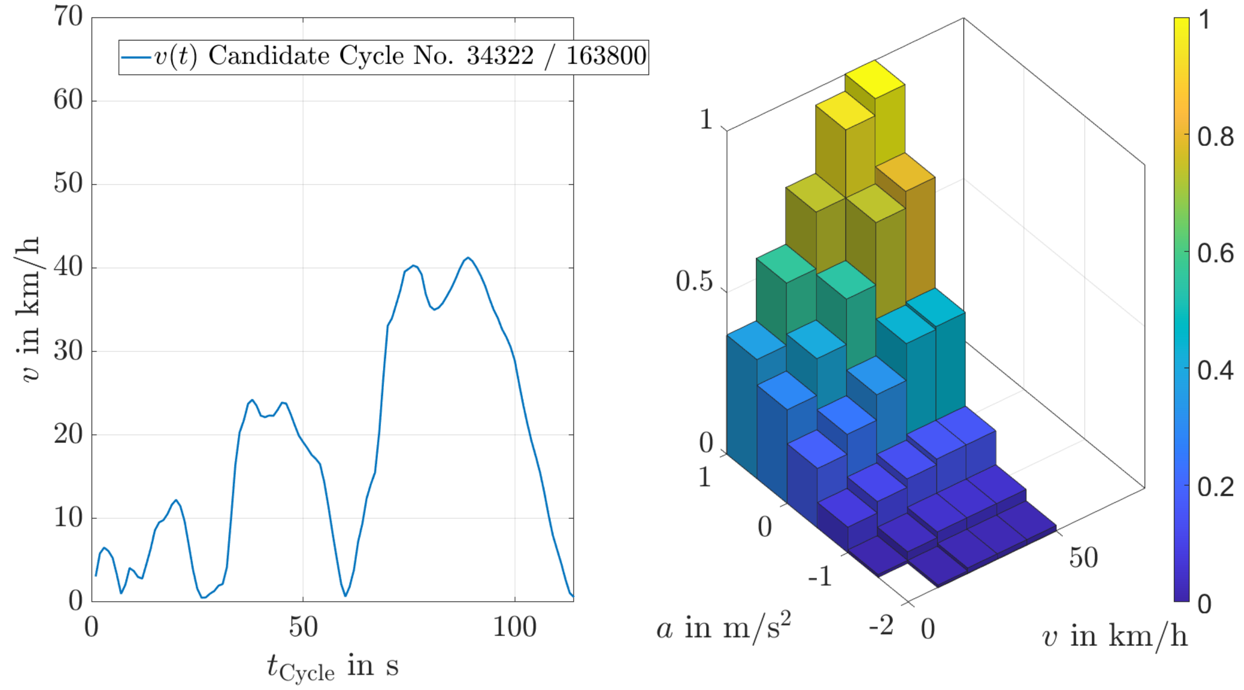

Figure 20: Velocity time series for candidate cycle 1 from 163800 cycles for Valladolid Bus Line C1 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right)

5.3. CHALLENGES FOR CITY BUS CYCLE DEVELOPMENT AND MODIFIED METHODOLOGY

The original short trip method [2] for the development of a driving cycle leads in the application of city buses to very short cycles in the application of city bus cycles as the short trips (time from stop to stop) are very short. The cycle time could be increased by …

- … using more computation time than available on a personal desktop computer (not efficient and not preferred),
- … increasing short trip time by defining a short trip as time from stop to 2nd, 3rd, 4th stop in a row,
- … defining wider intervals for chosen short trip durations (e.g. ±2 s instead of ±1 s)

Therefore, the known methodology [2] was adopted by increasing short trip time (use e.g. 10 short trips and summarize them to extended short trips) and by adapting the intervals for chosen short trip duration. By adapting those parameters desired cycle times can be achieved for individual data sets.

5.4.GENERATED DRIVING CYCLE ACCORDING TO ADOPTED METHOD

Analogous to Figure 17 the short trip duration distribution is plotted in Figure 21 for the adopted methodology with extended short trips (*n*=10) for Valladolid bus line C1.

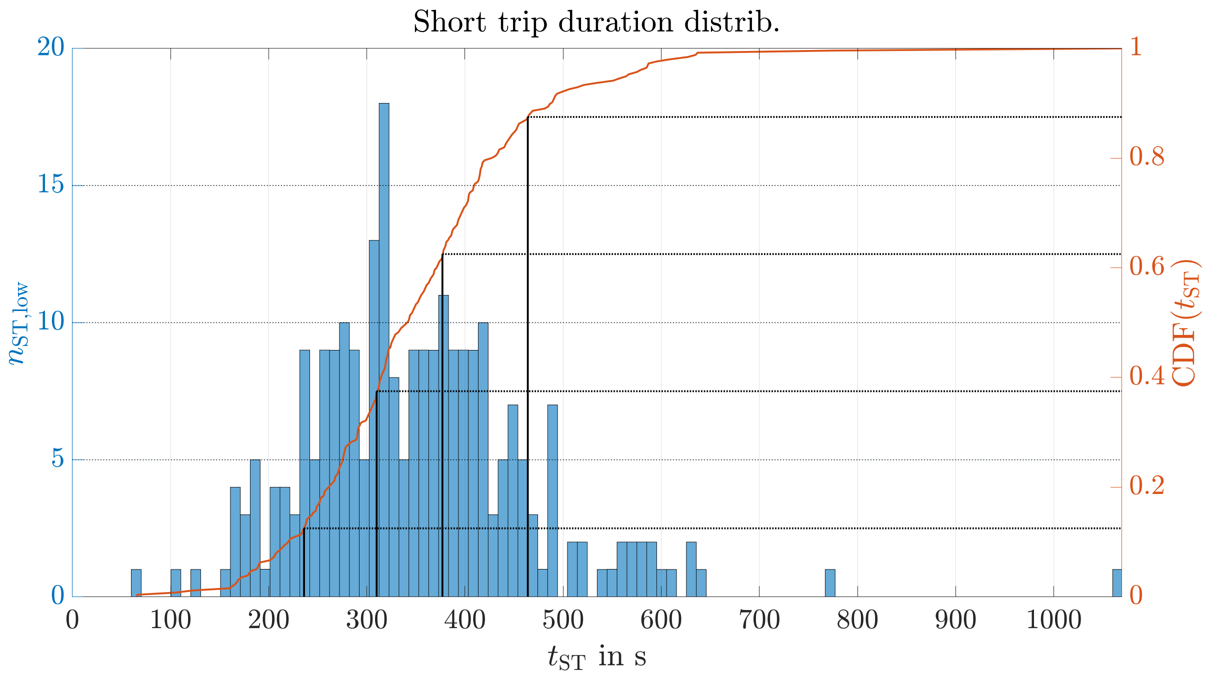

Figure 21: Distribution of short trip durations: histogram (left blue axes) and cumulative density function (right orange axes) for Valladolid Bus Line C1

Based on the extended short trips chosen with the data in Figure 21 candidate cycles are generated and visualized as velocity time profiles in Figure 22. Two exemplary cycles are shown in Figure 23 (cycle no. 1 from 400) and Figure 24 (cycle no. 166 from 400). Cycle no 166 was plotted as it turned out to be the cycle candidate that was closest to the statistical properties of the measured database according to the cumulative speed-acceleration-distribution.

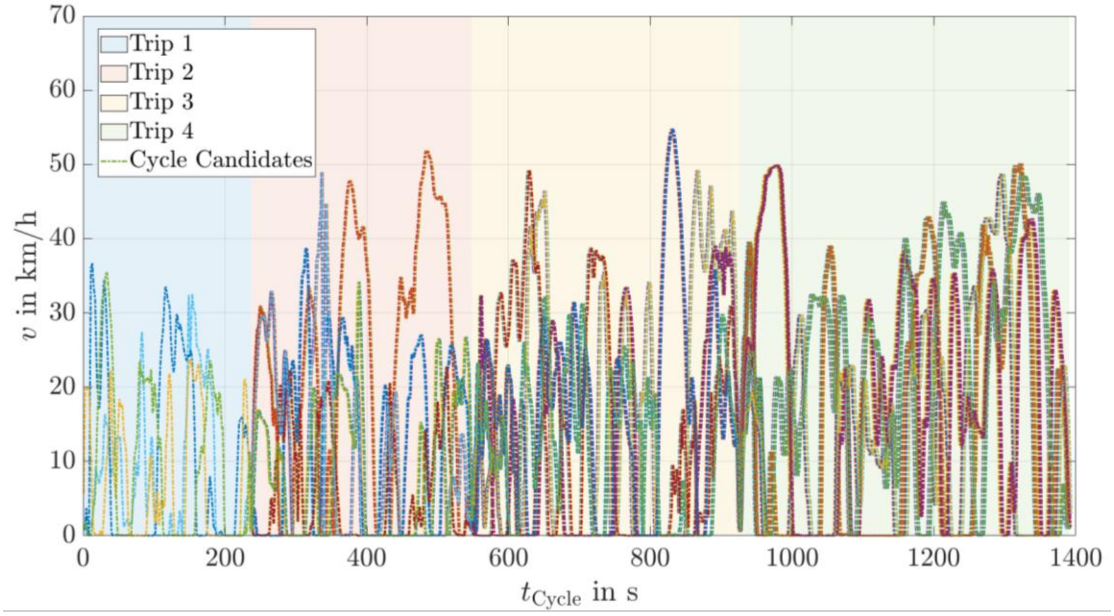

Figure 22: Candidate cycles generated from extended short trips for Valladolid Bus Line C1

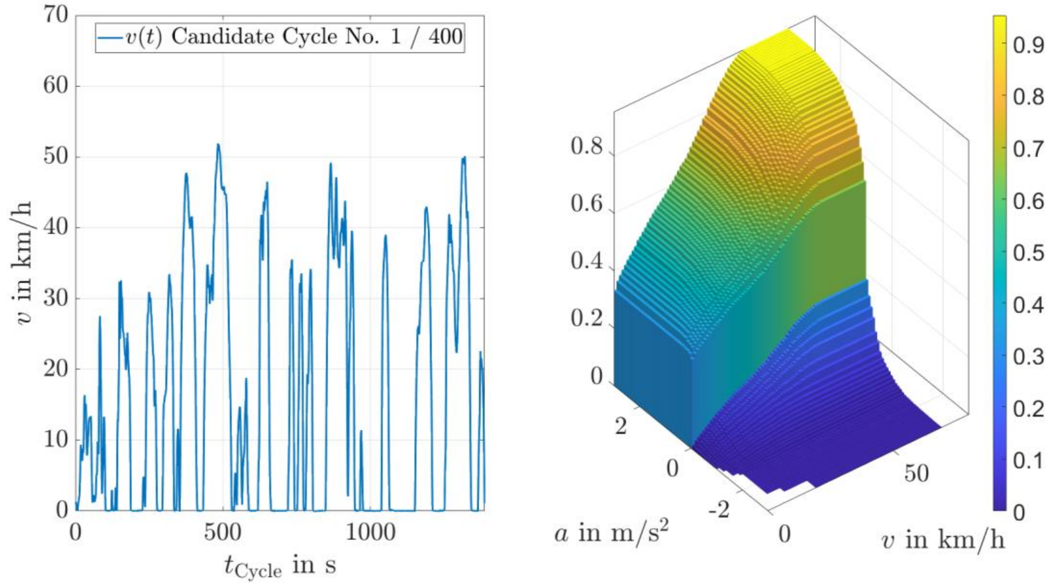

Figure 23: Velocity time series for candidate cycle 1 from 400 cycles for Valladolid Bus Line C1 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection.

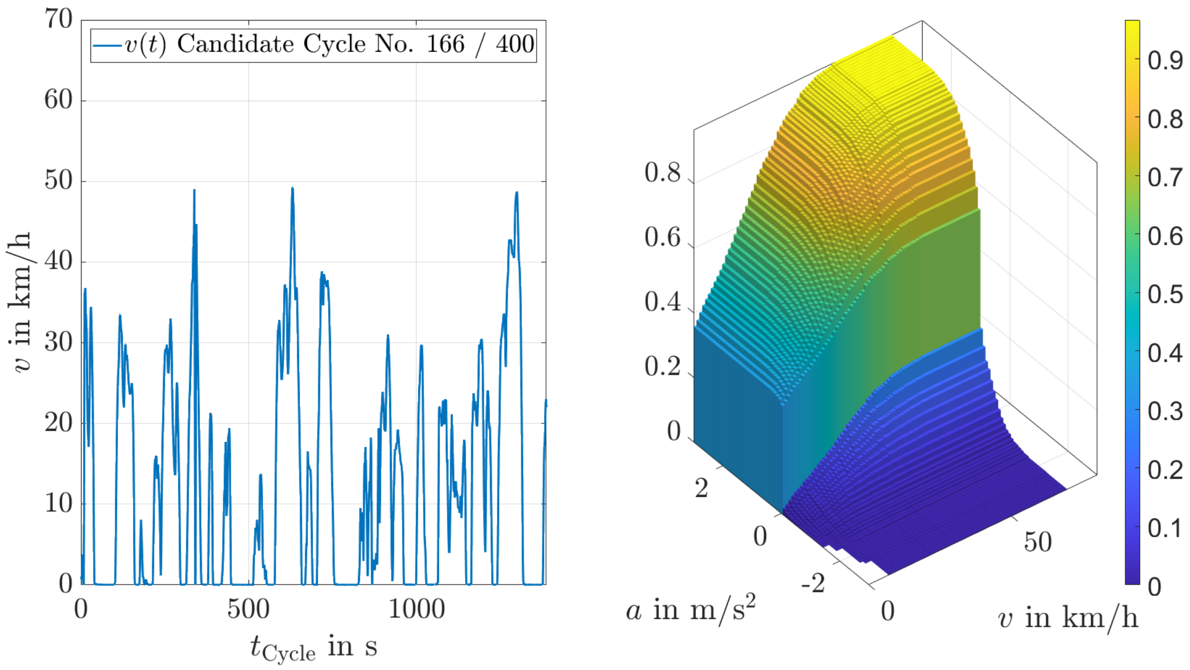

Figure 24: Velocity time series for candidate cycle 166 from 400 cycles for Valladolid Bus Line C1 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection.

5.5. STATISTICAL COMPARISON OF DRIVING CYCLE AND MEASURED COLLECTIVE AND DISCUSSION

As mentioned in the section above, the candidate cycles (400 in case of Valladolid line C1) were compared to the measured database. Therefore, the sum of squared differences of the cumulative velocity-acceleration-distribution were calculated for each cycle candidate. Those differences are plotted in Figure 25 the cycle candidate with the lowest deviation from the database is highlighted by means of the orange arrow (cycle no. 166).

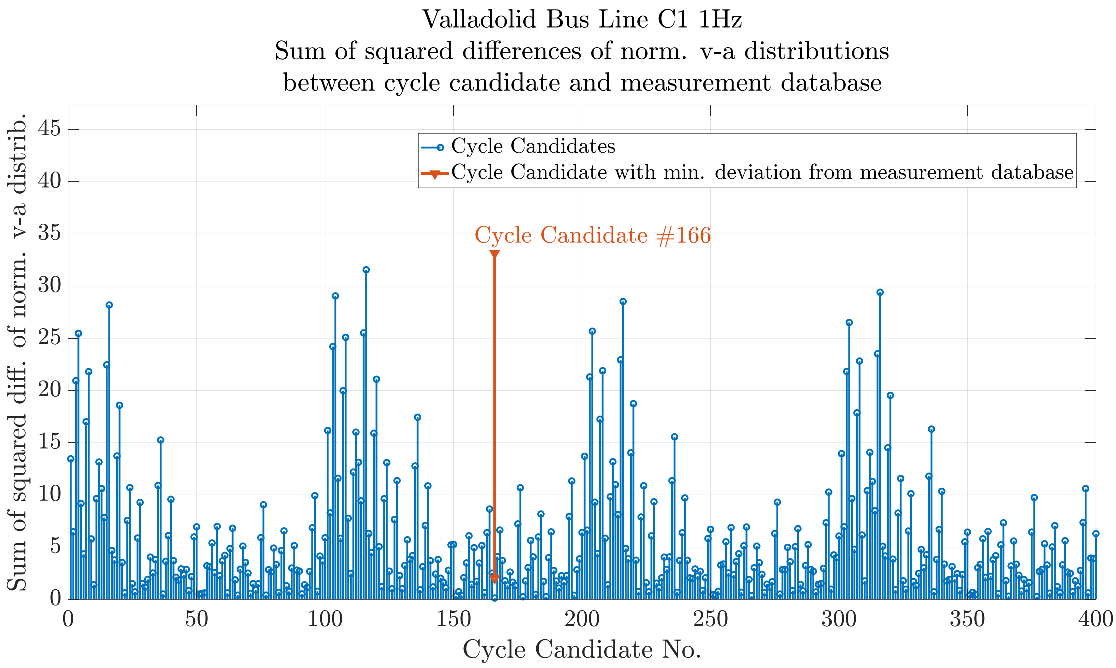

Figure 25: Difference between candidate cycles and whole measurement database in terms of the sum of squared differences of the cumulative density functions of velocity-acceleration-distribution for Valladolid Bus Line C1

To visualize the similarity of the best candidate cycle for Valladolid Bus Line C1 (cycle candidate no. 166) and the measured database, the corresponding cumulative velocity and acceleration distributions are plotted in Figure 26. This diagram shows that the newly generated cycle for Valladolid Bus Line C1 and the measured database are within the tolerance of line thickness. According to the method described above all bus lines are analysed and cycles for each bus line are generated. Those results are shown in the annex.

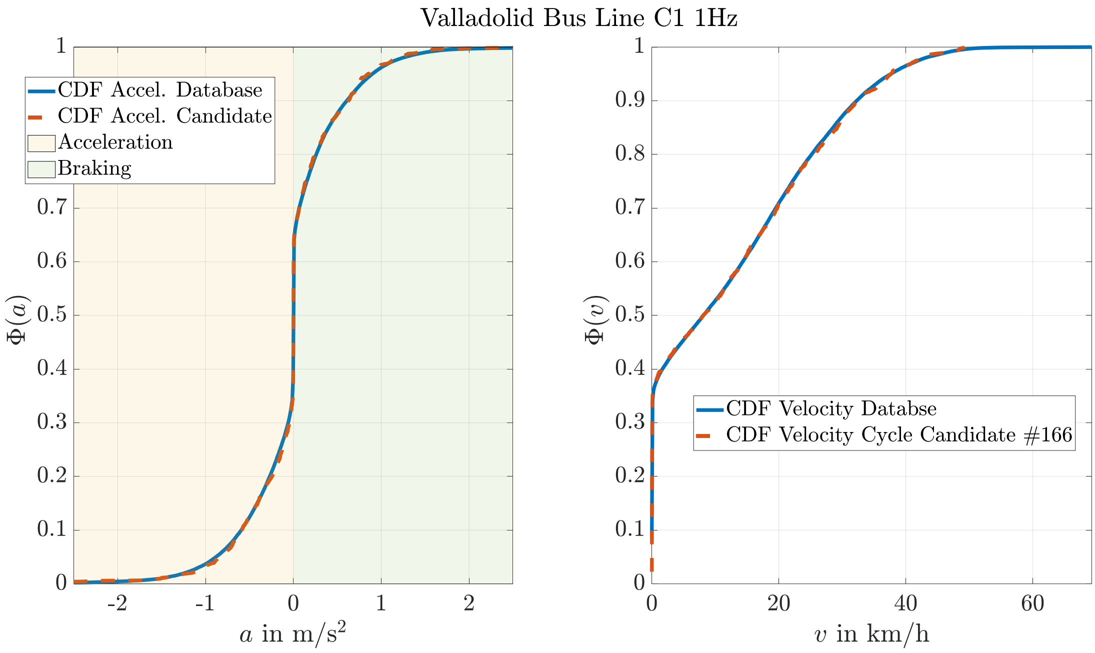

Figure 26: Comparison of measured database (Valladolid Bus Line C1) against best candidate cycle in terms of cumulative density functions for acceleration and velocity

6. LINKS WITH OTHER WPS

The results generated in Task 2.1 will be used in Task 2.2 (Definition of dynamometer testing protocol and determination of the baseline of brake polluting emissions) and 2.4 (Lab-Testing of real brake part with real retrofit brake dust particle filter) for the dynamometer tests that are used for the measurement of particle emission factors with and without retrofit solutions. There is no link to other work packages.

7. CONCLUSIONS

Based on the current state of the art a method for driving cycle generation was chosen and applied to city bus cycles for brake emissions. This adaption was necessary to achieve adequate cycle times. Measurements were performed to collect data as a database. The measured database was analysed regarding its statistical properties, especially speed-acceleration-distribution. A driving cycle generation method was adopted to generate an adequate driving cycle for each bus line in each partner city. These cycles will be used in the following tasks in dynamometer measurements.

8. BIBLIOGRAPHY

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9. ANNEX

9.1. VALLADOLID BUS LINE 2

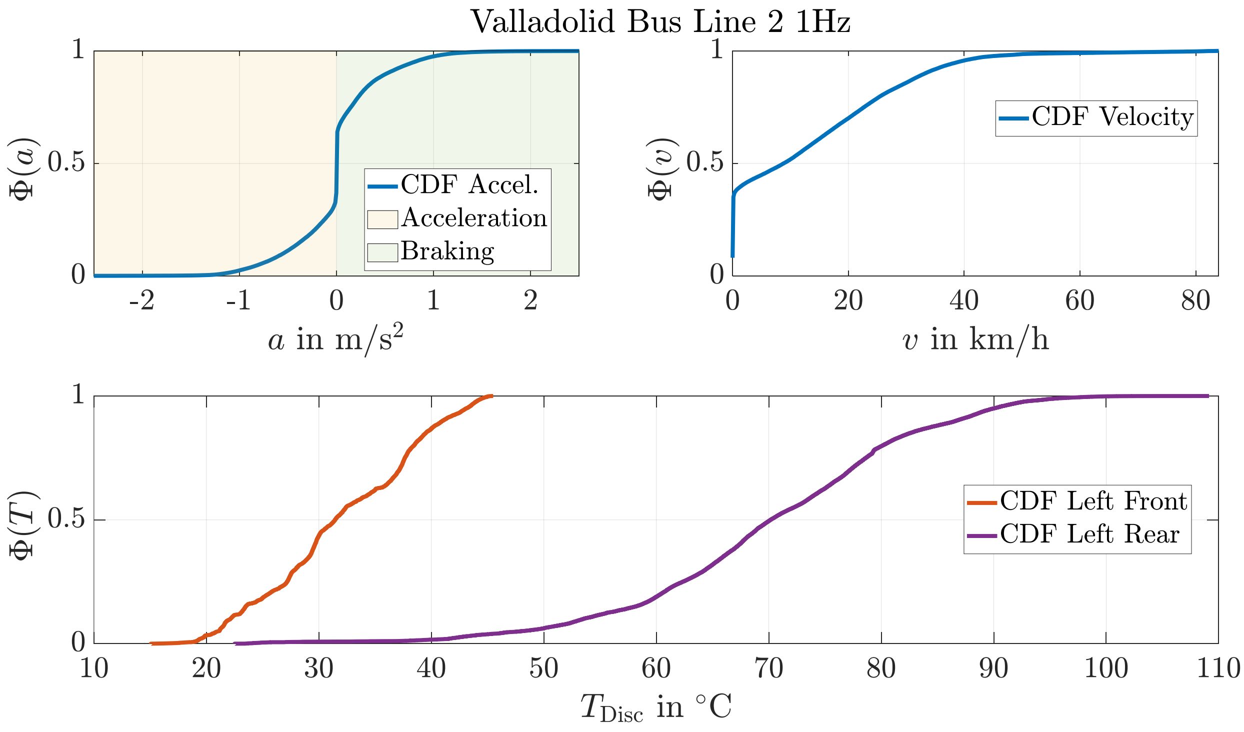

Figure 27 Cumulative Density Function of acceleration, velocity and disc temperatures for Valladolid Bus Line 2

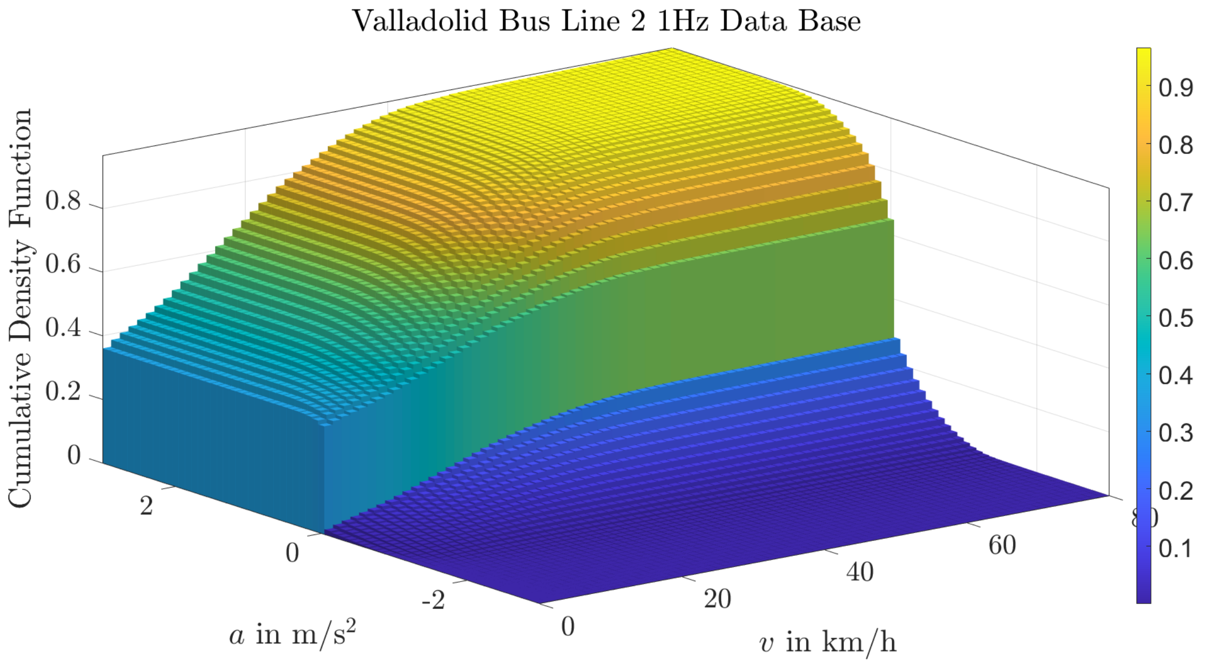

Figure 28: Two-Dimensional Cumulative Density Function of velocity and acceleration for Valladolid Bus Line 2

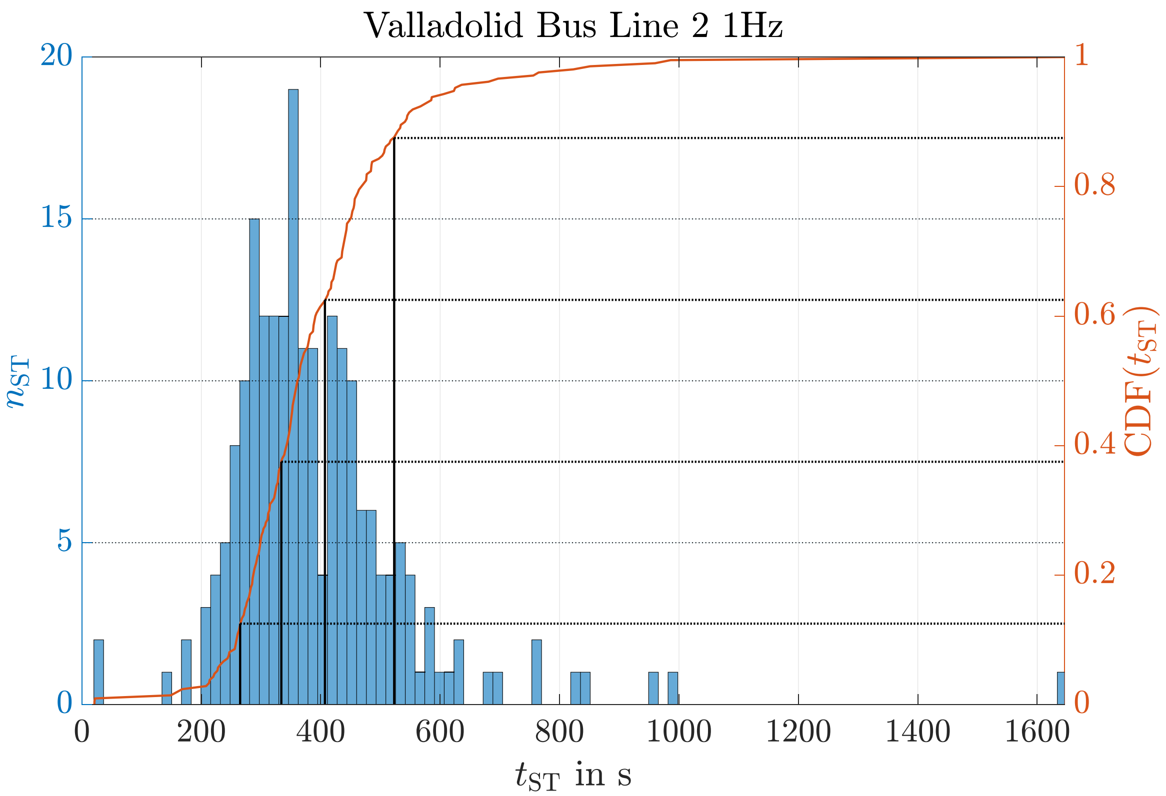

Figure 29: Distribution of short trip durations: histogram (left blue axes) and cumulative density function (right orange axes) for Valladolid Bus Line 2

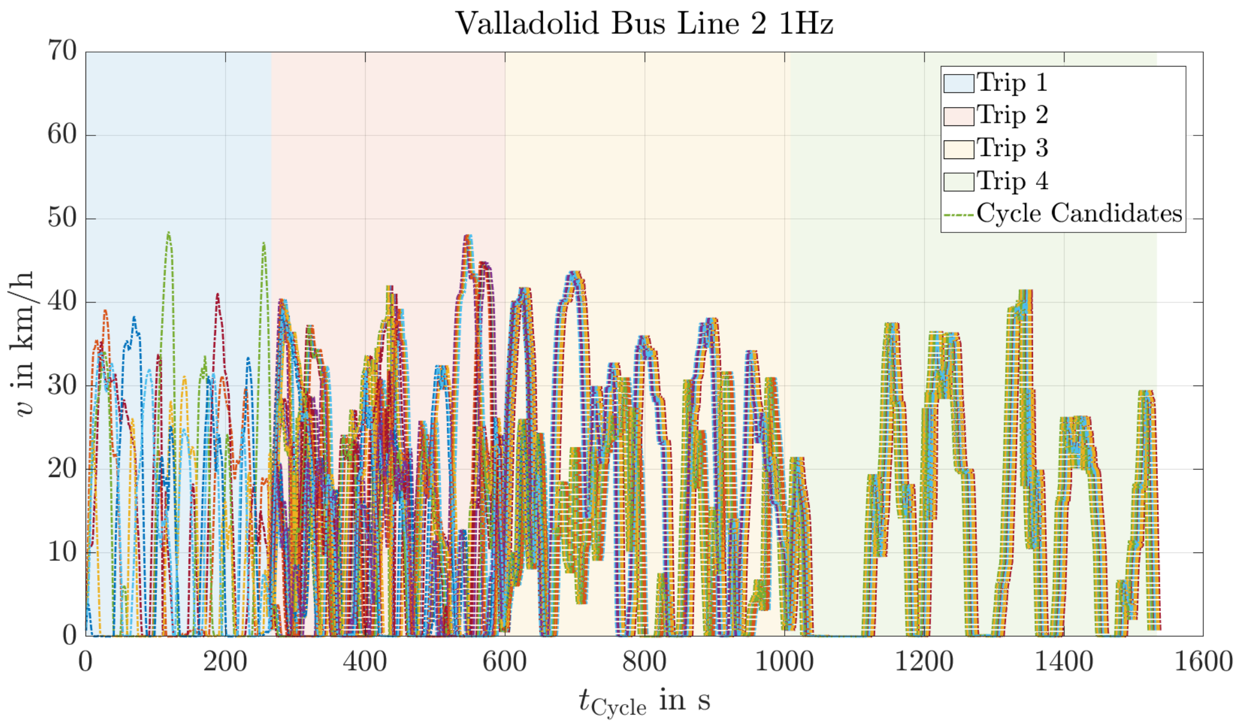

Figure 30 Candidate cycles generated from extended short trips for Valladolid Bus Line 2

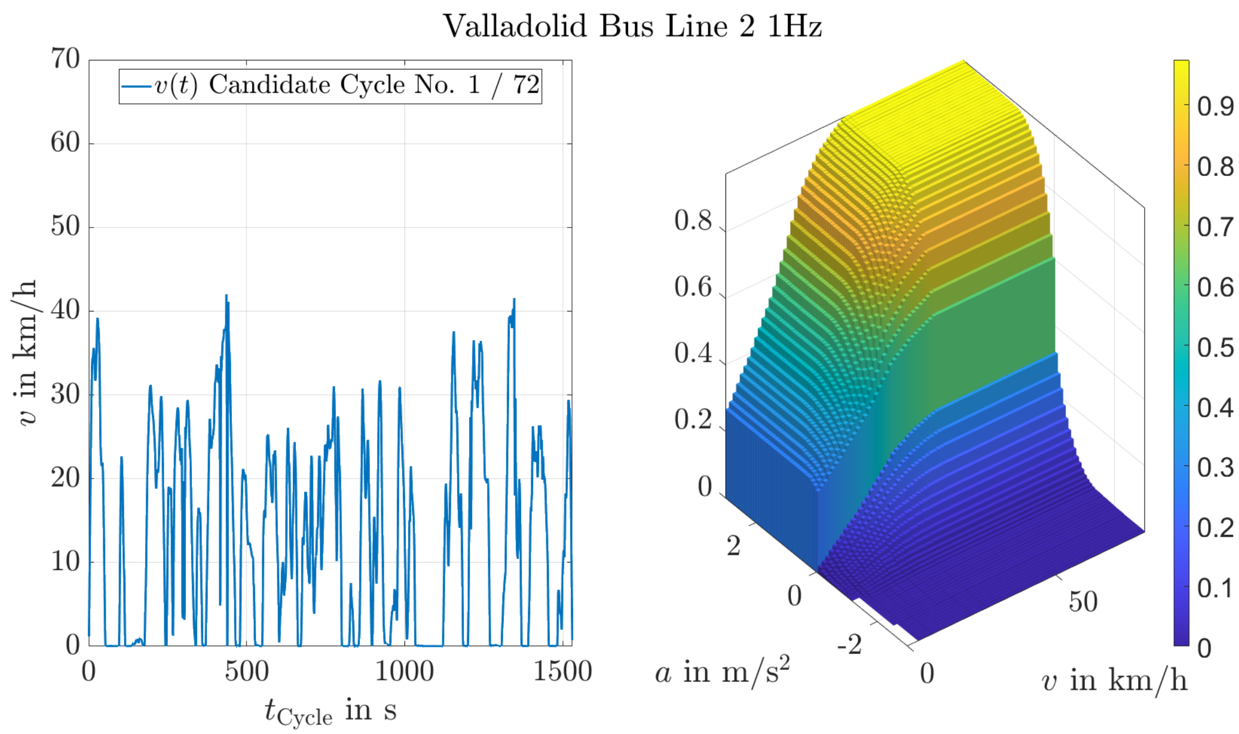

Figure 31: Velocity time series for candidate cycle 1 of 72 cycles for Valladolid Bus Line 2 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

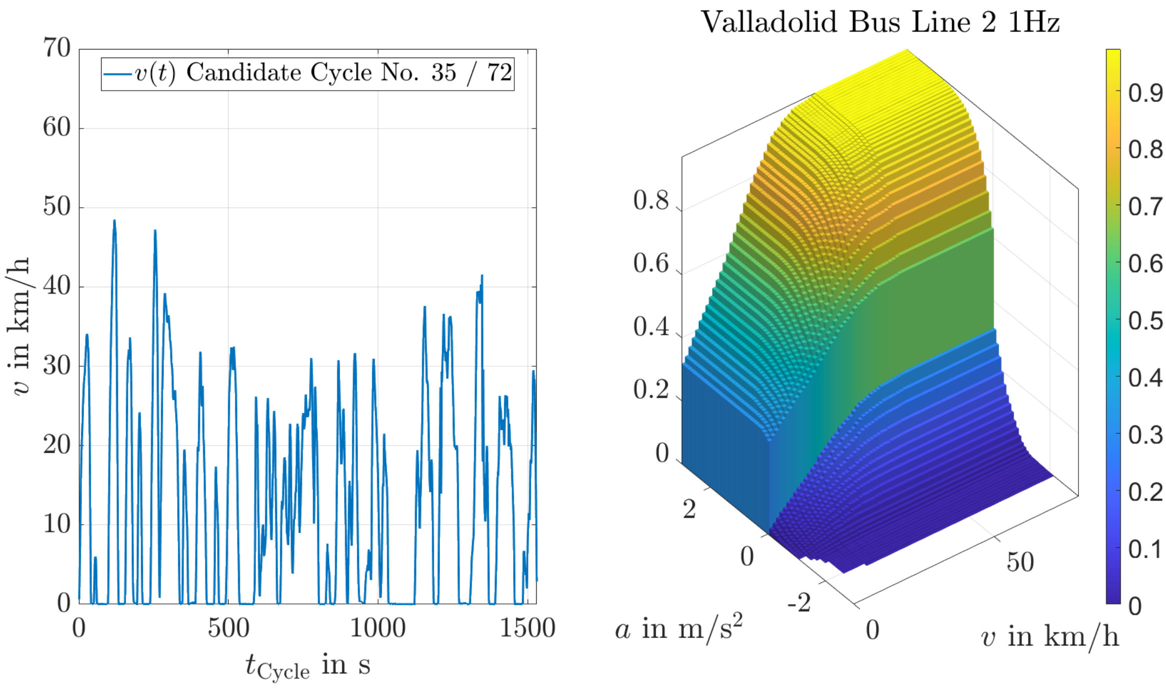

Figure 32: Velocity time series for candidate cycle 35 of 72 cycles for Valladolid Bus Line 2 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

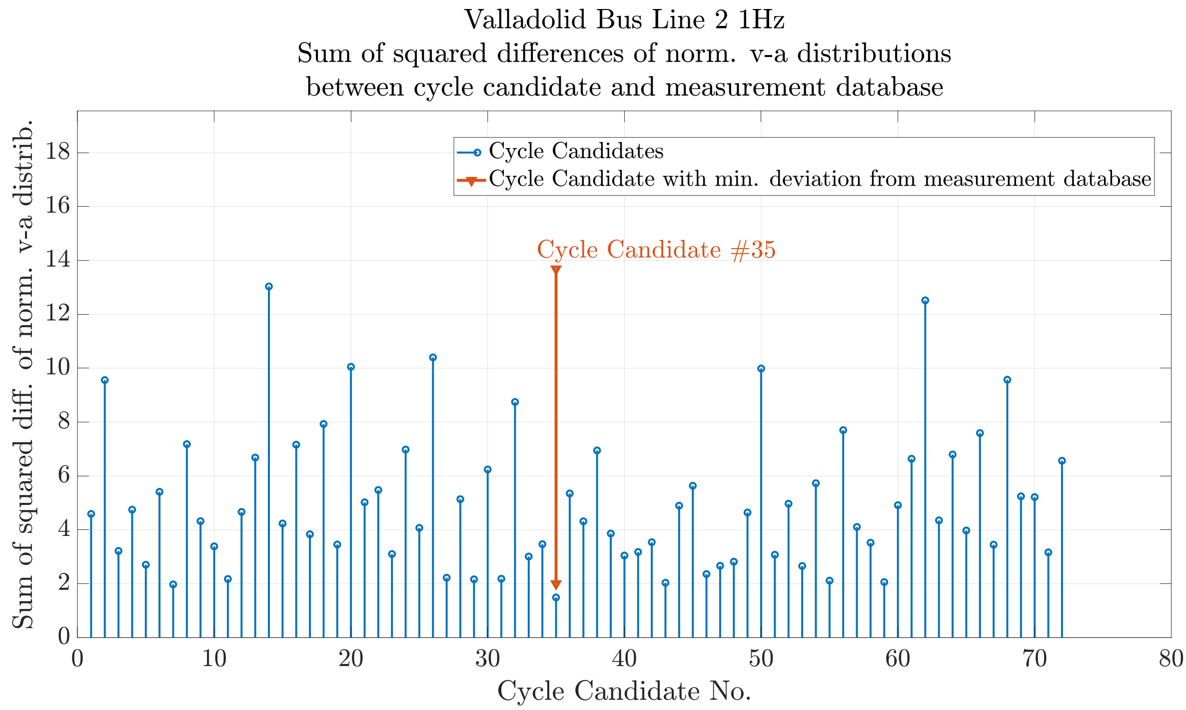

Figure 33: Difference between candidate cycle and whole measurement database in terms of the sum of squared differences of the cumulative density functions of velocity-acceleration-distribution for Valladolid Bus Line 2

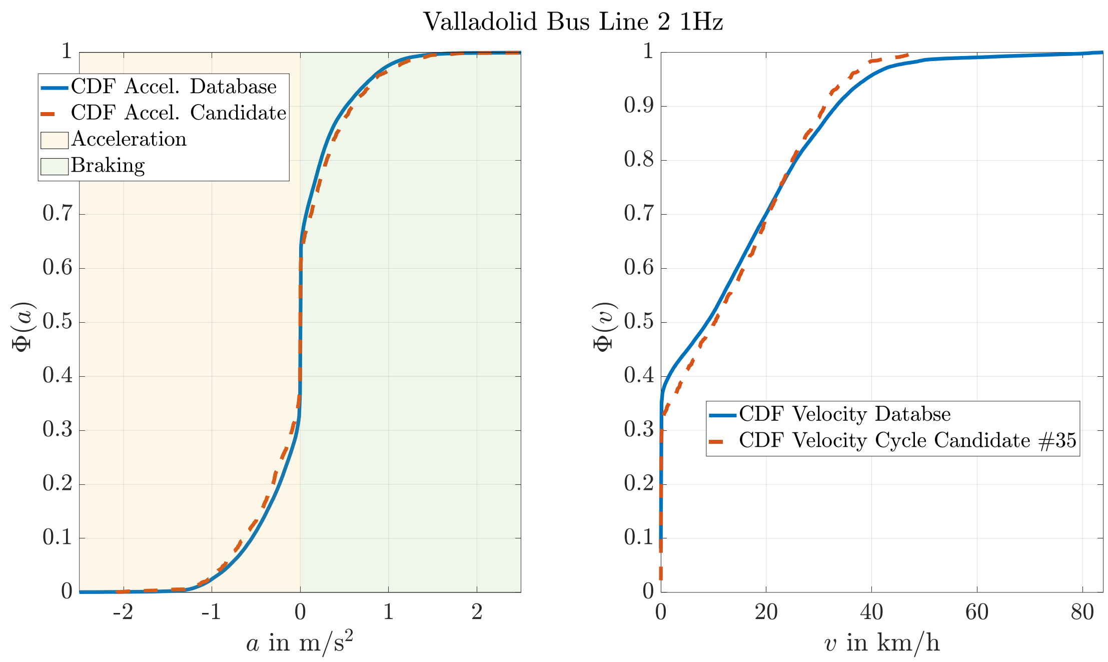

Figure 34: Comparison of measured database (Valladolid Bus Line 2) against best candidate cycle in terms of cumulative density functions for acceleration and velocity

9.2. VALLADOLID BUS LINE 3

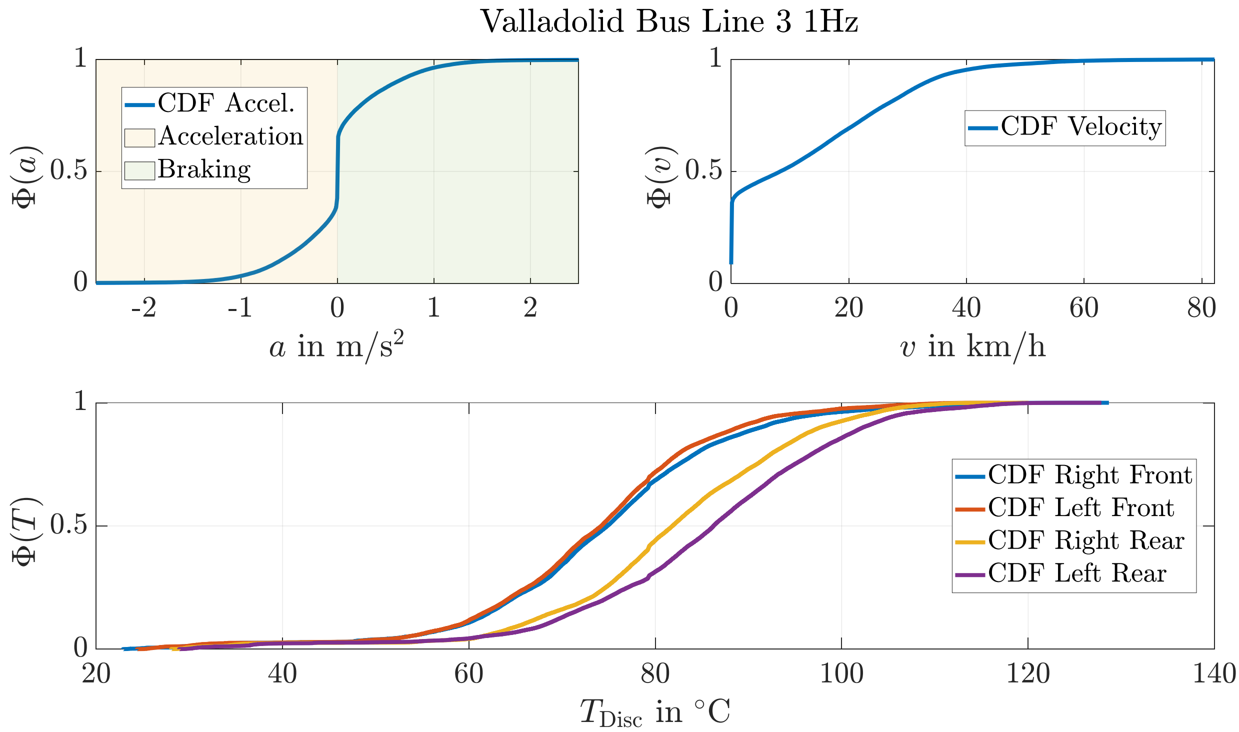

Figure 35: Cumulative Density Function of acceleration, velocity and disc temperatures for Valladolid Bus Line 3

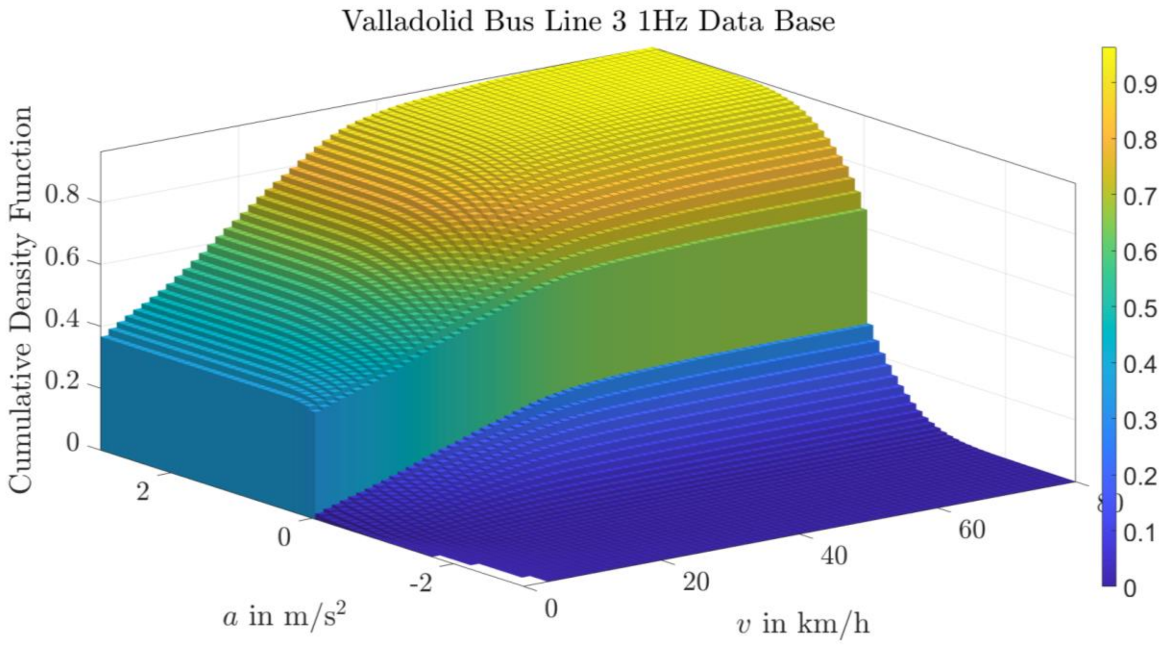

Figure 36: Two-Dimensional Cumulative Density Function of velocity and acceleration for Valladolid Bus Line 3

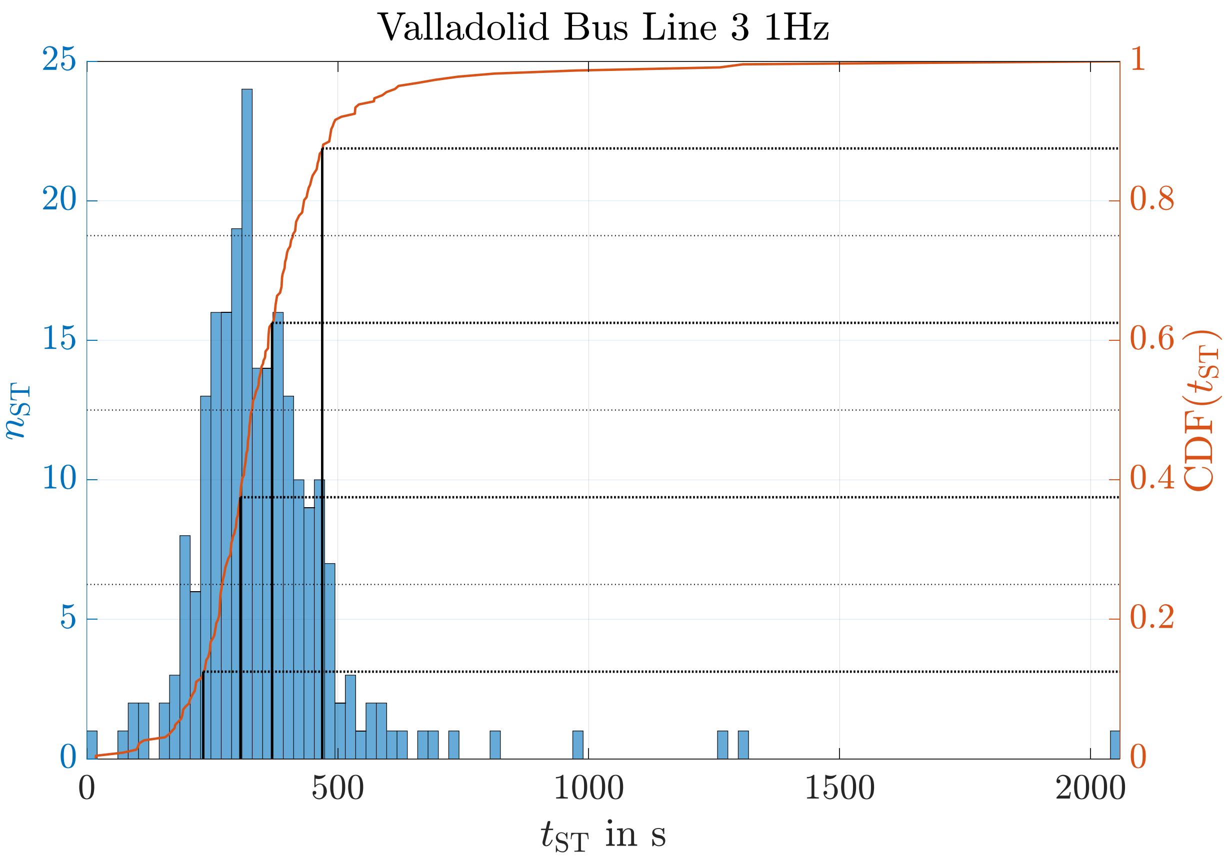

Figure 37: Distribution of short trip durations: histogram (left blue axes) and cumulative density function (right orange axes) for Valladolid Bus Line 3

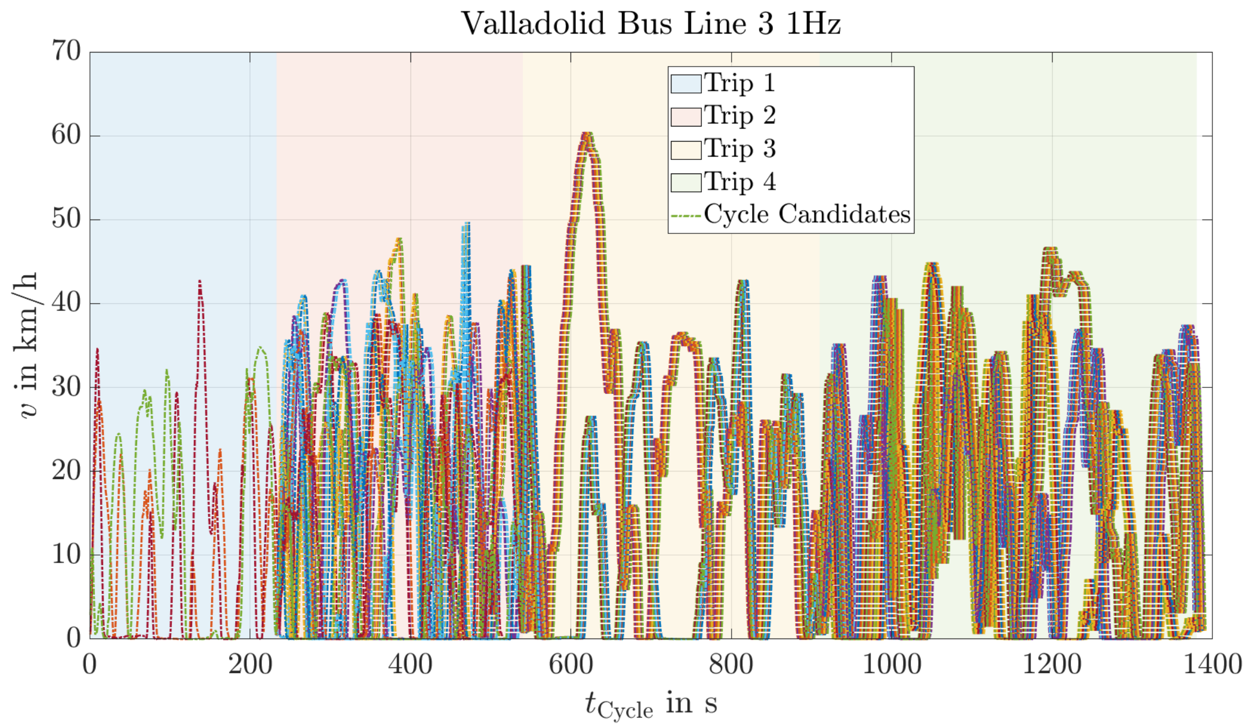

Figure 38: Candidate cycles generated from extended short trips for Valladolid Bus Line 3

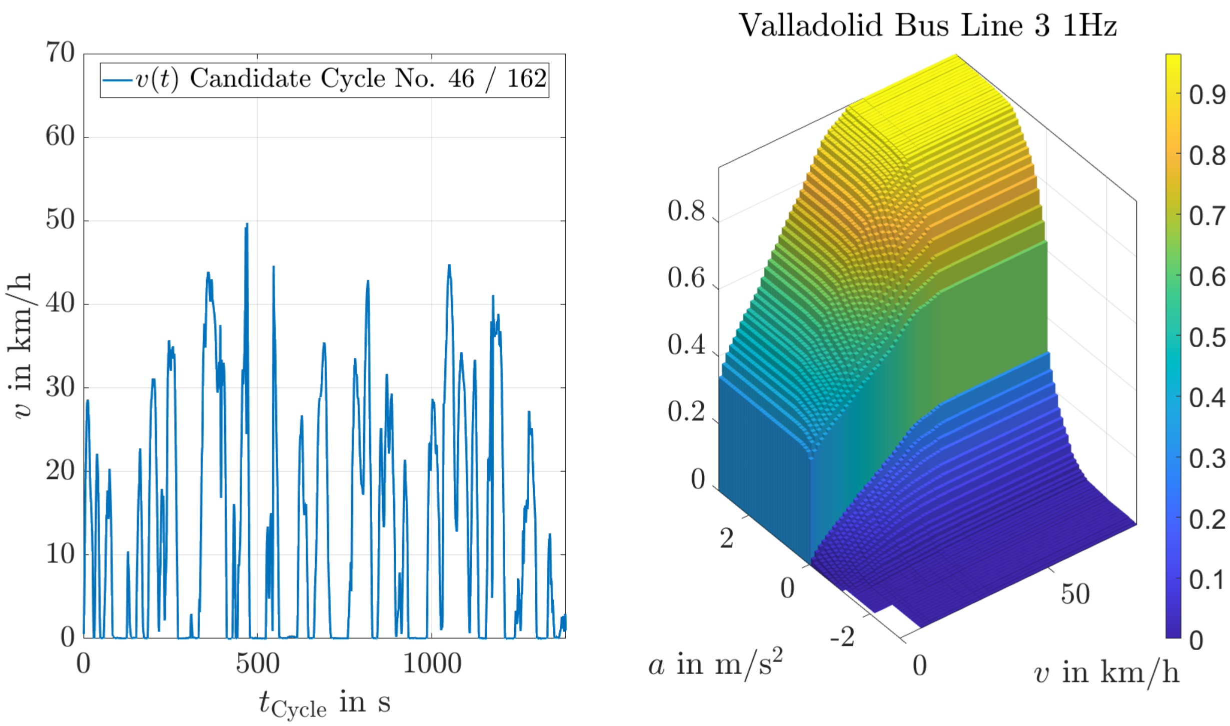

Figure 39: Velocity time series for candidate cycle 46 of 172 cycles for Valladolid Bus Line 3 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

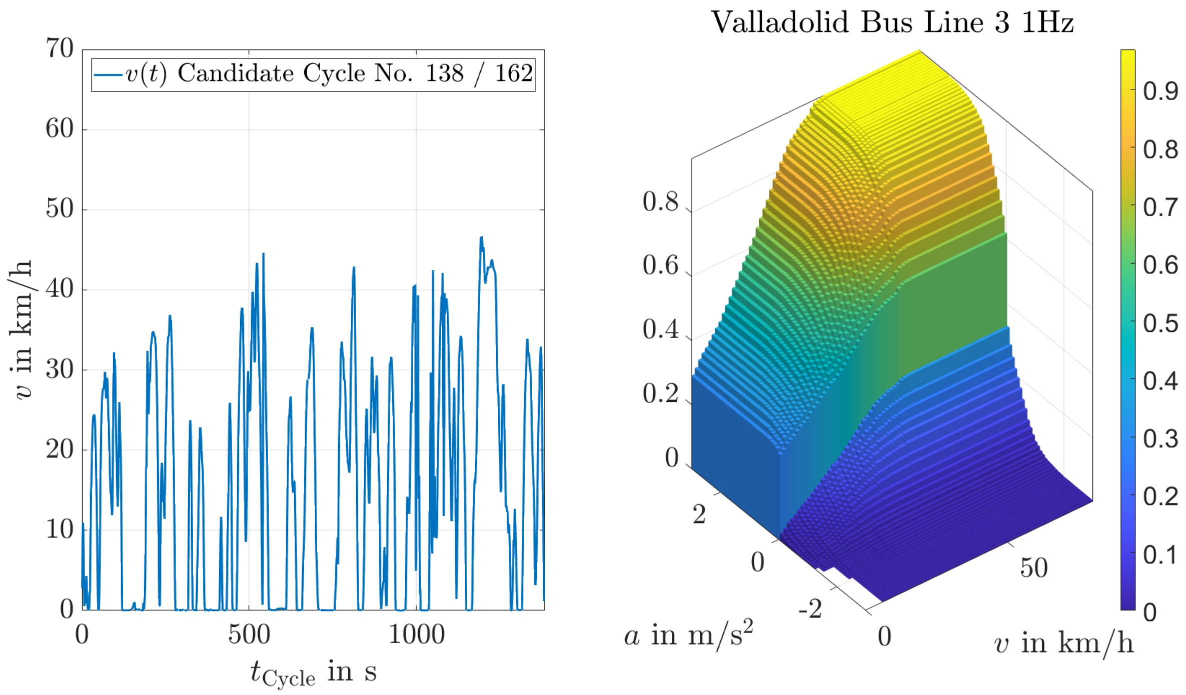

Figure 40: Velocity time series for candidate cycle 138 of 72 cycles for Valladolid Bus Line 2 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

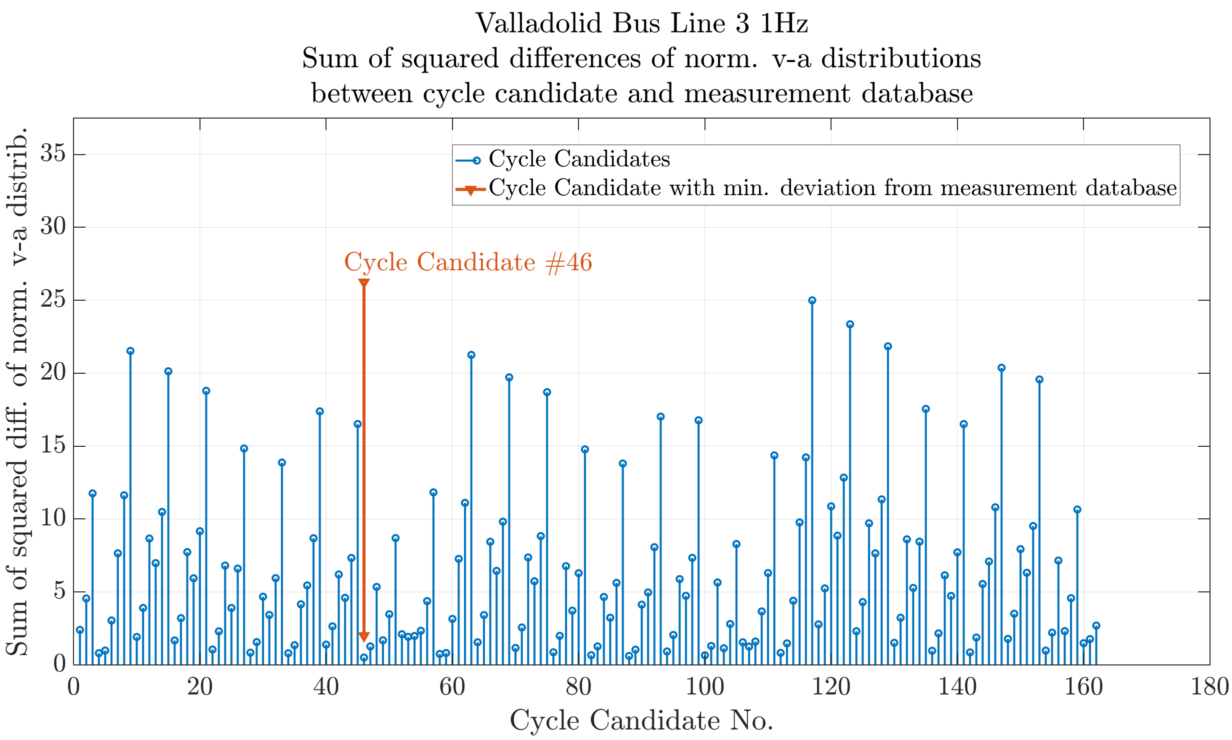

Figure 41 : Difference between candidate cycle and whole measurement database in terms of the sum of squared differences of the cumulative density functions of velocity-acceleration-distribution for Valladolid Bus Line 3

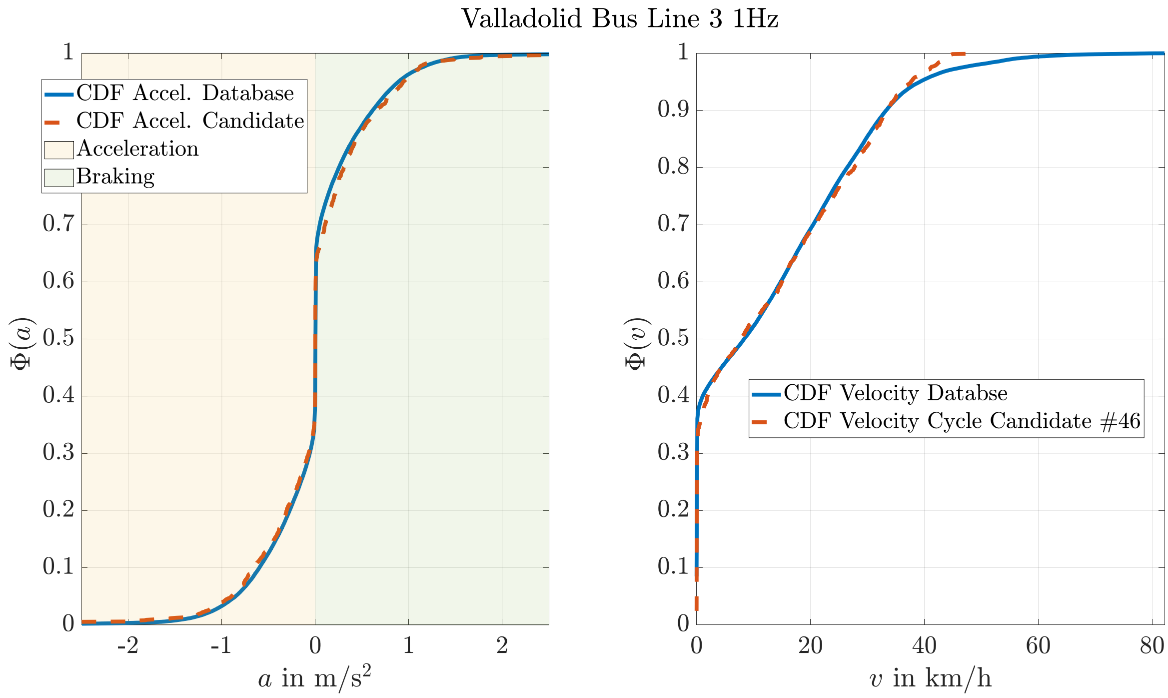

Figure 42: Comparison of measured database (Valladolid Bus Line 3) against best candidate cycle in terms of cumulative density functions for acceleration and velocity

9.3. ANCONA CONEROBUS LINE 286

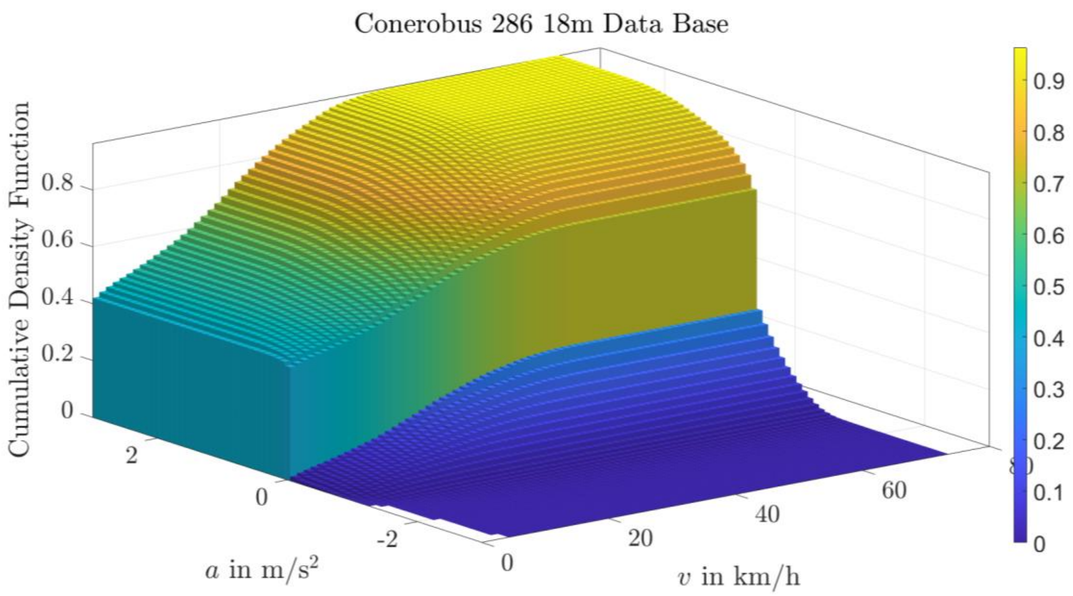

Figure 43: Two-Dimensional Cumulative Density Function of velocity and acceleration for Ancona Conerobus Line 286 with 18 m bus

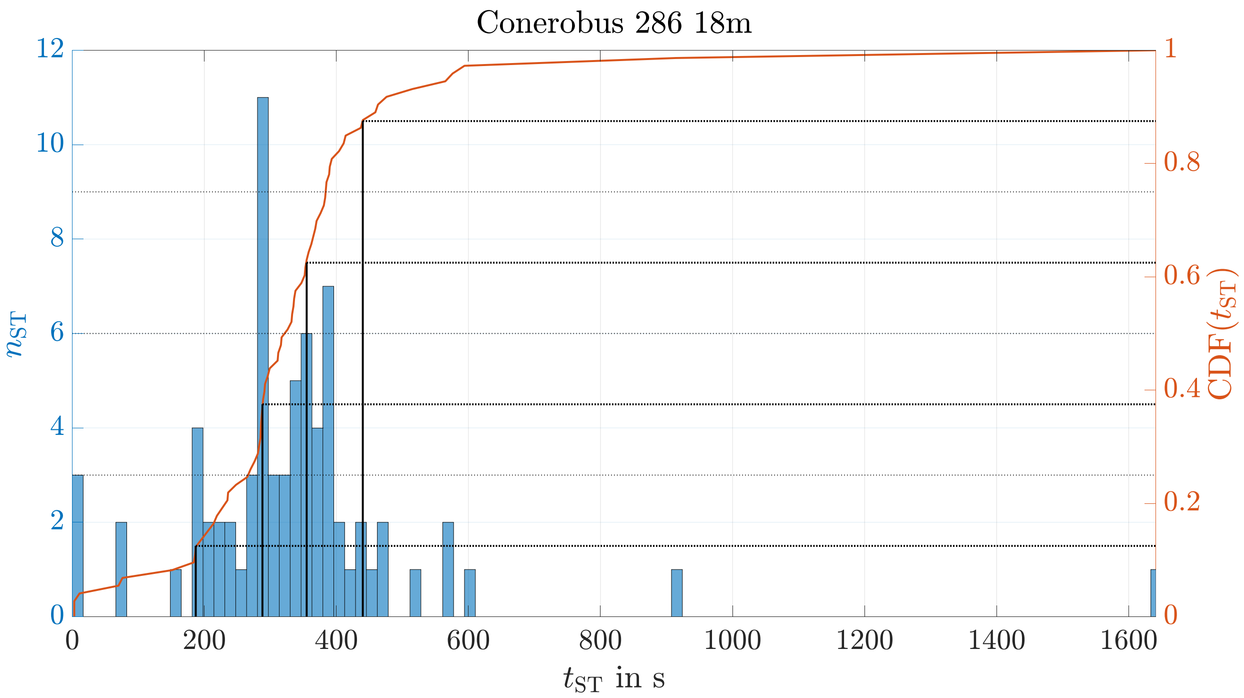

Figure 44: Distribution of short trip durations: histogram (left blue axes) and cumulative density function (right orange axes) for Conerobus Bus Line 286

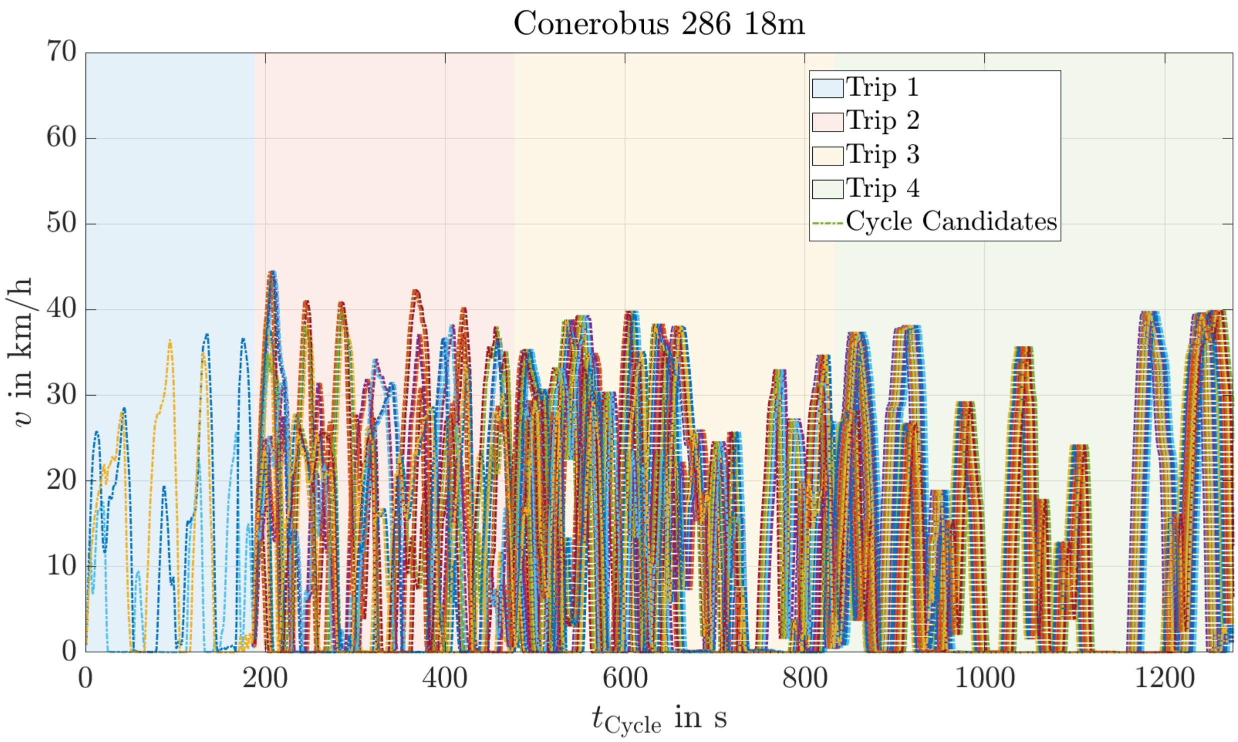

Figure 45: Candidate cycles generated from extended short trips for Conerobus Bus Line 286

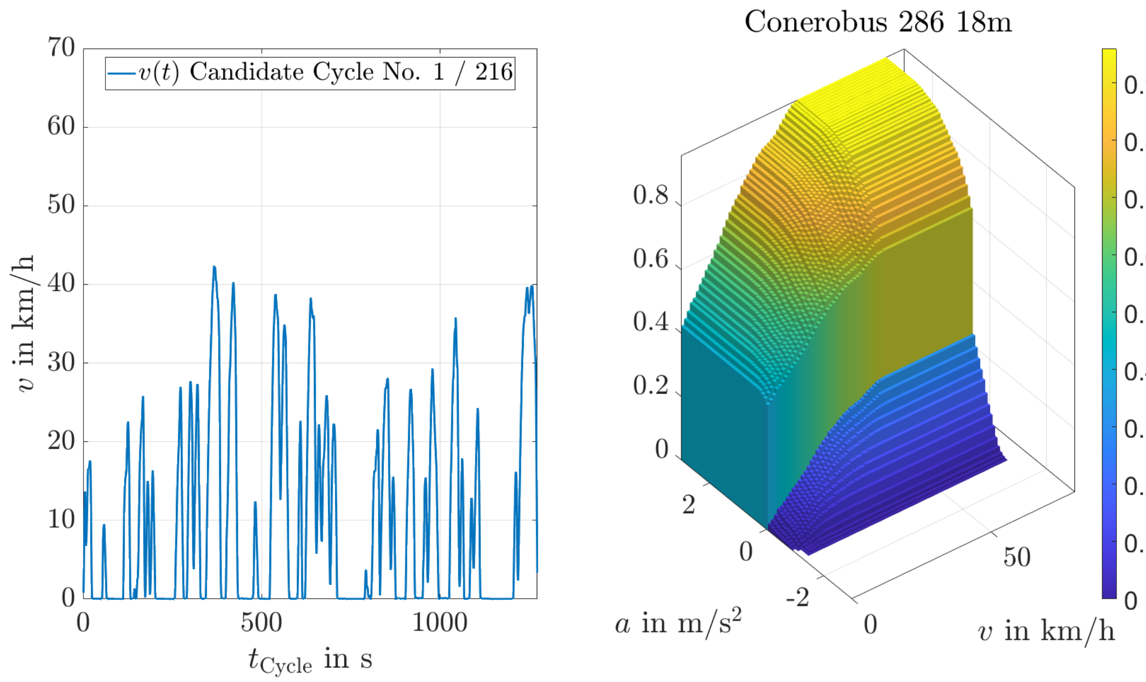

Figure 46: Velocity time series for candidate cycle 1 of 216 cycles for Conerobus Line 286 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

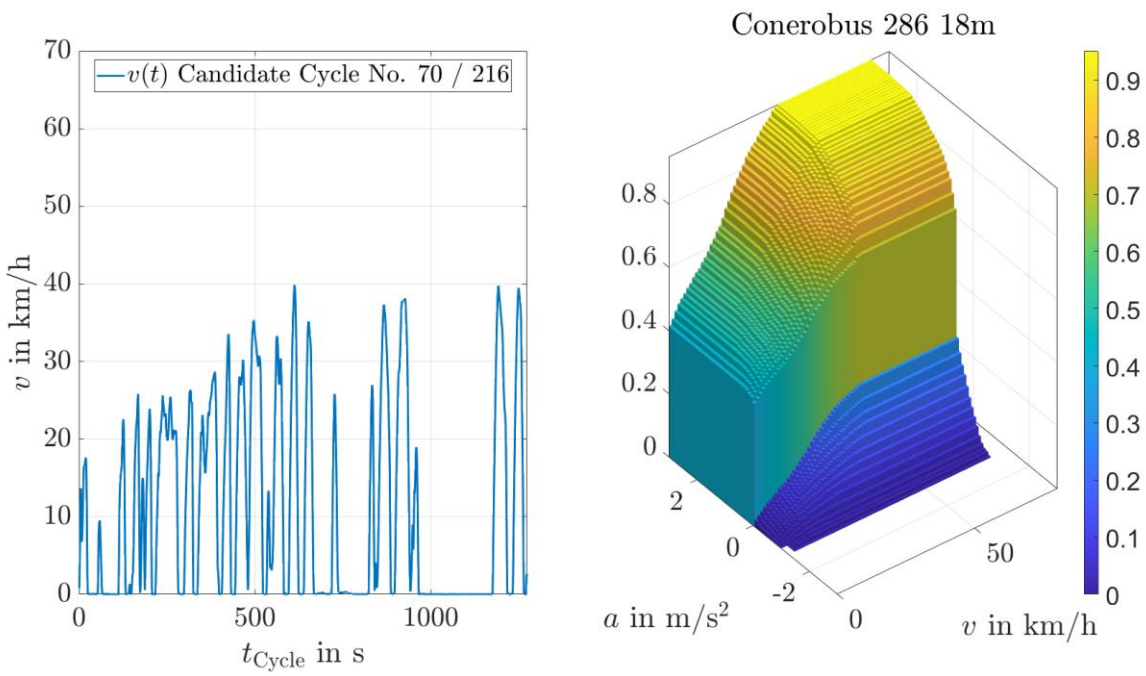

Figure 47: Velocity time series for candidate cycle 70 of 216 cycles for Conerobus Line 286 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

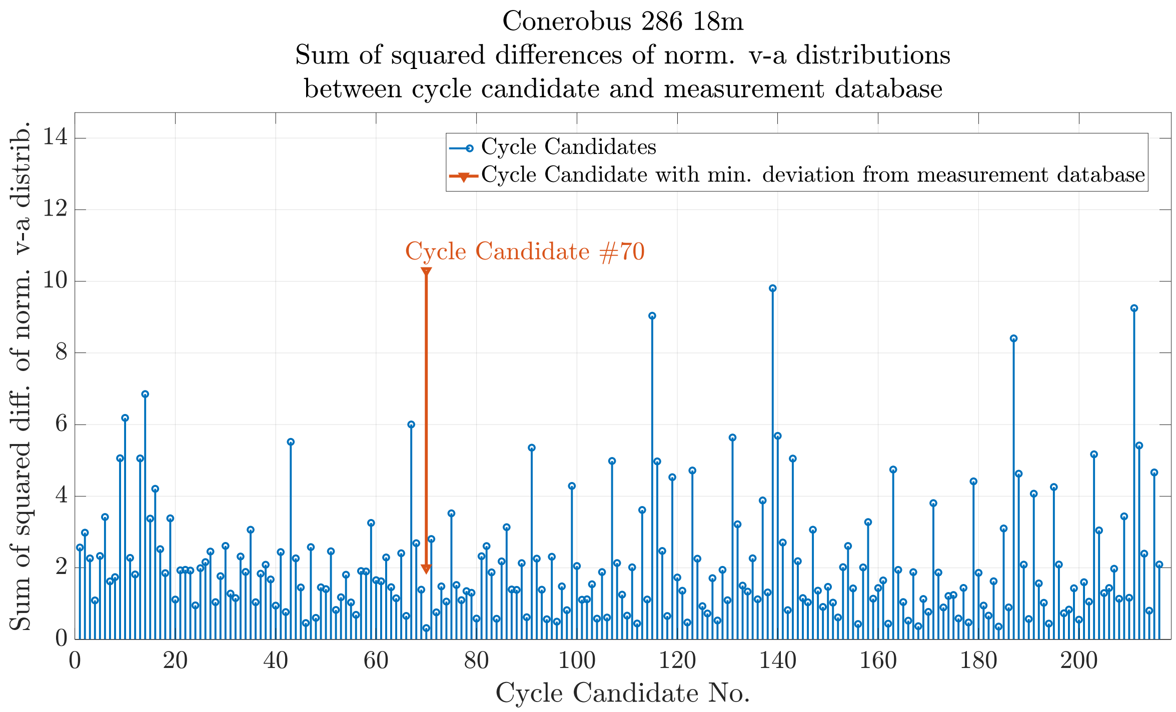

Figure 48: Difference between candidate cycle and whole measurement database in terms of the sum of squared differences of the cumulative density functions of velocity-acceleration-distribution for Conerobus Bus Line 286

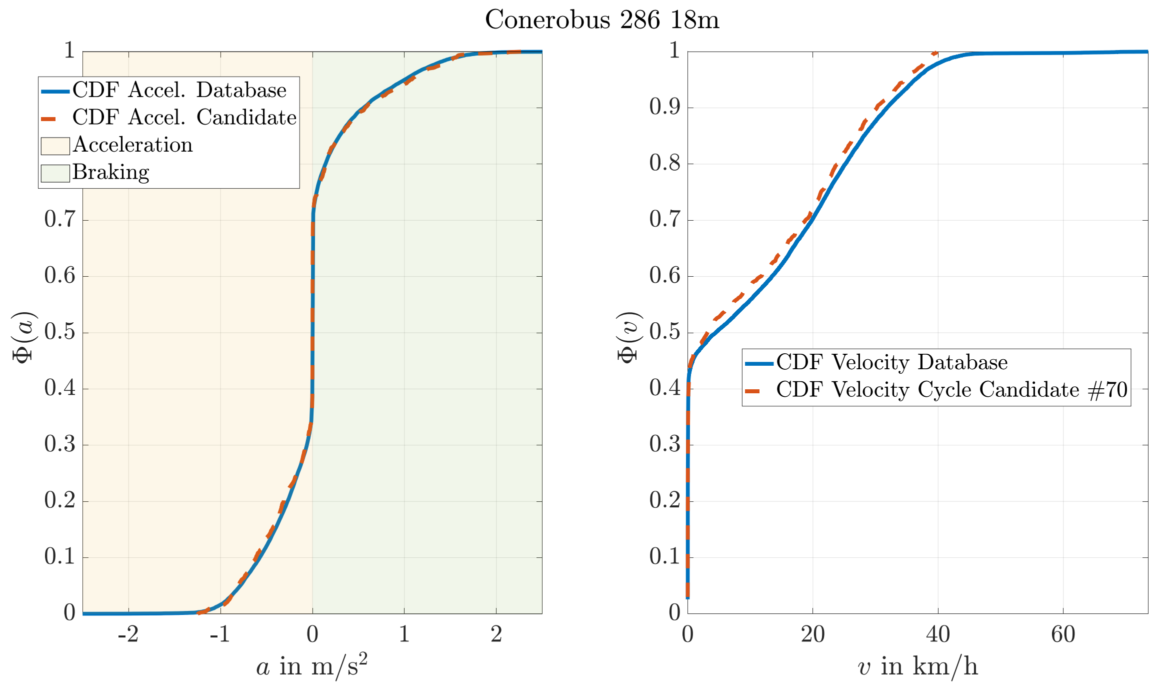

Figure 49: Comparison of measured database (Conerobus Line 286 18 m bus) against best candidate cycle in terms of cumulative density functions for acceleration and velocity

9.4.ANCONA CONEROBUS LINE 418

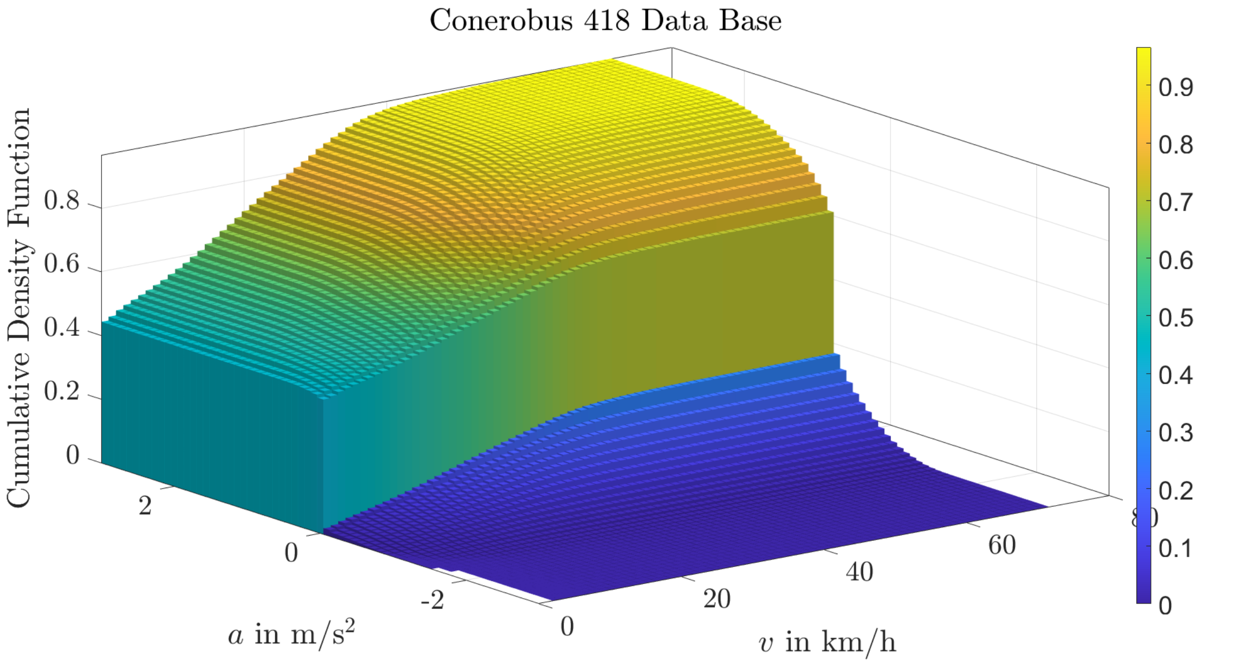

Figure 50: Two-Dimensional Cumulative Density Function of velocity and acceleration for Ancona Conerobus Line 418 bus

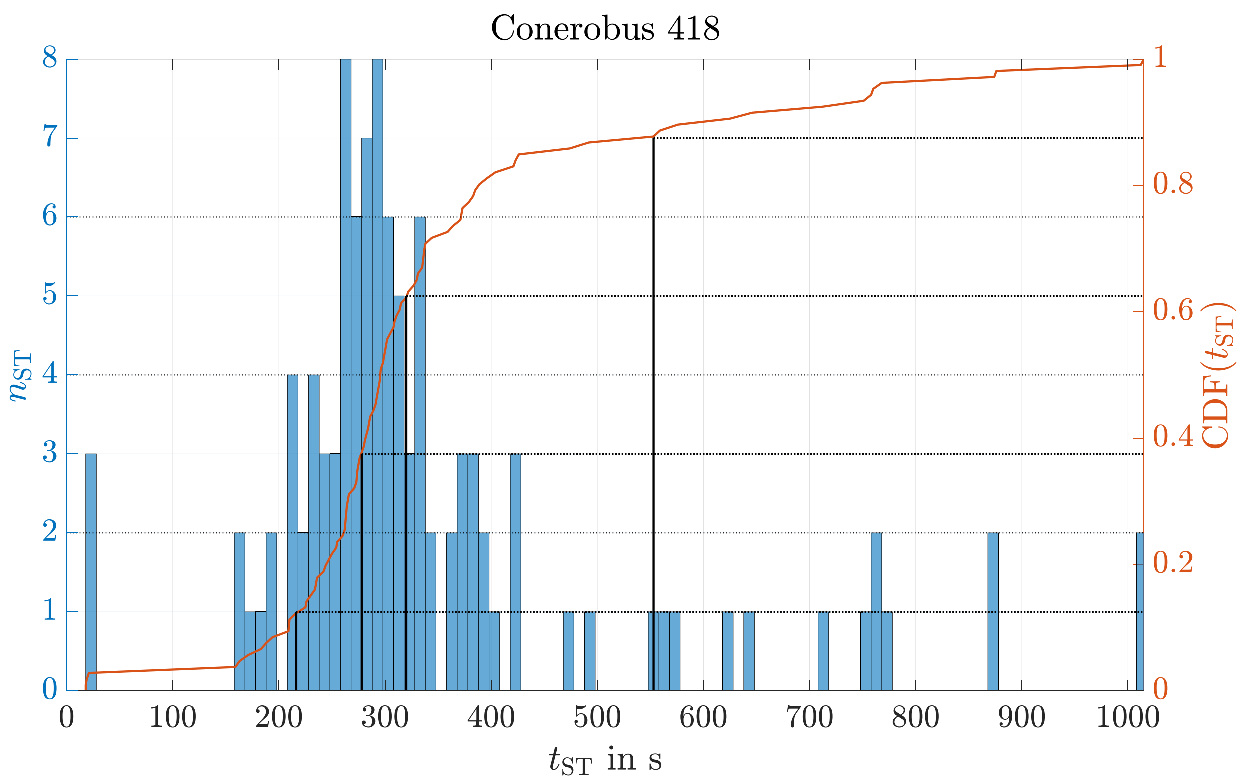

Figure 51: Distribution of short trip durations: histogram (left blue axes) and cumulative density function (right orange axes) for Conerobus Bus Line 418

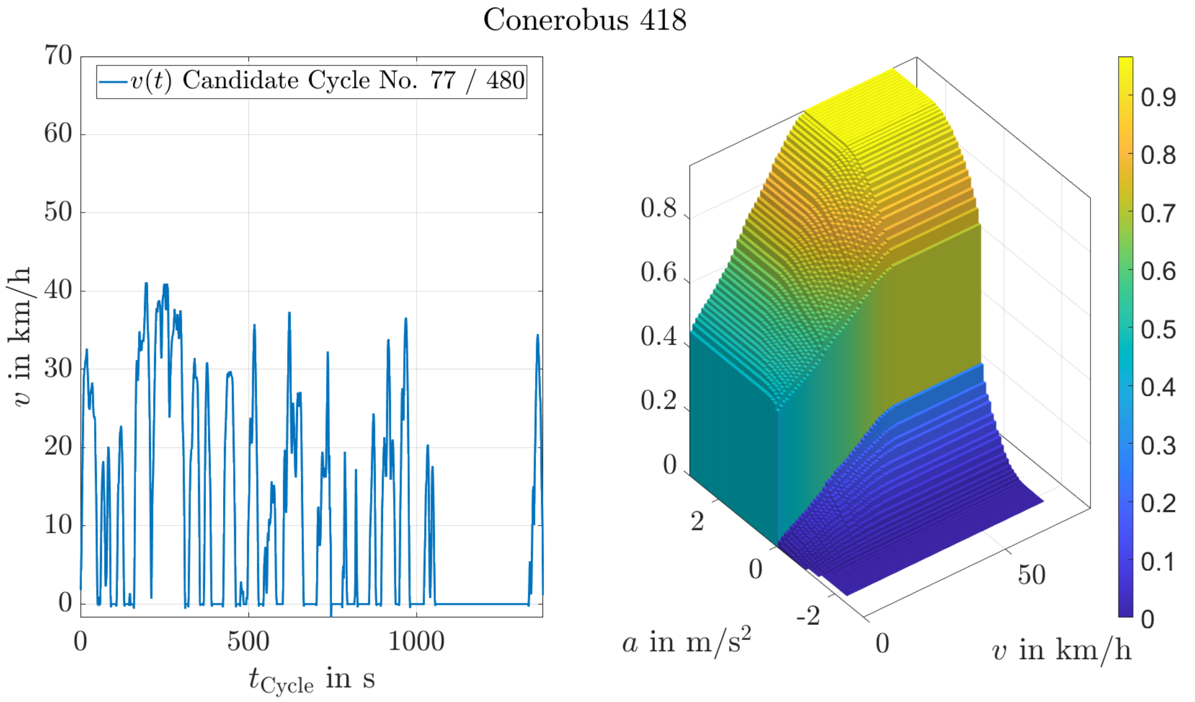

Figure 52: Velocity time series for candidate cycle 77 of 480 cycles for Conerobus Line 418 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

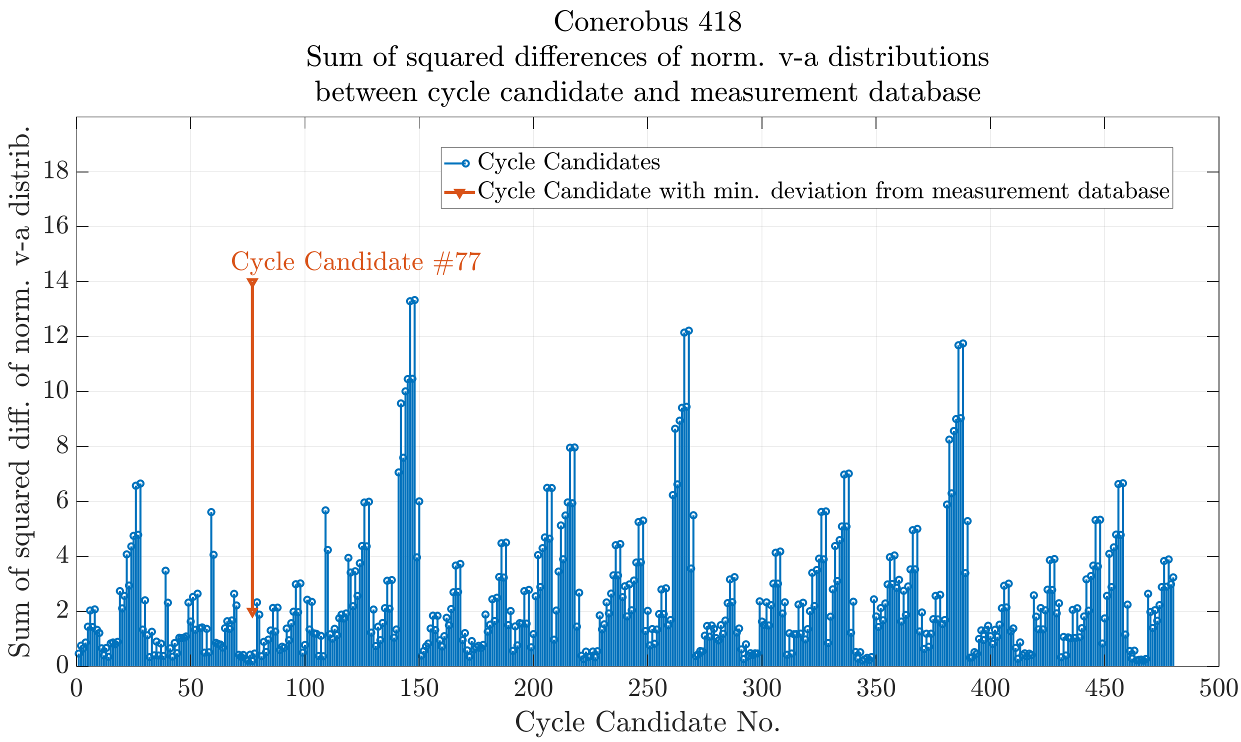

Figure 53: Difference between candidate cycle and whole measurement database in terms of the sum of squared differences of the cumulative density functions of velocity-acceleration-distribution for Conerobus Bus Line 418

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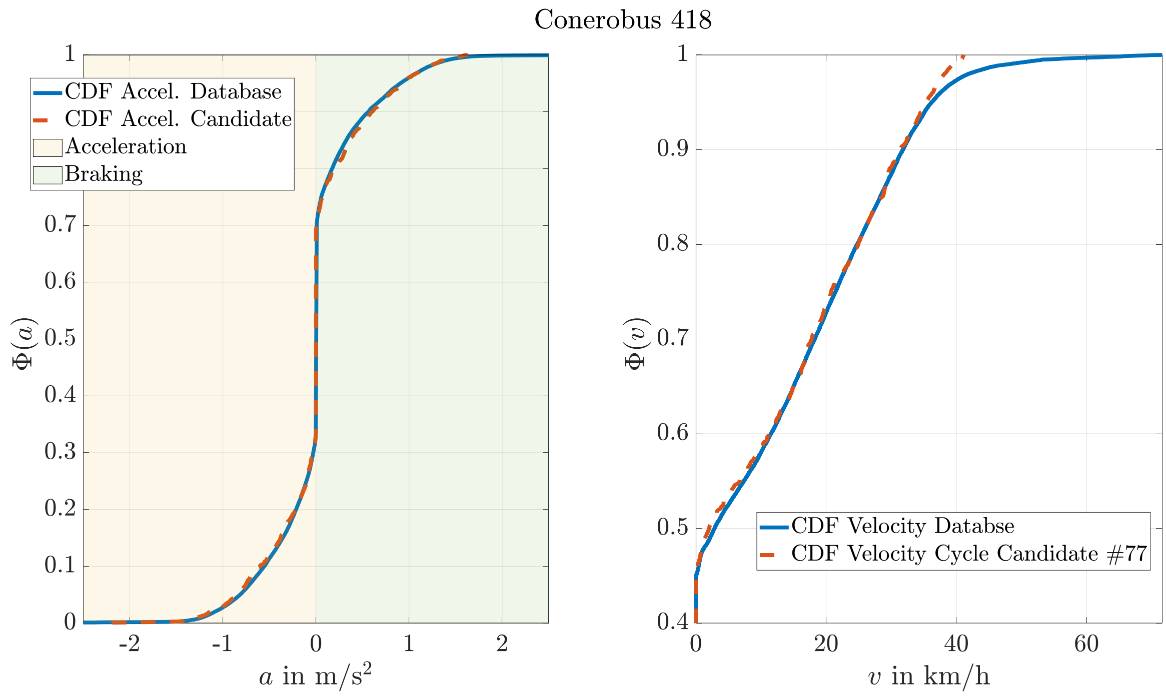

Figure 54: Comparison of measured database (Conerobus Line 418) against best candidate cycle in terms of cumulative density functions for acceleration and velocity