CALIFORNIA
AIR RESOURCES BOARD

Tier 5 Rulemaking: Off-Road Low Load Cycle Development

August 8, 2022

Outline

- Background
  - Need for potential off-road Low Load Cycle (LLC)
  - Review of the development of Nonroad Transient Cycle (NRTC) and on-road LLC
- Data sources
  - Long-term monitoring data
  - Short-term testing data
- Proposed methods
  - Microtrip-based method
  - "Day-in-the-life" method
- Results
- Questions

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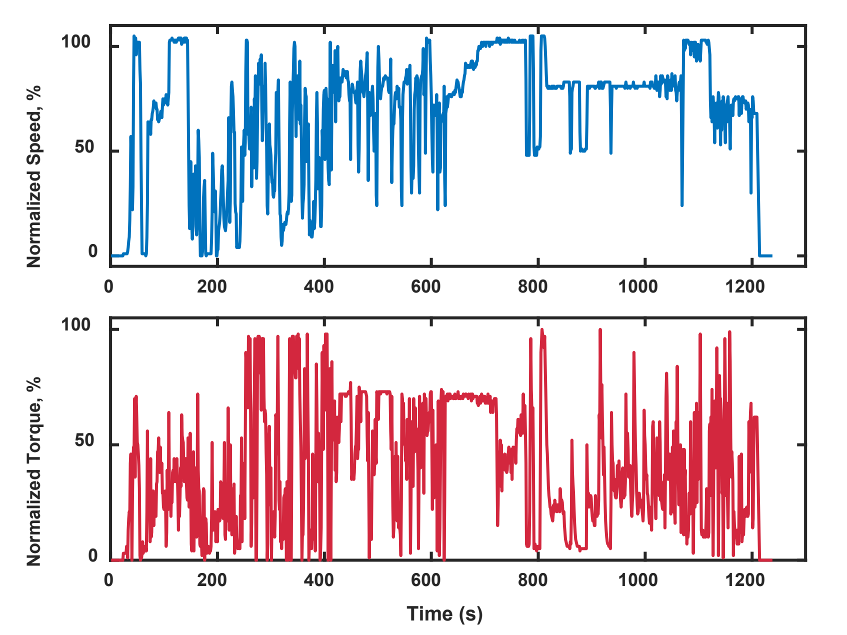
Background

Certification Test Cycles

- Transient Testing
  - NRTC
  - Applies to variable speed off-road diesel engines ≤ 560 kilowatt (kW) only
  - ~39% engine load
  - Normalized torque is above 25% for ~80% of the time
- Steady-State Testing
  - Various modal cycles, e.g., C1, C2, D1, D2, depending on power and speed type
  - Applies to all variable and constant speed off-road diesel engines



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New Potential Off-Road LLC

- Low load operations are common in real-world applications.
  - Data provided by engine manufacturers indicated that some off-road engines have more than 40% idle time.
- Previous analysis showed that NRTC does not sufficiently represent the low-load conditions that occur in real-world duty cycles.
  - Southwest Research Institute (SwRI) developed the Low Load Application Cycle (LLAC) based on proprietary data.
  - Oxides of Nitrogen (NOx) emission rates during the LLAC were up to 19 times higher than during the NRTC.
  - Sustained low load operation decreases exhaust temperatures for today's engine, and the aftertreatment system cannot effectively control emissions when the engine resumes higher load operations.
- The objective is to develop an LLC applicable to variable speed off-road diesel engines between 56 and 560 kW that is indicative of engine operations under low load and low exhaust temperature conditions.

Development of the NRTC

- The U.S. Environmental Protection Agency (EPA), Truck and Engine Manufacturers Association, and SwRI developed the NRTC.
- A set of duty cycles were created from actual speed and load data recorded in-use on eight pieces of equipment in seven applications.
- Two primary strategies were used to develop individual application cycles:
  - Microtrip-based method: the Agricultural Tractor cycle, the Backhoe Loader cycle and the Crawler/Dozer cycle
  - "Day-in-the-Life"-based method: the Skid Steer Loader cycle, the Arc Welder cycle, the Rubber Tire Loader cycle, and the Excavator cycle
- Individual application cycles were combined to create the NRTC.

Microtrip-Based Method Used to Develop the NRTC

- A microtrip is a very short string of engine activity data from actual equipment operation.
  - Microtrips ranged from 22 seconds to 5.6 minutes in the development of application cycles for the NRTC.
- Calculate characteristics of normalized speed, torque, and power of microtrips, and compare them with the full body of data
- Most representative microtrips were assembled to form a cycle.

“Day-in-the-Life”-Based Method Used to Develop the NRTC

- Applied to ~123 hours of data from 5 pieces of equipment
- The analysis was conducted using a 19-minute window incremented at one-minute intervals.
- The window of activity that best represented the full body of data for that piece of equipment was selected as the most typical duty cycle.

Development of On-Road LLC

- The development of on-road LLC used the microtrip-based method with advanced statistical analysis.
- Included data from 751 vehicles in 44 vocational designs
- The on-road LLC includes three emission control challenges
  - High Load-to-Low Load Transition
  - Sustained Low Load
  - Low Load-to-High Load Transition

Off-Road Data Sources

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Data Used for Potential Off-Road LLC Development

- The California Air Resources Board is working with SwRI, U.S. EPA and the Center for Environmental Research & Technology at University of California Riverside to develop off-road LLC.
- Included data from 240 off-road diesel engines in different applications
- Long-term monitoring data: multiple weeks of real-world monitoring for each engine
  - Construction activity data: 56 engines, 7,428 hours of engine operation
  - Agriculture activity data: 52 engines, 11,514 hours of engine operation
  - Off-road yard tractor data: 2 engines, 5,893 hours of engine operation. The data needs separate analysis to avoid bias.
- Short-term testing data: a few hours of data for each engine
  - Received data from 10 engine manufacturers
  - 130 engines, ~932 hours of engine operation

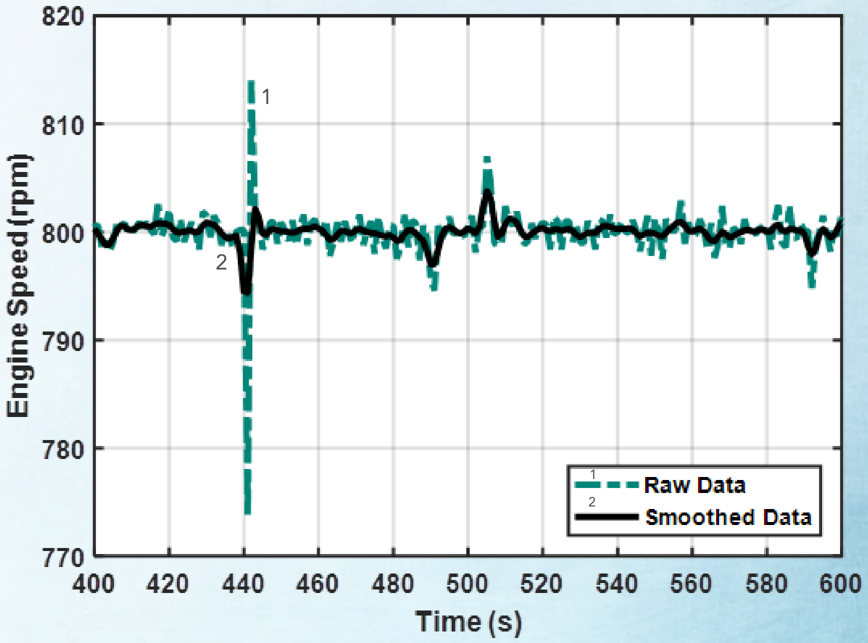
Methodology for Potential Off-Road LLC

Development of Potential LLC – General Approach

- Perform data pre-processing and cleanup
- Conduct data analysis
  - Microtrip-based method for long-term monitoring data
  - "Day-in-the-life"-based method for short-term testing data
- Generate a frequency distribution of average loads and identify the cutoff point for the low load region
- Perform k-means clustering analysis with low load windows
- Select engine profiles and refine with SwRI
- Conduct cycle translation and testing at SwRI

Using Moving Average to Smooth Data

- Broadcast data may have some signal noise.
- Using 5-second (s) weighted moving average window to smooth data
- All parameters are smoothed.



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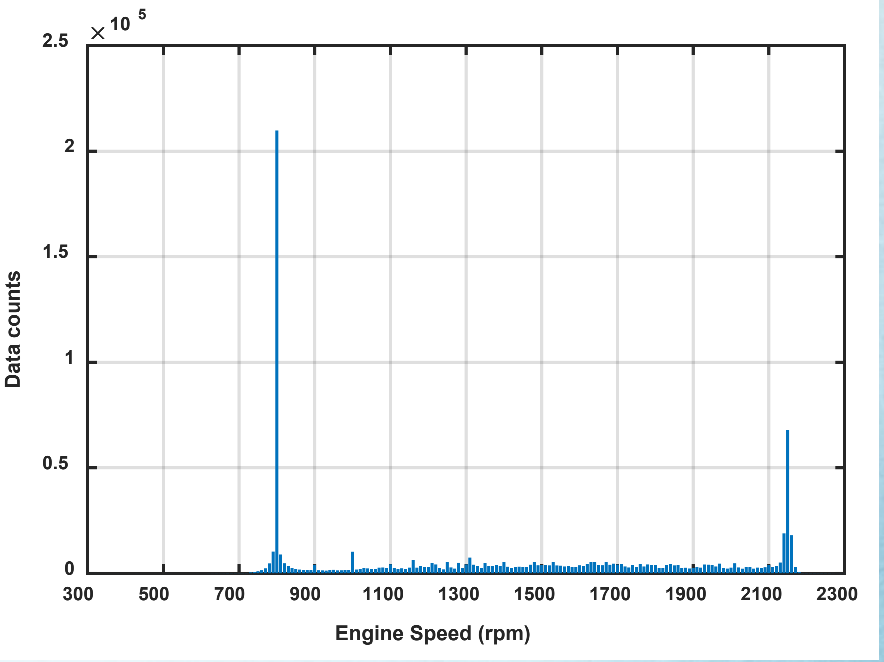
Microtrip Breakpoint

- Staff used engine speed data to divide engine activities into microtrips.
- A microtrip is an operations segment between two breakpoints.
  - The "breakpoint speed" is the most frequent engine speed below 1100 revolutions per minute (RPM) for each engine.
  - A breakpoint is when the engine operated at the "breakpoint speed" for more than 10s.



The "breakpoint speed" is 800 RPM for the example engine.

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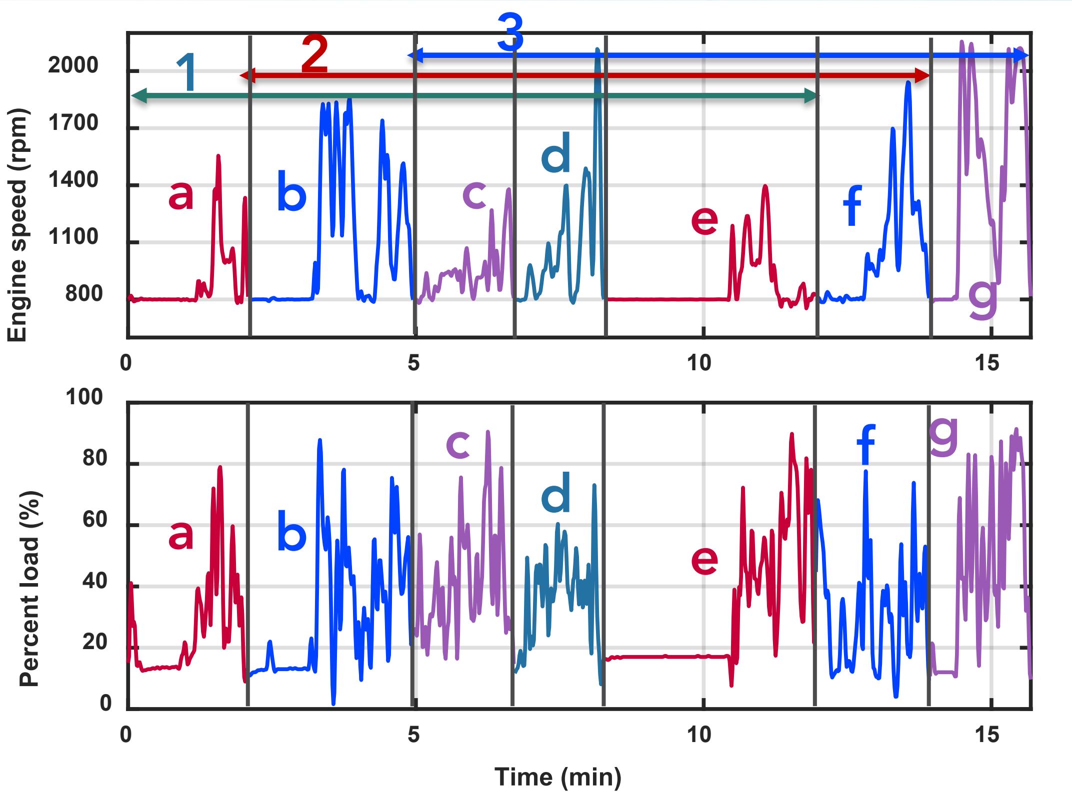
Moving Microtrip Window

- A moving average window includes 5 microtrips.
- Window moves by one microtrip each time.
- The median length of 5 microtrip windows is 1651 seconds.



- Seven microtrips (a to g) are shown in different colors
- Microtrips may have different lengths
- Arrows indicate three moving average windows (1 to 3)

Results

Load Distribution Analysis from On-Road LLC Development

- The histogram of window average load can be fitted with three Gaussian distributions.
- $f(x) = a * e^{-\left(\frac{x-b}{c}\right)^2}$
- Coefficient a determines the height of the peak.
- Coefficient b determines the location of the peak (median).
- Coefficient c determines the width of the peak (standard deviation).

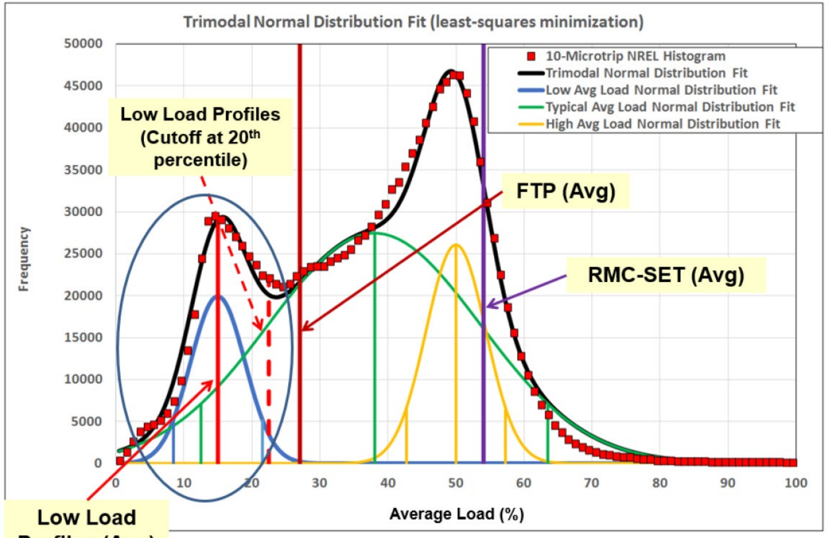


FIGURE 17. OVERALL DISTRIBUTION OF 10-MICROTRIP WINDOWS VS. WINDOW AVERAGE LOAD

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Lessons Learned from On-Road LLC

- In the development of on-road LLC, the cutoff point of low load was set at the 20th percentile of the overall distribution, which is located at about 22% average load.
- The bottom 20% windows that had average load lower than the cutoff point were considered low load windows.
- As a result, only low load windows were included in the subsequent clustering analysis.
- **A similar cutoff point will be determined for off-road LLC.**

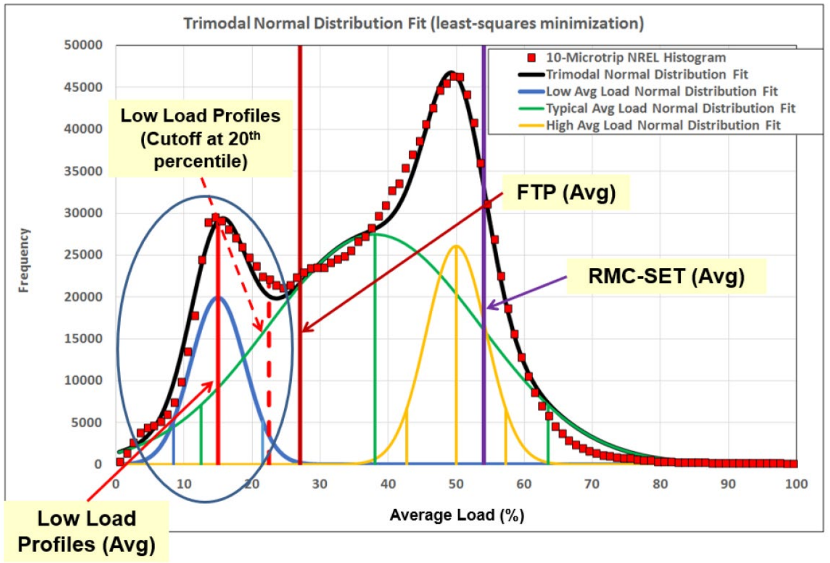

FIGURE 17. OVERALL DISTRIBUTION OF 10-MICROTRIP WINDOWS VS. WINDOW AVERAGE LOAD

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Window Average Load Distribution for All the Data Received

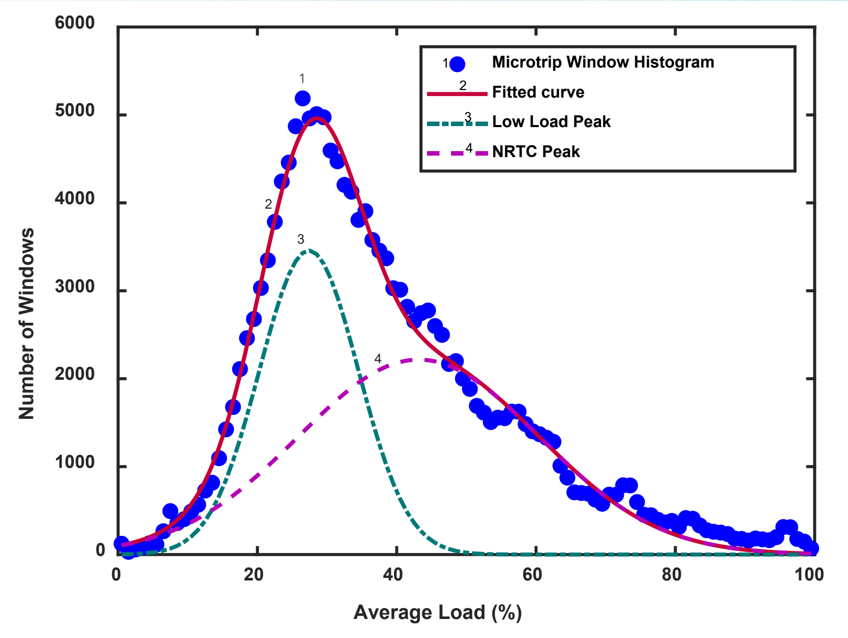
- Included both long-term monitoring and short-term testing data
  - 159,417 windows in total
  - Yard tractors are analyzed separately
- General 2 term Gaussian model:

$$f(x) = a_1 * e^{-\left(\frac{x-b_1}{c_1}\right)^2} + a_2 * e^{-\left(\frac{x-b_2}{c_2}\right)^2}$$

- Fit Coefficients (with 95% confidence bounds):
  - a_1 = 3458 (3159, 3757)
  - **b_1 = 27.39 (27.04, 27.74)**
  - c_1 = 10.05 (9.273, 10.82)
  - a_2 = 2217 (2044, 2390)
  - **b_2 = 43.16 (41.02, 45.3)**
  - c_2 = 24.38 (22.88, 25.89)

Low load peak

NRTC peak

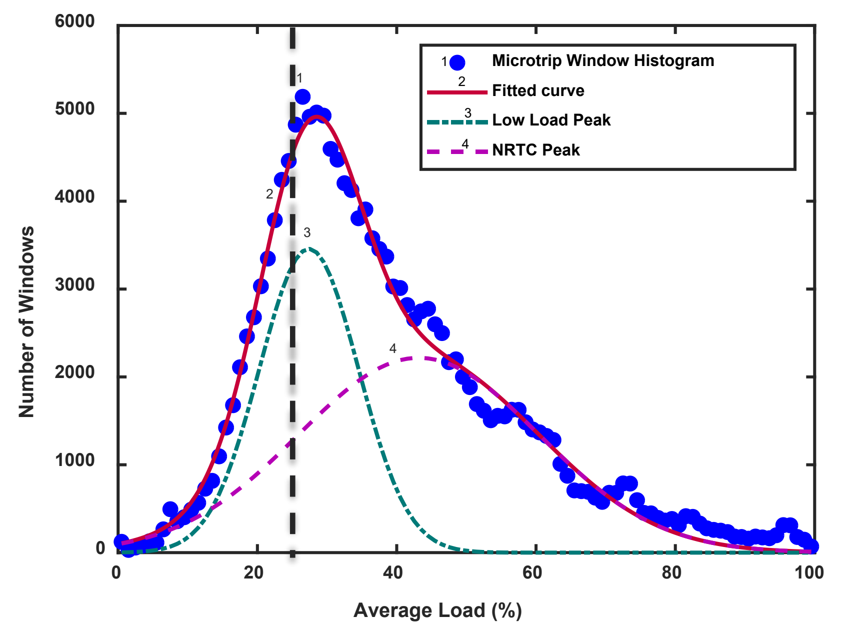


R^2=0.988, RMSE = 197.0

The low load peak location is similar across applications

Identifying the Low Load Cut Point

- Comparable with the on-road LLC development, the 20th percentile of the overall distribution is at around 24% average load for all the received data except for yard tractors.
  - The 20th percentile of the distribution of yard tractor data is at around 27% average load.
- Staff is analyzing 15%, 20%, and 25% average loads as possible cutoff points for low load operations.
- Only low load windows will be included in the subsequent clustering analysis.



The dashed black line indicates the 20th percentile of the histogram.

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Staff will Conduct a Clustering Analysis Using Low Load Windows Characteristics

- Average engine load
- Maximum engine load
- Median load
- Standard deviation of engine load
- Number of engine loading events per hour
- Loading ratio (ratio of increasing to decreasing loading rate time)
- % of operation below 25% engine load
- % of operation staying below 25% engine load for 300 consecutive seconds

Next Steps in Development of Potential LLC

- Requesting comments on today's presentation
- Requesting data for constant speed engines
- Hosting small group follow-up LLC meetings during August and September 2022 with interested stakeholders
- Proposing and refining candidate engine profiles in September 2022 for SwRI
- SwRI will conduct an LLC project advisory group meeting in the 4th quarter of 2022.
- Starting cycle translation and engine dynamometer testing by SwRI in late 2022
- Testing results will be available in early 2023.

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Backup slides

Average Load Distribution of Yard Tractors

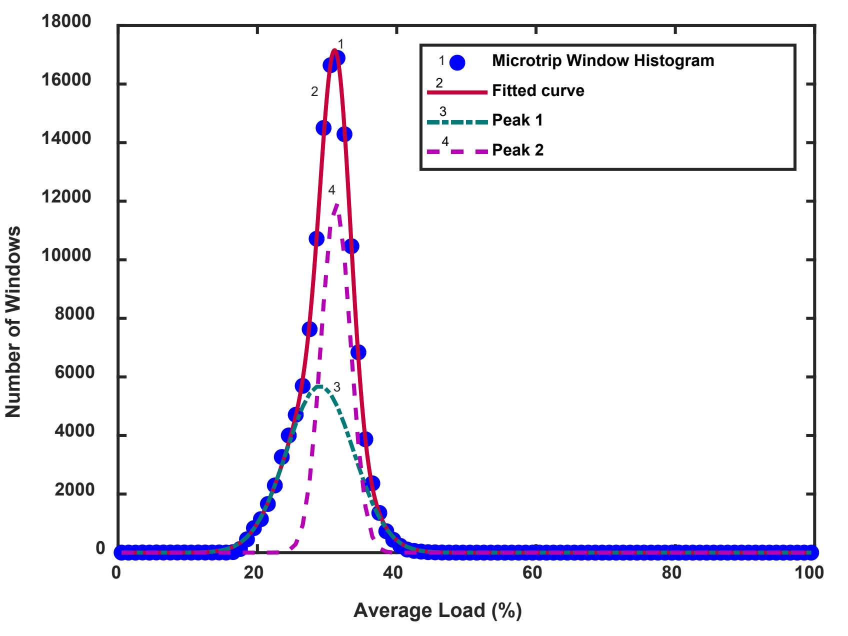
- 131,448 windows in total
- General 2 term Gauss model:

$$f(x) = a_1 * e^{-\left(\frac{x-b_1}{c_1}\right)^2} + a_2 * e^{-\left(\frac{x-b_2}{c_2}\right)^2}$$

- Fit Coefficients (with 95% confidence bounds):
  - a_1 = 5694 (5400, 5988)
  - **b_1 = 28.99 (28.84, 29.14)**
  - c_1 = 6.819 (6.676, 6.962)
  - a_2 = 1.201e4 (1.171e4, 1.231e4)
  - **b_2 = 31.25 (31.22, 31.28)**
  - c_2 = 2.981 (2.92, 3.042)

Peak 1

Peak 2



R^2=0.9995, RMSE = 81.0

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