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CanmetMINING BEV field test series: LHD duty cycle analysis and energy consumption model

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Outline

- Objectives
- Methodology
- Classification of activities
- Energy results (per lap/bucket and activities)
- Energy consumption model – ECM (for Transit)
- Summary



Objectives

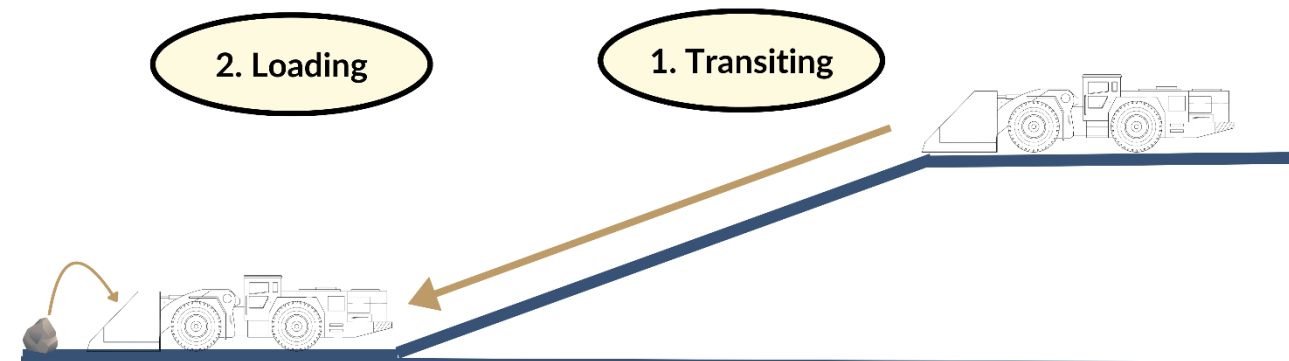
- Measure net energy consumption per activity from field test data for an LHD operating in an up-ramp hauling (loaded) duty cycle
- Use the findings to calibrate an energy model that could be used for other mine site condition simulations



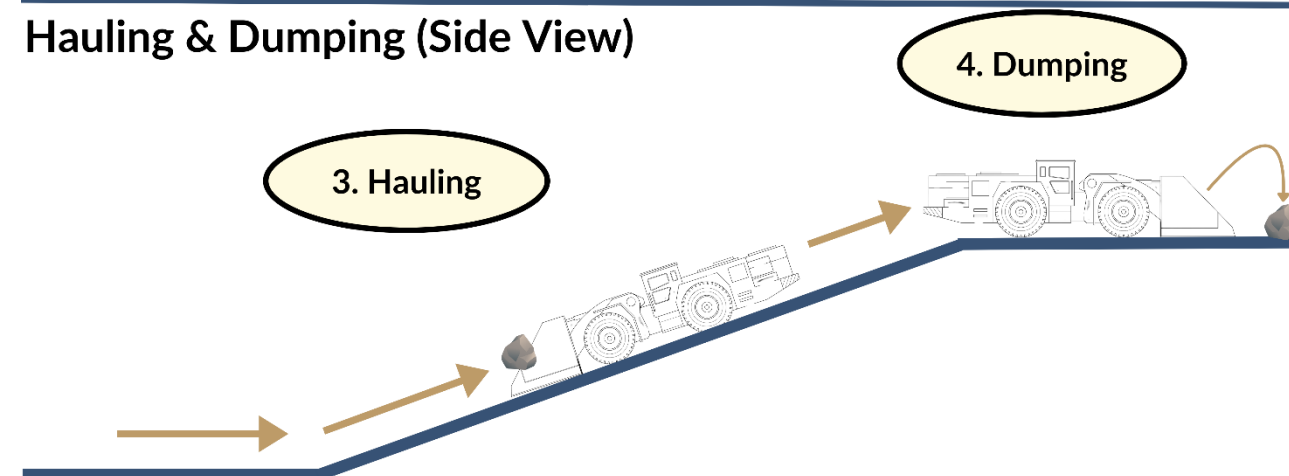
Methodology – LHD duty cycle

- LHD starts with bucket empty on top of the ramp and moves to bottom of ramp (**T**ransit)
- Drives into heading and loads bucket with material (**L**oad)
- Moves material to top of ramp (**H**aul) (~ 430 meters at 13%)
- Drives into heading and dumps material (**D**ump)
- Repeats cycle/lap (**TLHD**) until bottom heading is empty
- Swapping battery (when needed)

Transiting & Loading (Side View)



Hauling & Dumping (Side View)



Methodology

- Step 1 – Collect test data for LHD equipment during execution of duty cycle including traction and auxiliary power
- Step 2 – Classification of TLHD activities and net energy consumed:
 - Select set of inputs to define activities from data set
 - Group power and energy consumed per activity and per lap to estimate average traction and auxiliary power requirements
- Step 3 – Calibrate energy consumption model (ECM):
 - Use Transit activity (hauling empty) as payload weight was unknown; with average traction and auxiliary power to calibrate ECM, to find rolling resistance, vehicle efficiency and auxiliary power parameters.



Classification – inputs

- Field test data parameters for BEV LHD:
 - Battery pack voltage (L and R)
 - Battery pack power (L and R)
 - Battery pack SoC% (L and R)
 - Traction power
 - Auxiliary power
 - Average wheel speed
 - Acceleration pedal position %
 - Inclinometer x and y angle degrees (not calibrated before test)
 - Time stamp



Classification – inputs

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- Battery pack power (L and R)
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- Traction power
- Auxiliary power

- Average wheel speed

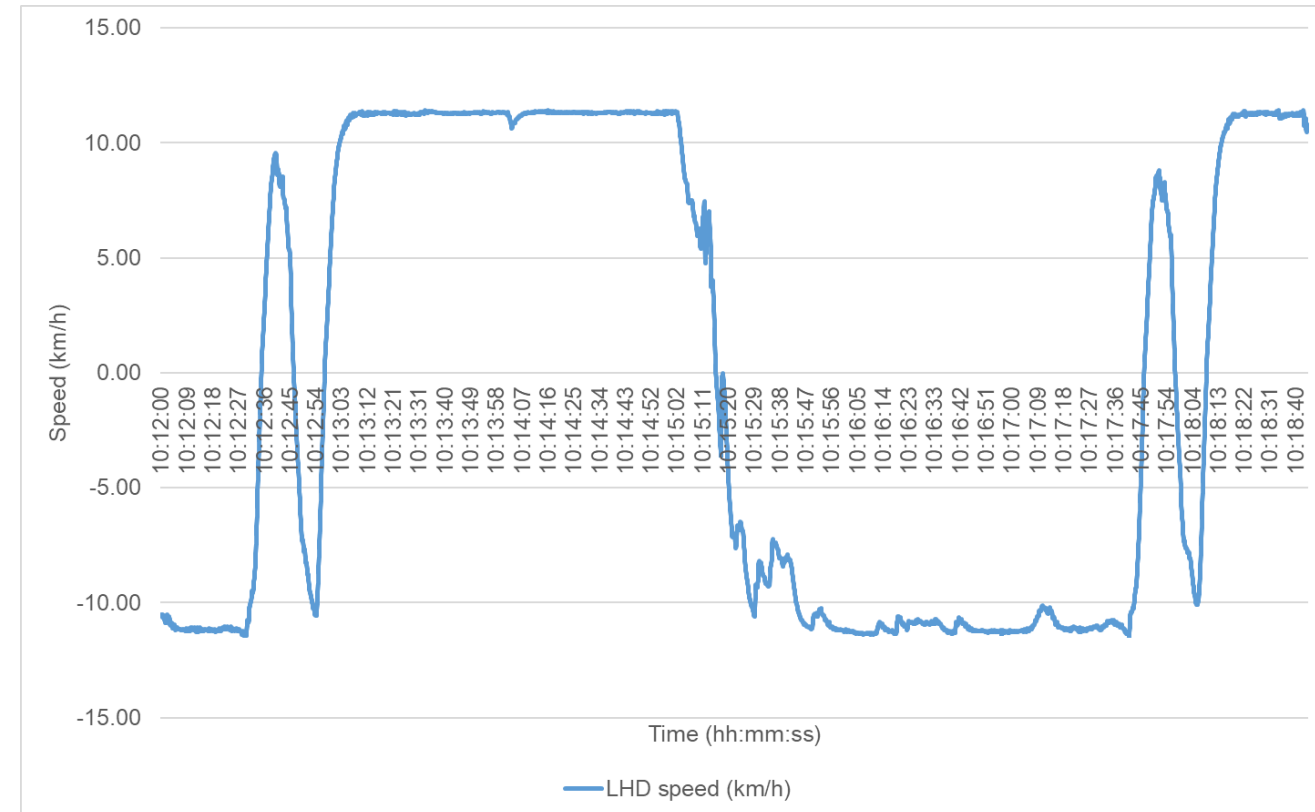
Shows when the equipment was moving or stopped and can be used to determine activities

- Acceleration pedal position %
- Inclinator x and y angle degrees (not calibrated before test)
- Time stamp



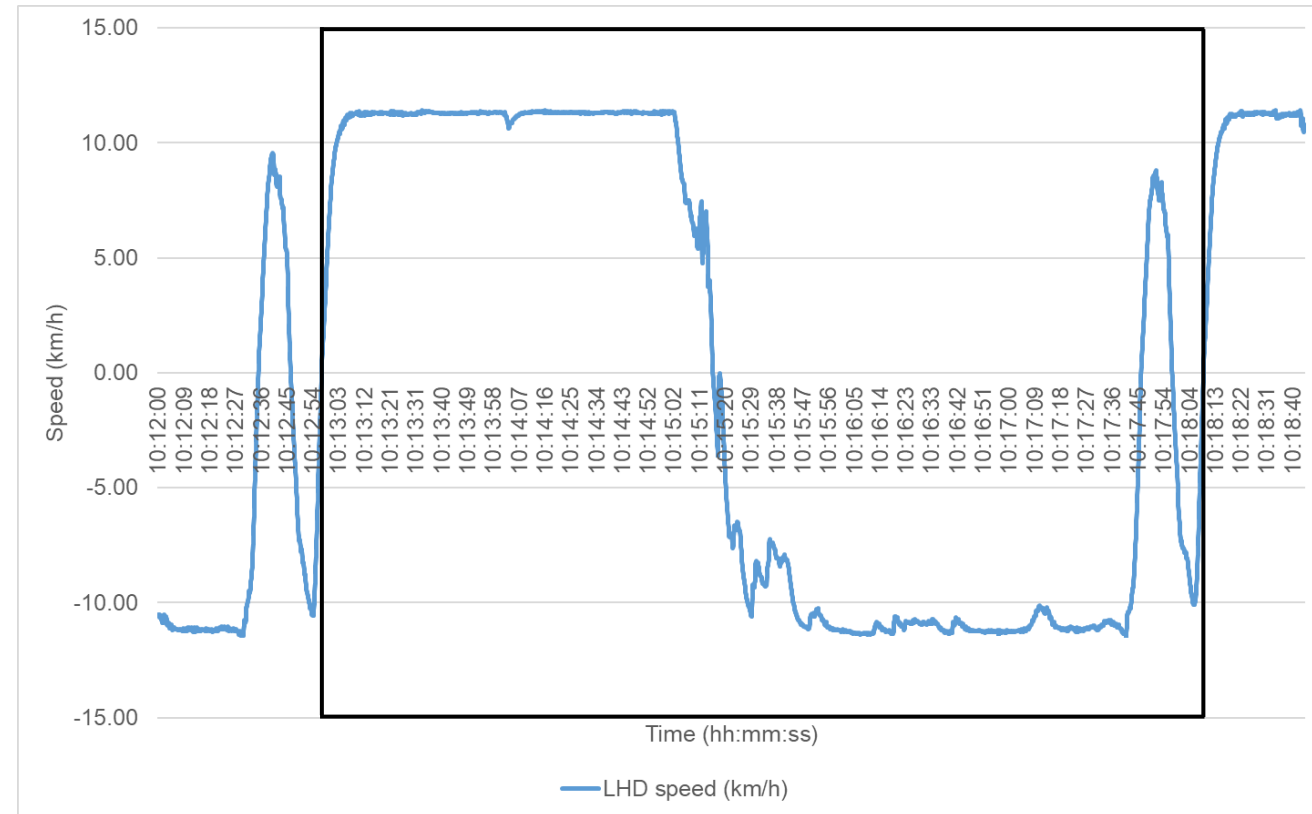
Classification – 1st input speed profile

- Duty cycle: up ramp loaded (development)
- Test duration: 2.17 hours
- Figure showing 1 sample lap

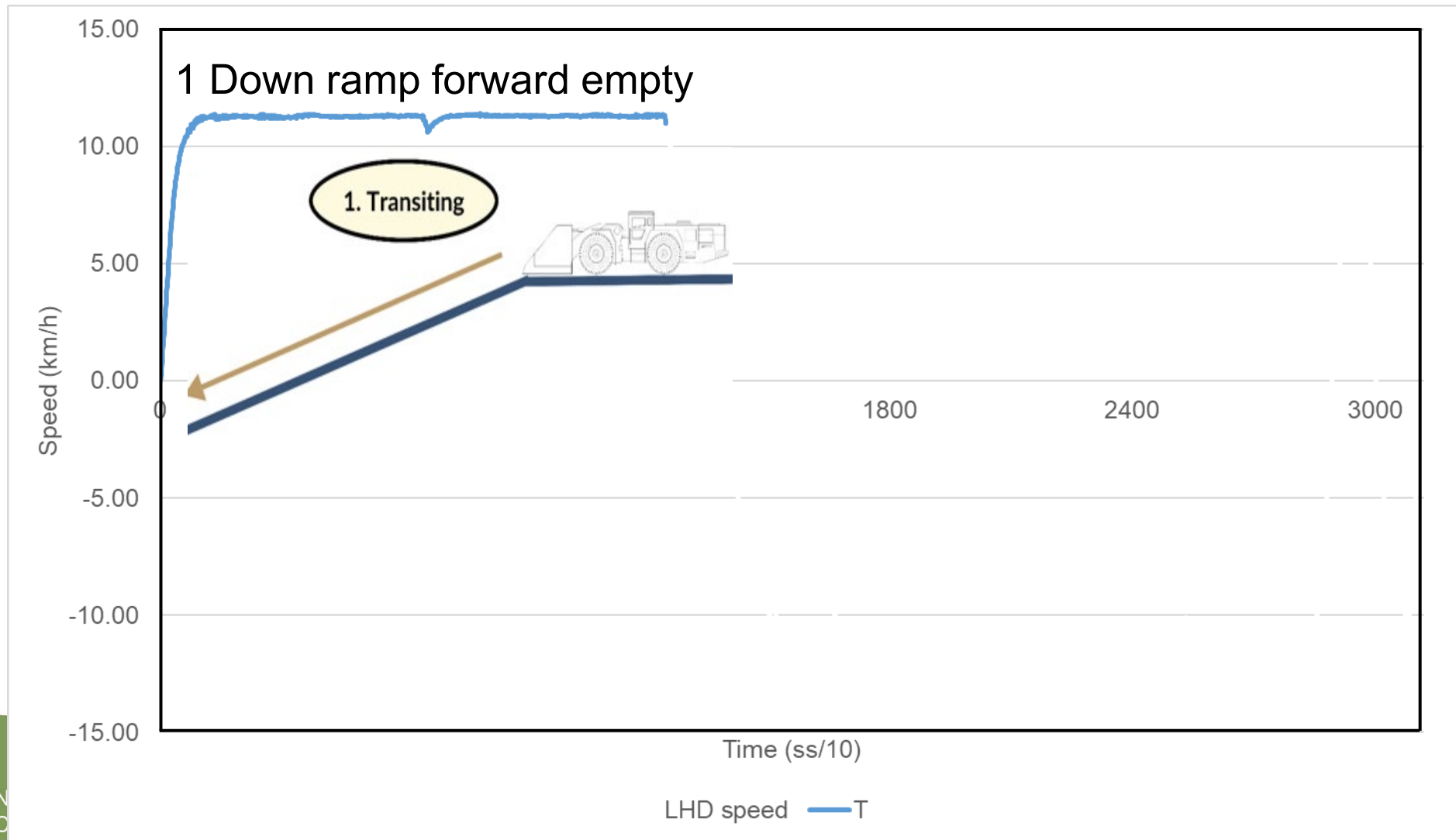


Classification – 1st input speed profile

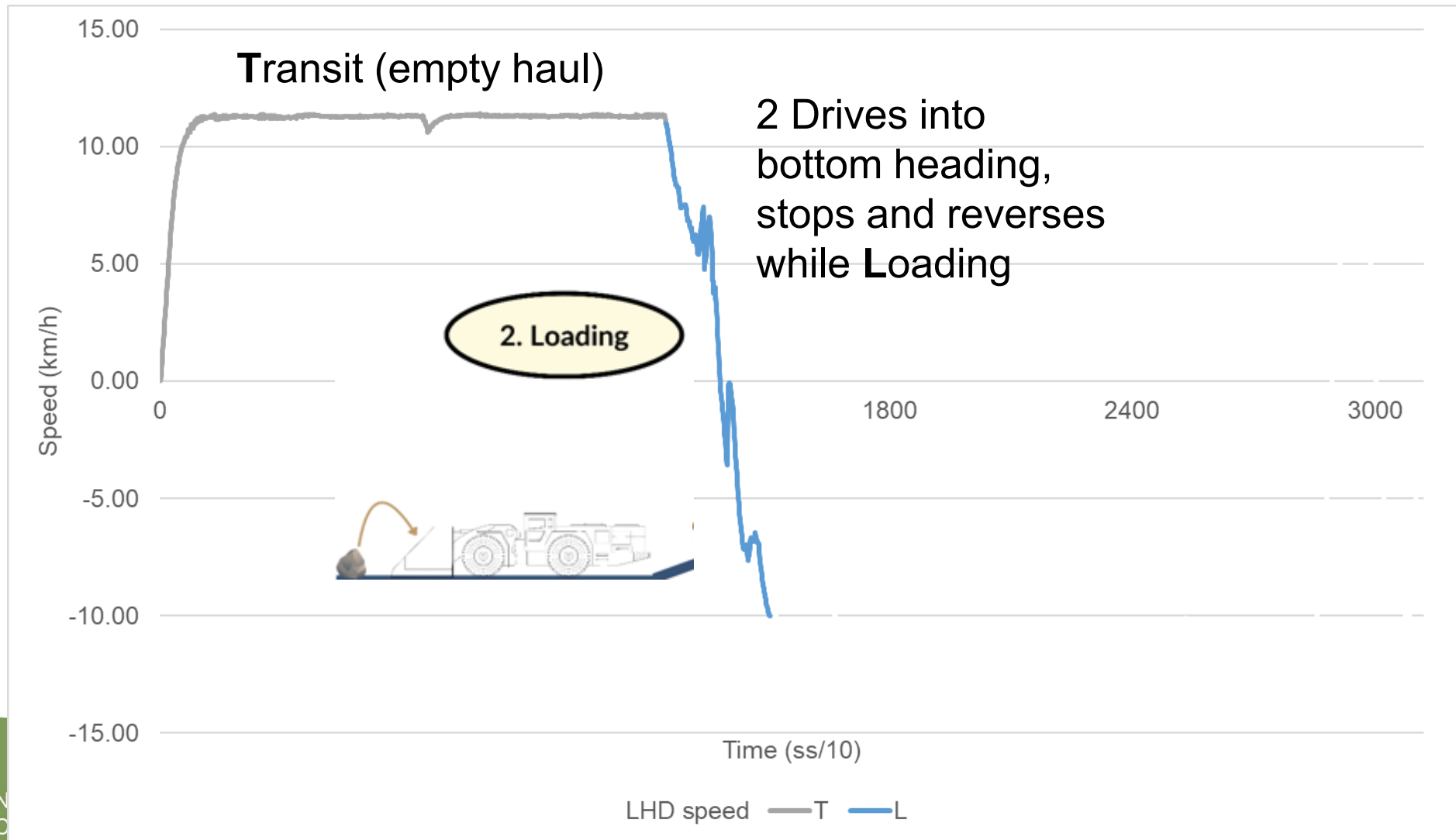
- Duty cycle: up ramp loaded (development)
- Test duration: 2.17 hours
- Sample duty cycle lap time:
 - ~ 5.5 min



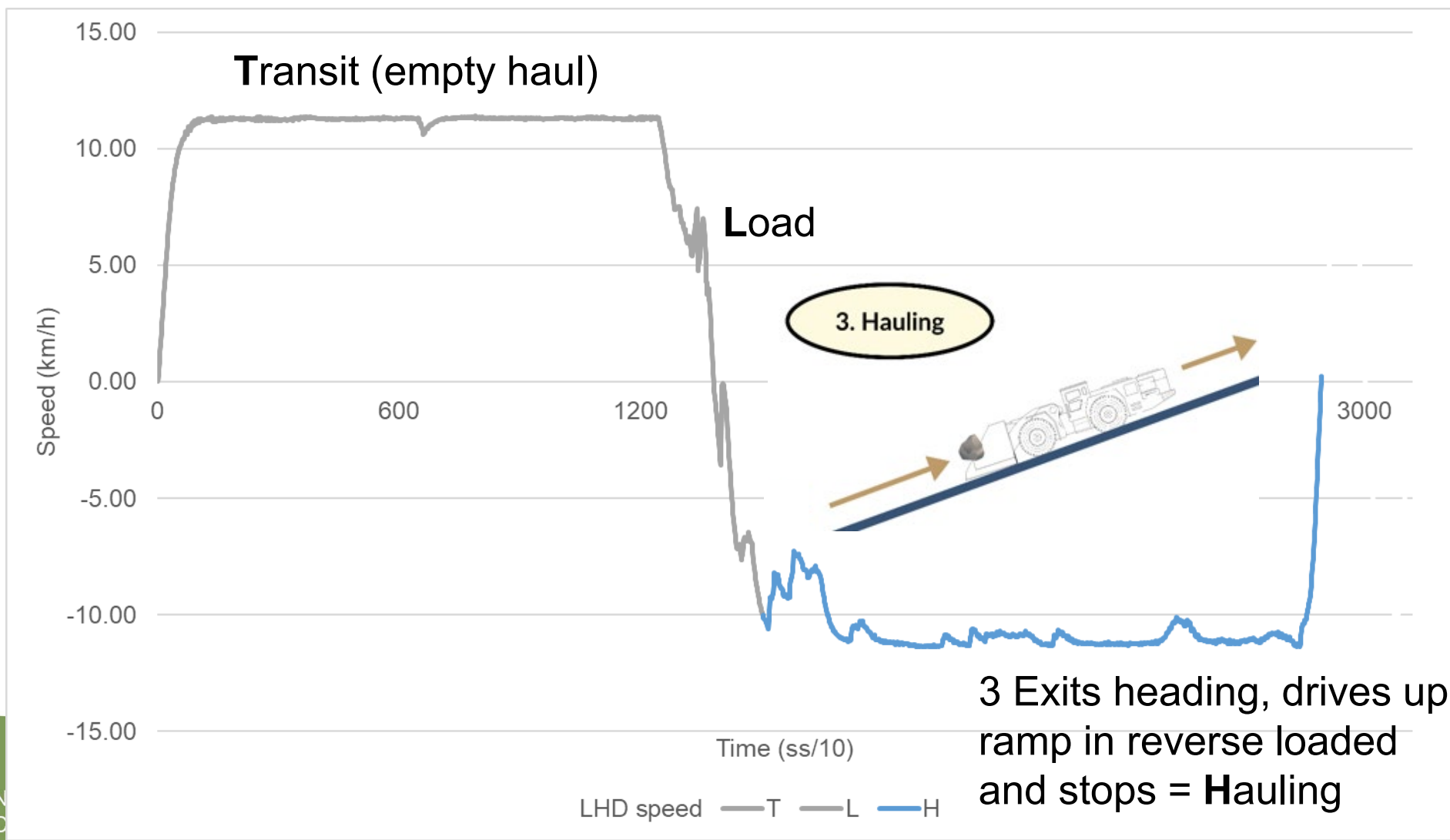
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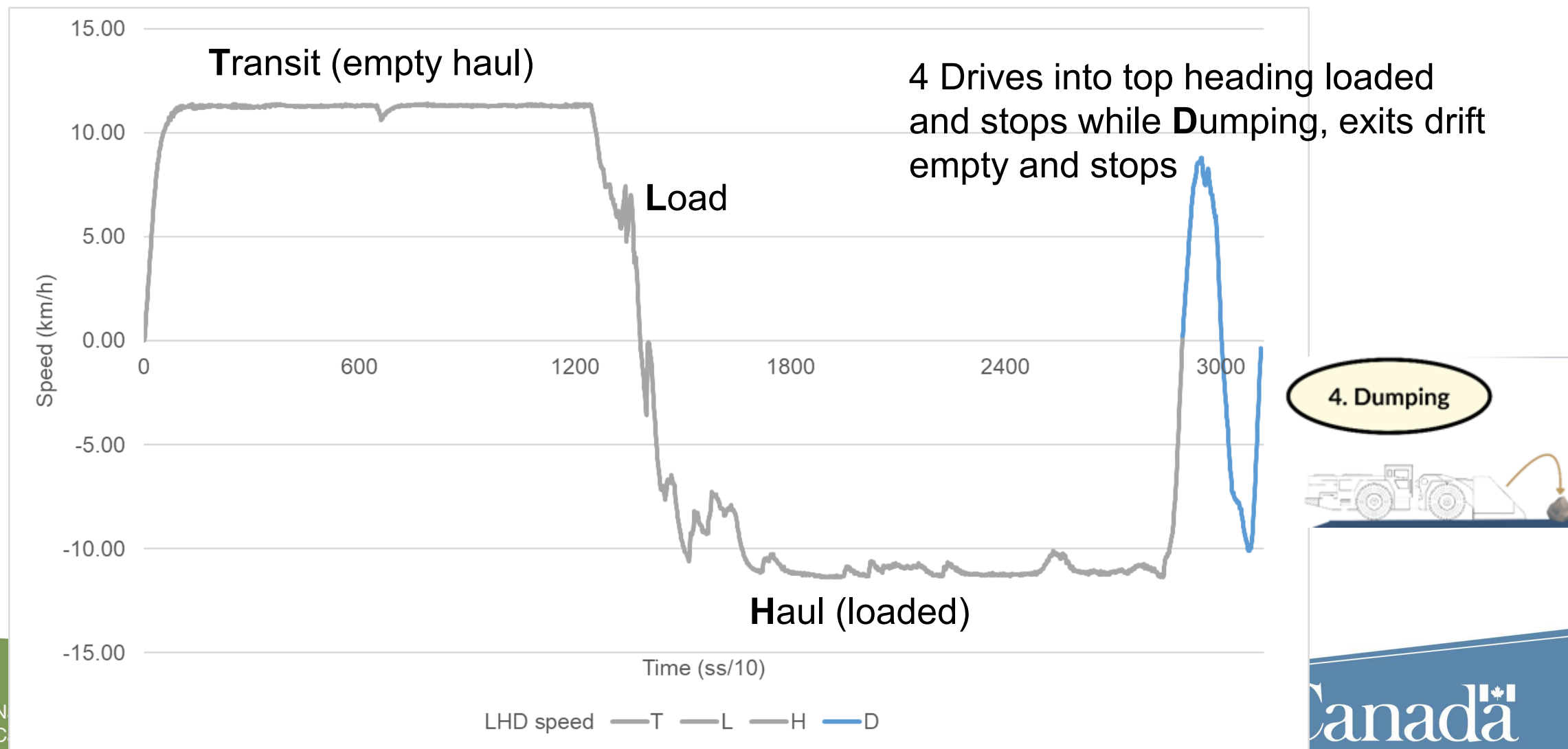
Classification – 1st input speed profile



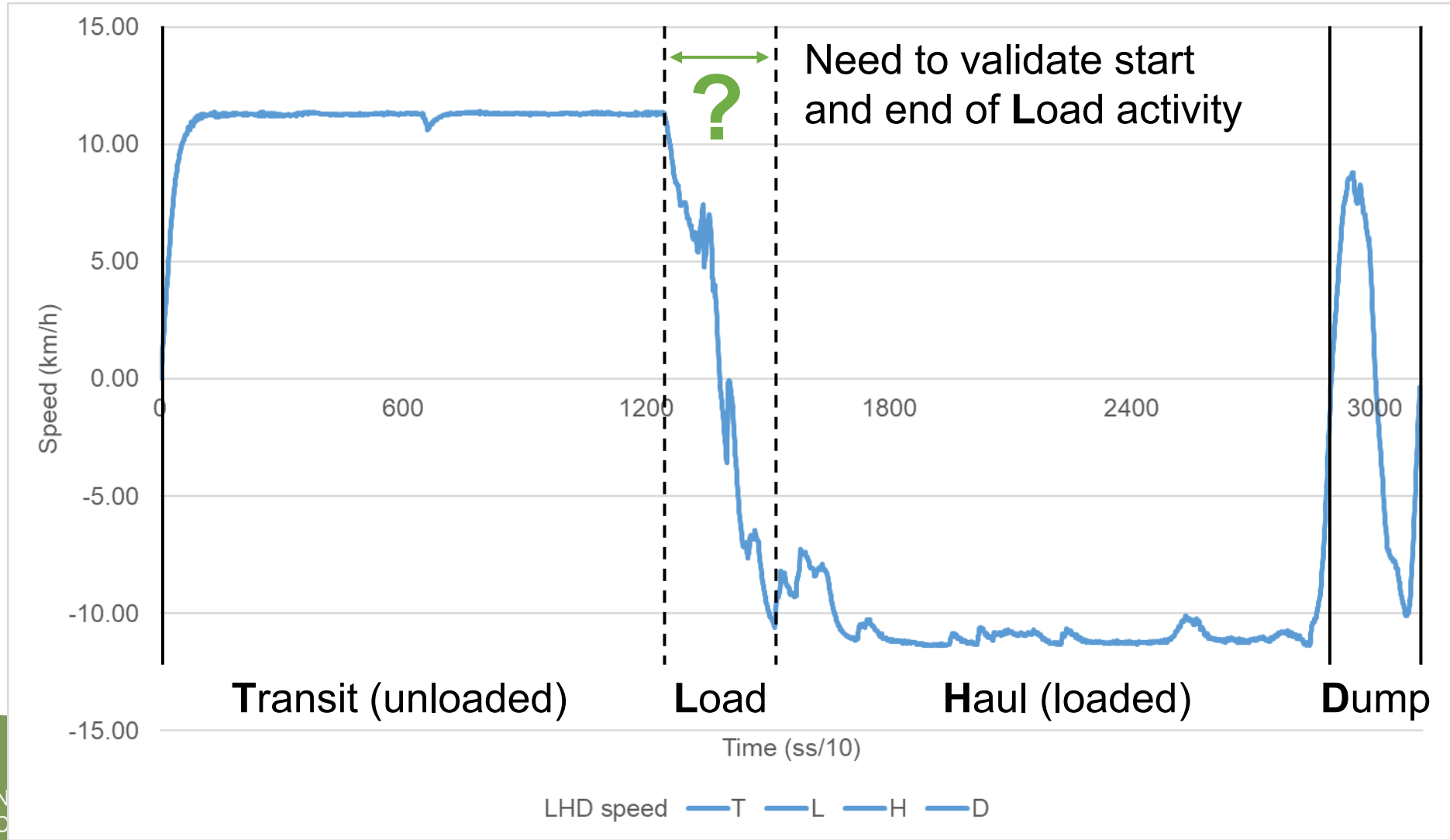
Classification – 1st input speed profile



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Classification – inputs

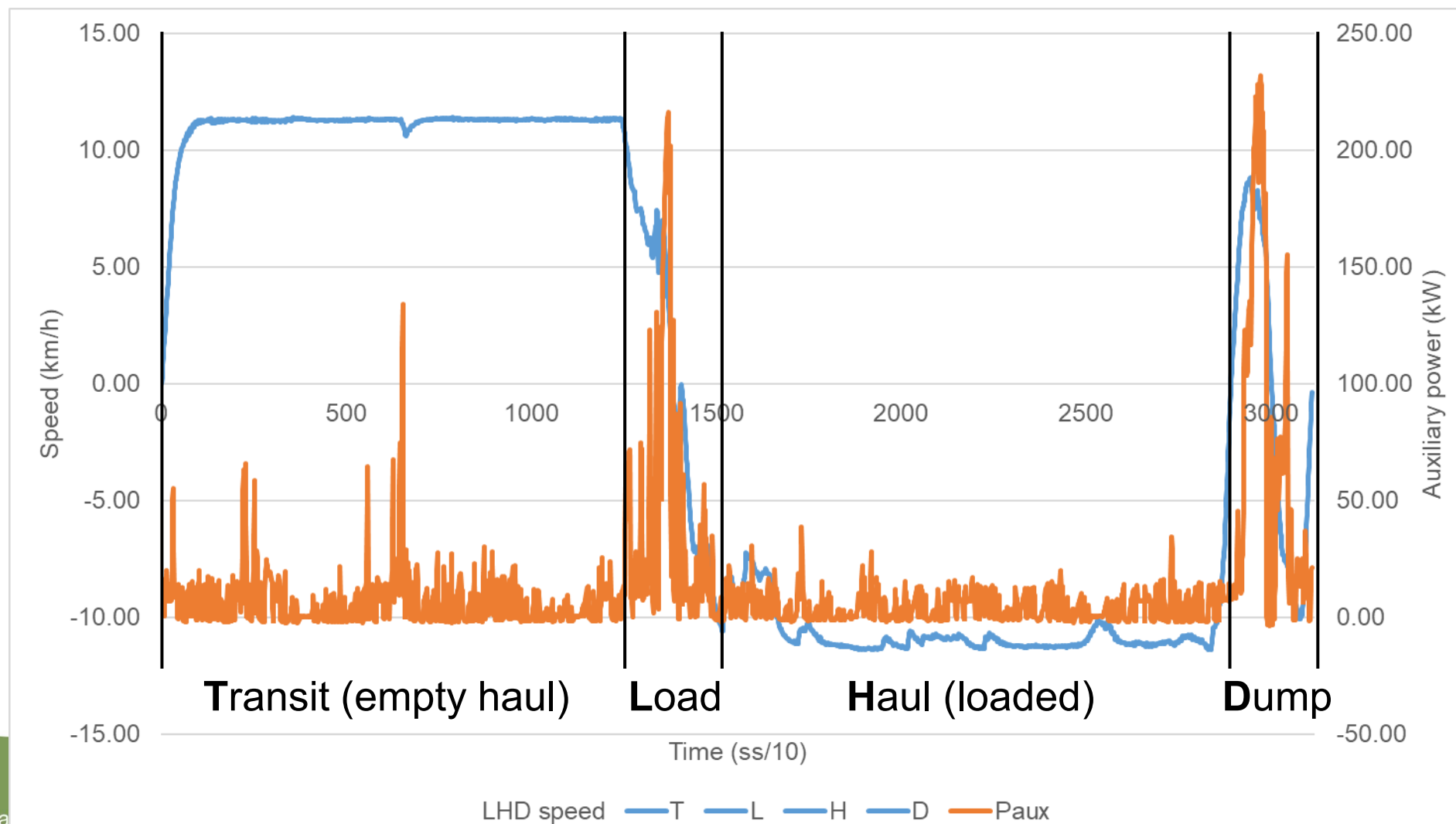
- Field test data parameters for BEV LHD:

- Battery pack voltage (L and R)
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- Battery pack SoC% (L and R)
- Traction power
- Auxiliary power
- Average wheel speed
- Acceleration pedal position %
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Peaks of auxiliary power shows when the bucket was lifted for loading and dumping

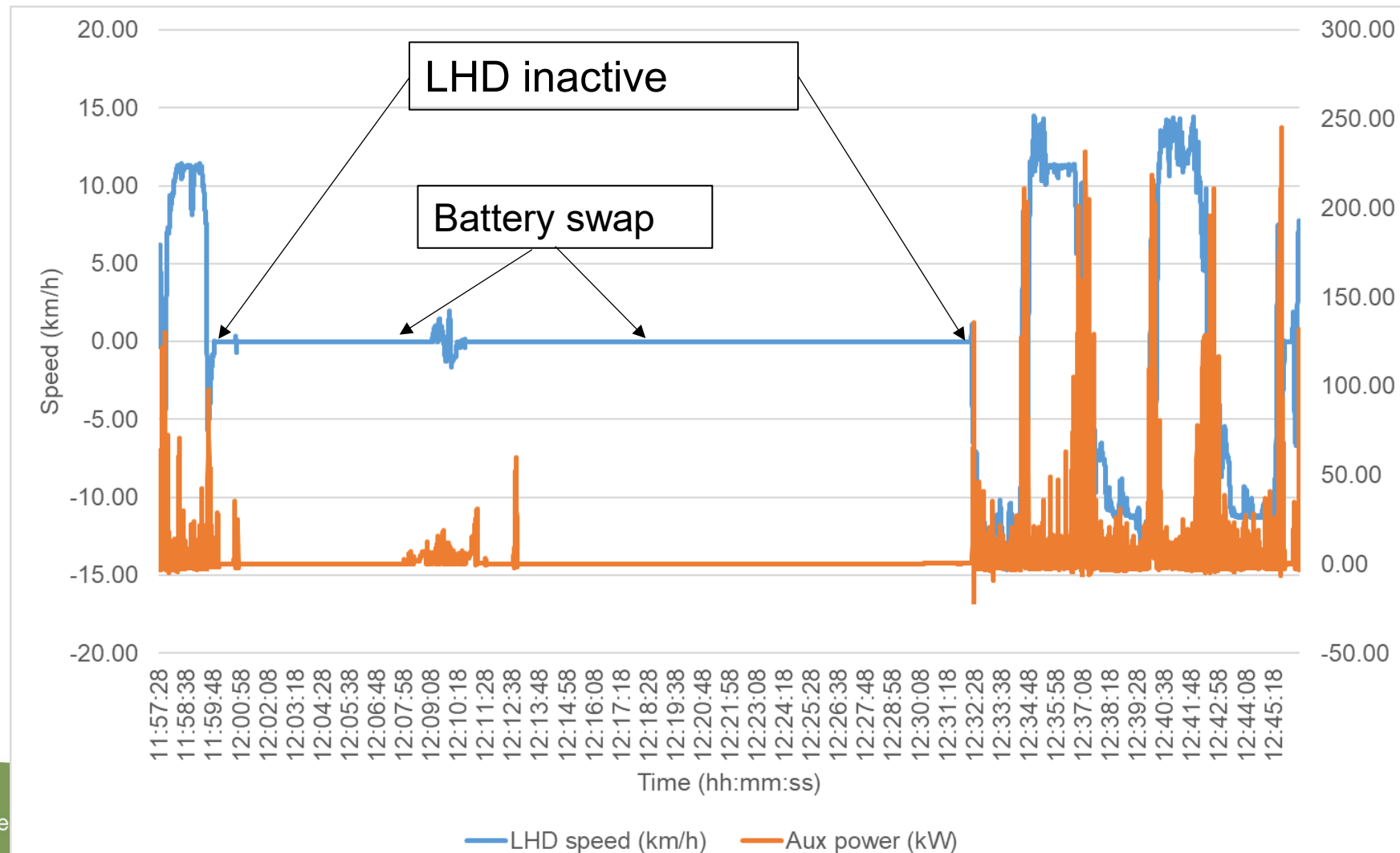


Classification – 2nd input auxiliary power



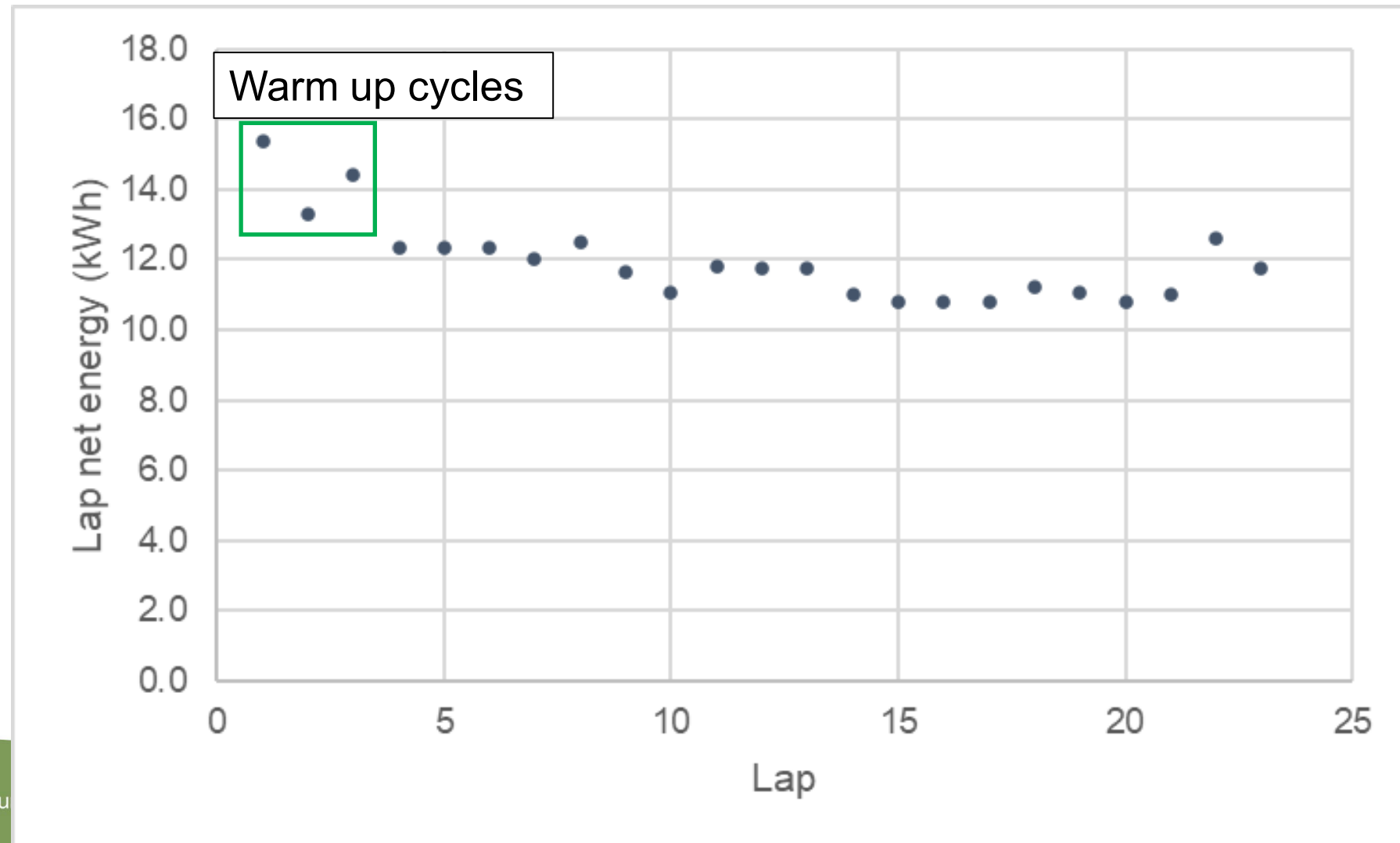
Classification – battery swapping activity

- Here is an example where we used speed to identify battery swapping
- Only one battery swap observed
- 11 minutes swap
- LHD inactive due to other test activities



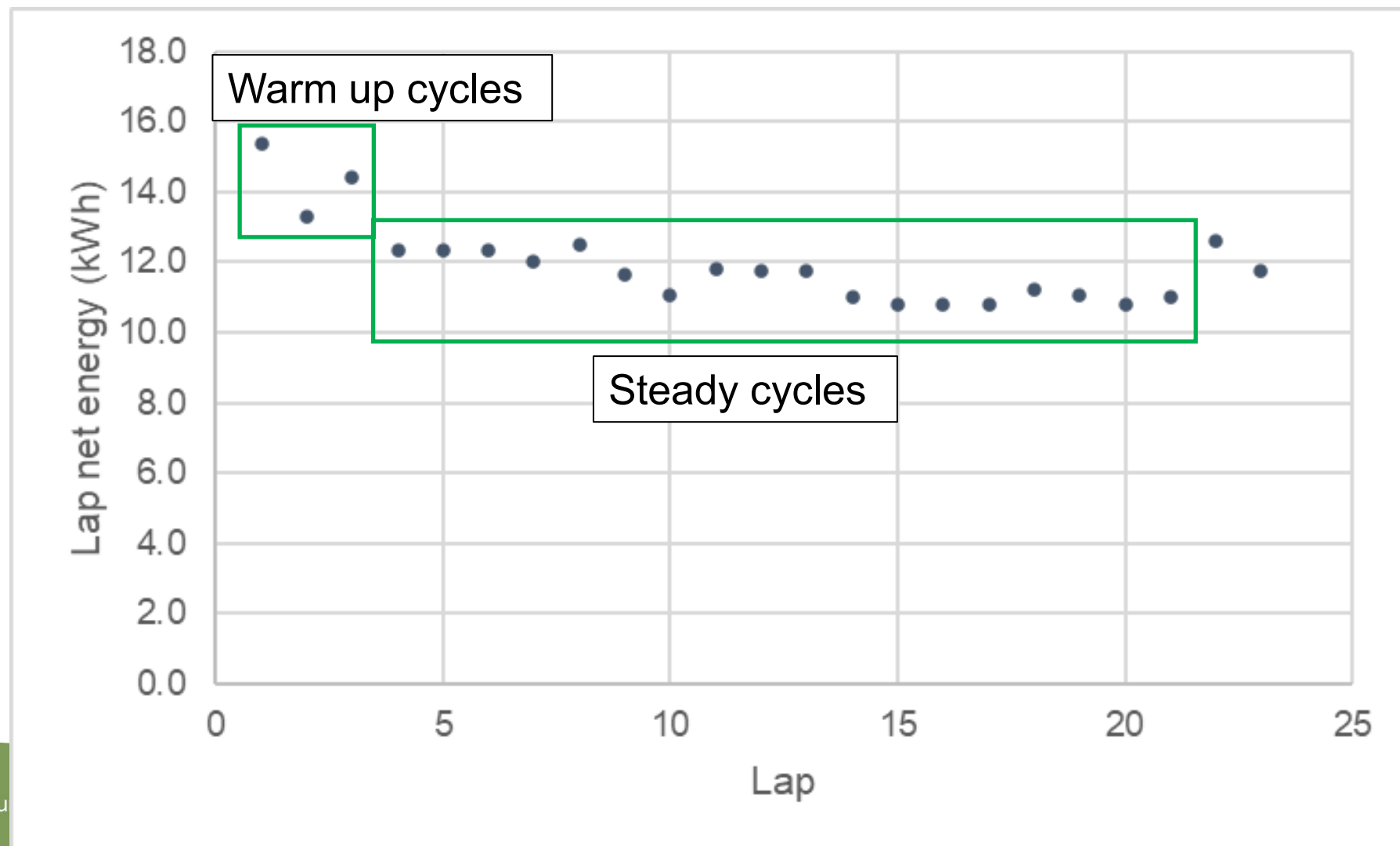
Energy results per lap

- Net energy consumed per lap (consumed minus regenerated or captured)
- Lap net energy includes traction and auxiliary energy



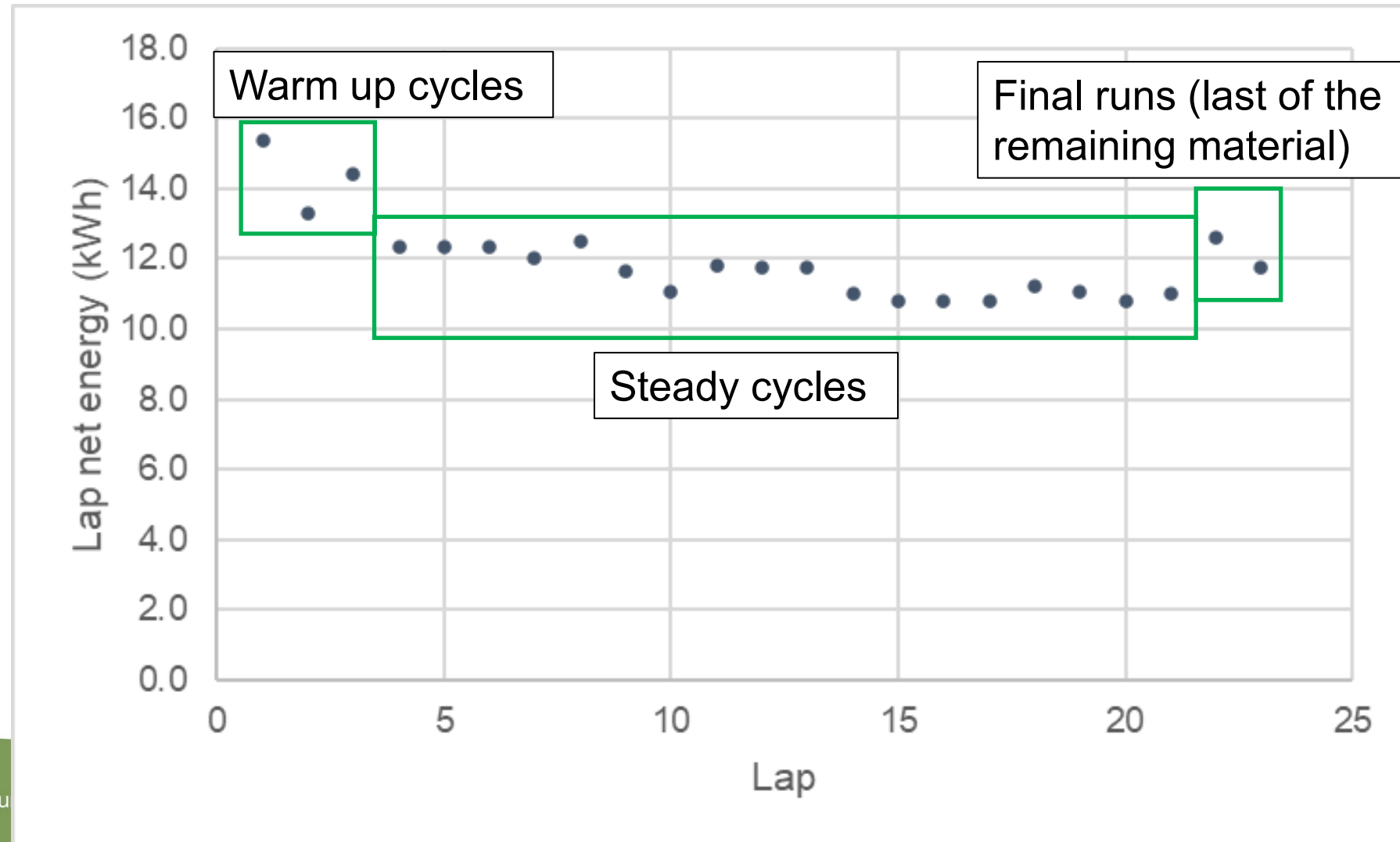
Energy results per lap

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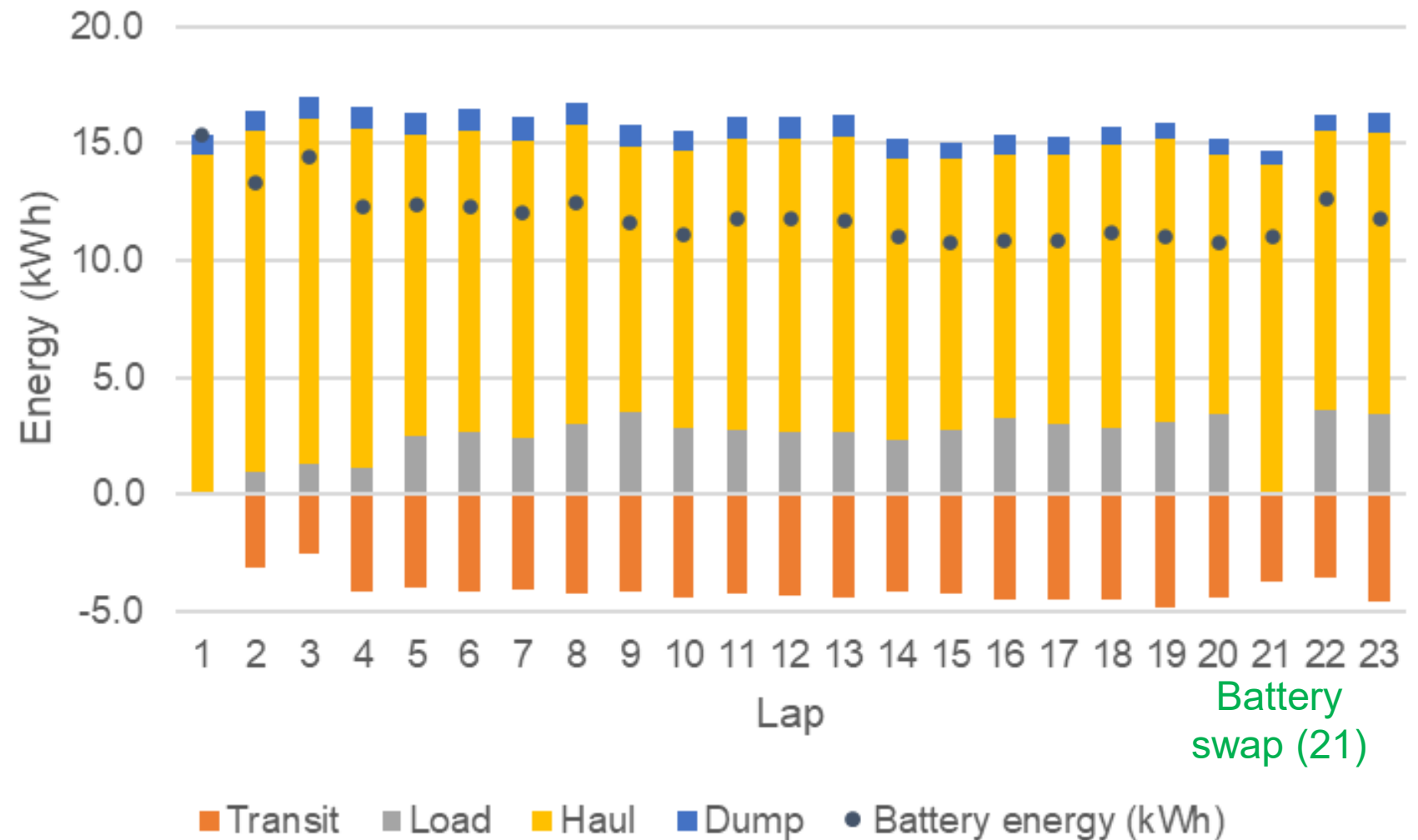
Energy results per lap

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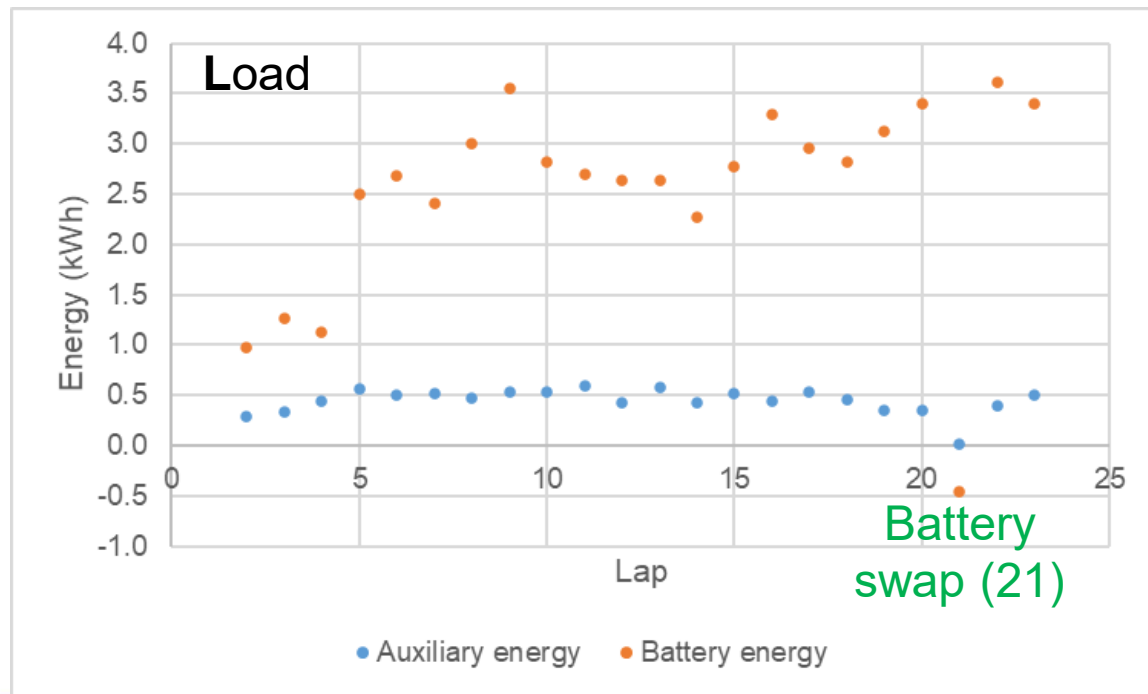
Energy results per lap and per activity

- Net energy average per activity:
 - Transit -4.1 kWh
 - Load 2.5 kWh
 - Haul 12.6 kWh
 - Dump 0.8 kWh
- Complete laps from 2 to 23
- 21 battery swap (no Load)



Energy results per activity (Load and Dump)

- Average battery energy is 2.5 kWh
- Average auxiliary energy is 0.4 kWh



Battery energy = traction + auxiliary energy



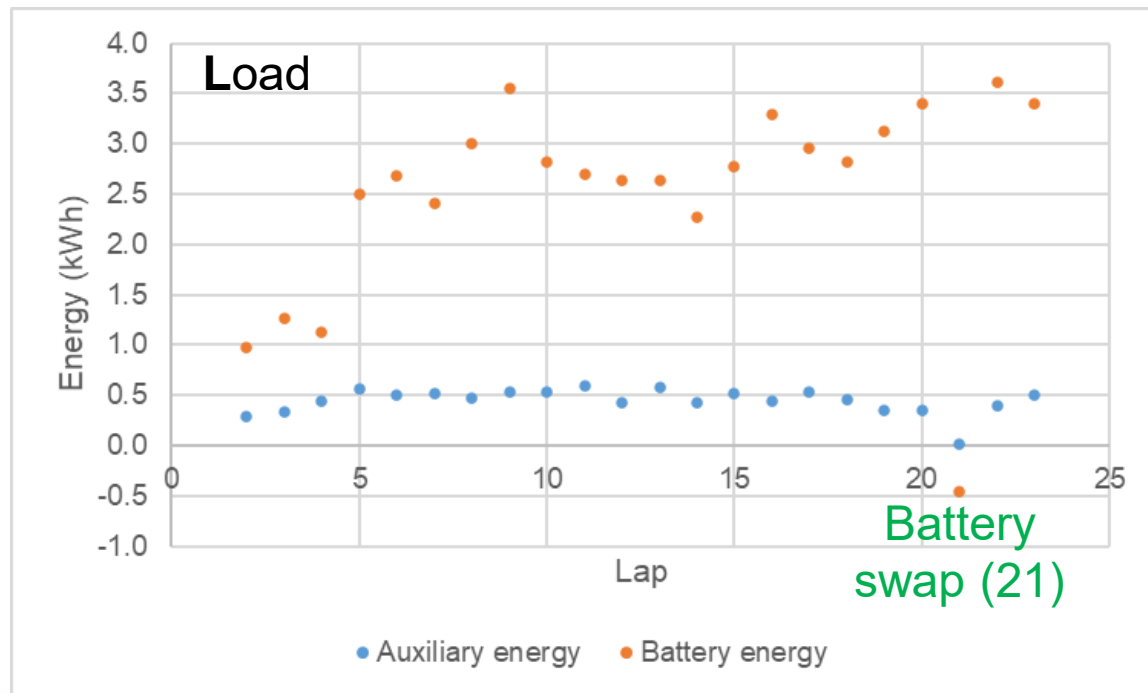
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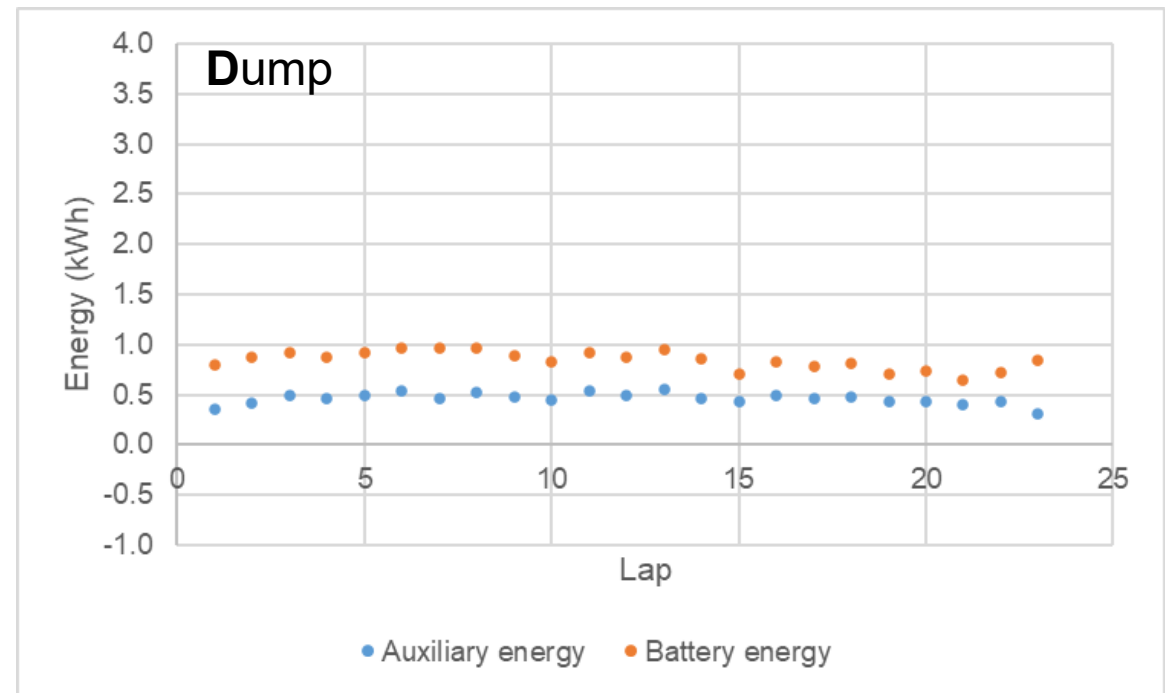
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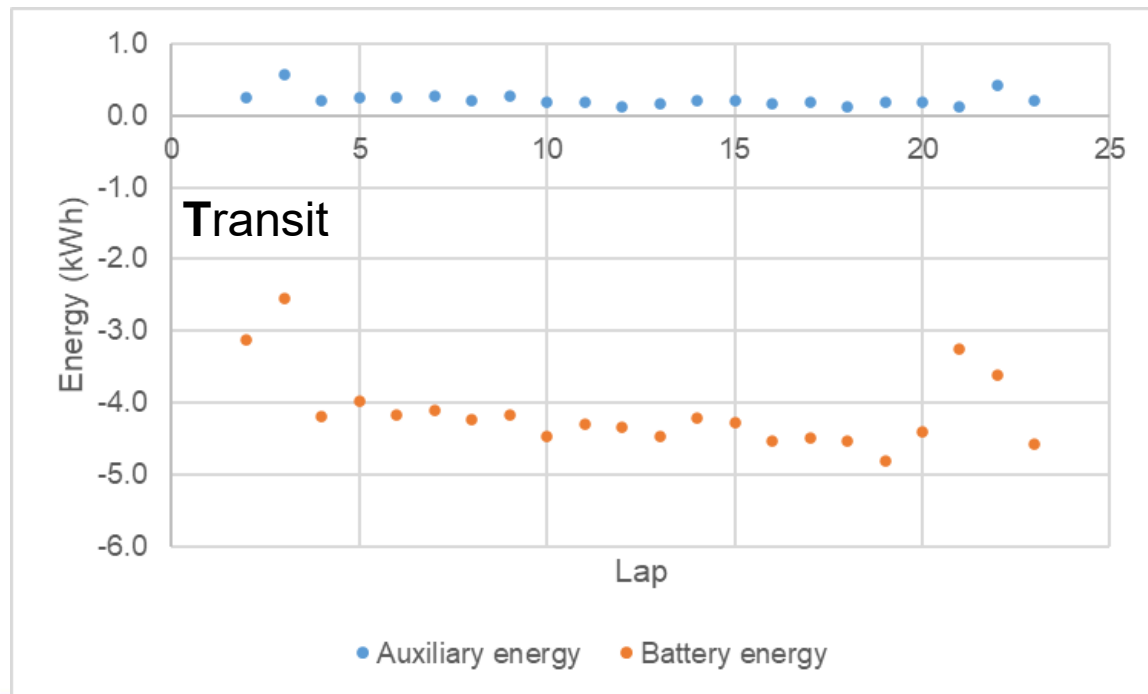
- Average battery energy is 0.8 kWh
- Average auxiliary energy is 0.5 kWh



Battery energy = traction + auxiliary energy

Energy results per activity (Transit and Haul)

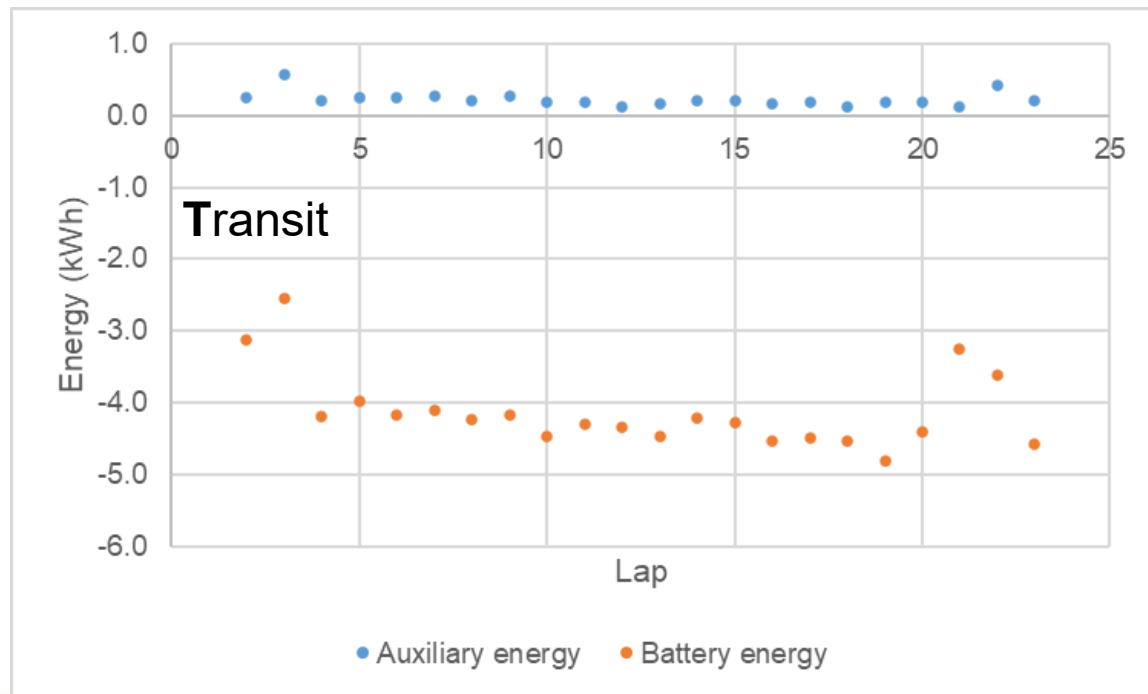
- Average battery energy is -4.1 kWh
- Average auxiliary energy is 0.2 kWh



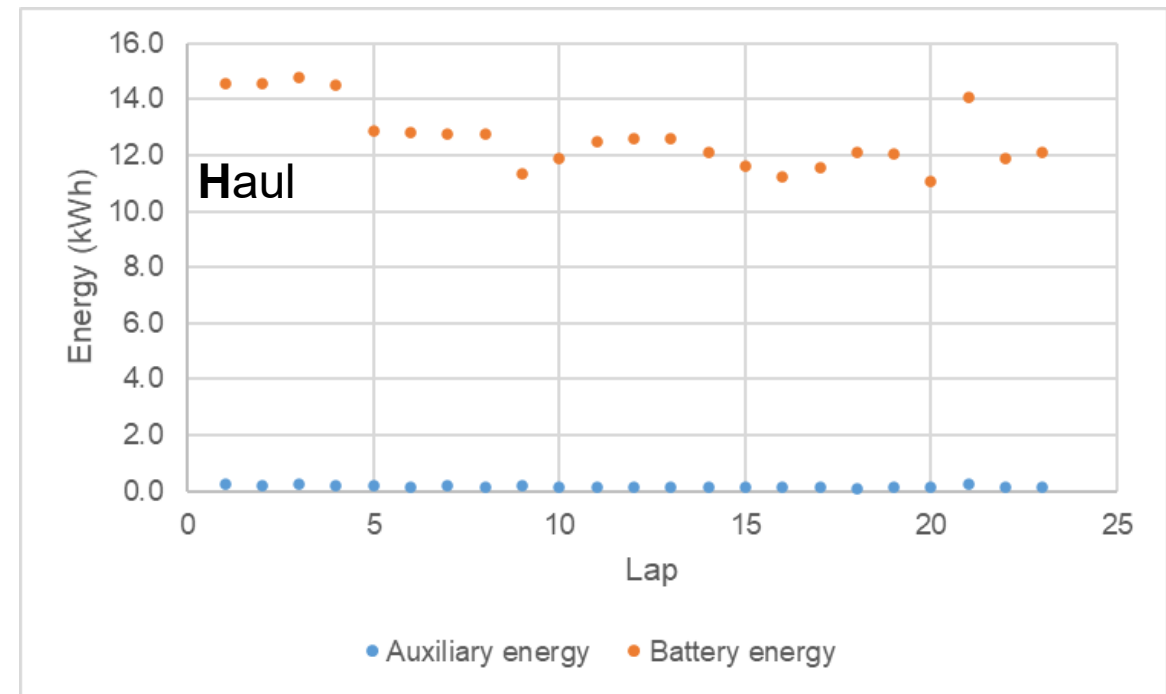
Battery energy = traction + auxiliary energy

Energy results per activity (Transit and Haul)

- Average battery energy is -4.1 kWh
- Average auxiliary energy is 0.2 kWh



- Average battery energy is 12.6 kWh
- Average auxiliary energy is 0.2 kWh



Battery energy = traction + auxiliary energy

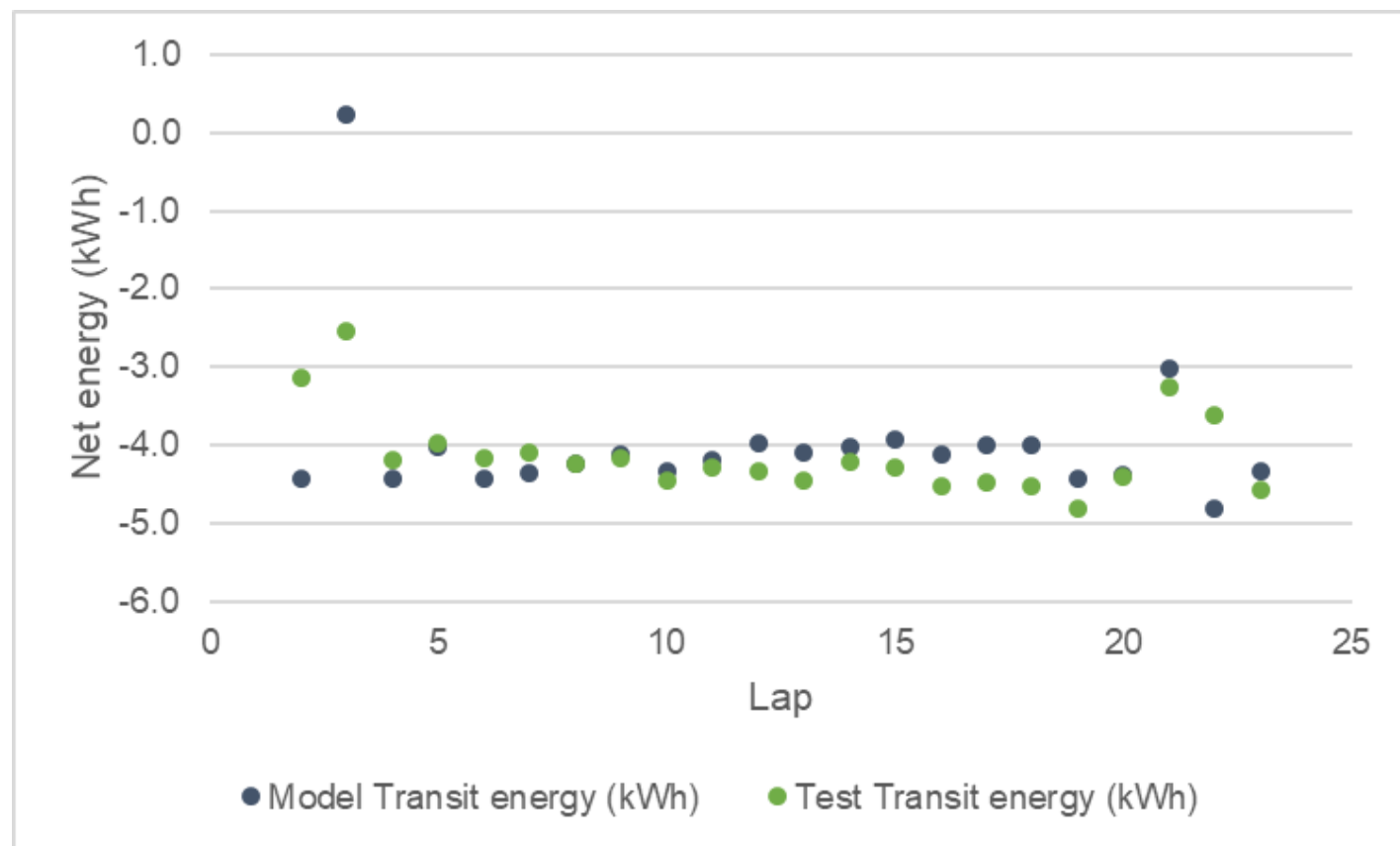
Energy consumption model – ECM

- Energy consumption model (ECM) calibration uses field test data to determine:
 - Rolling resistance (%)
 - Vehicle battery to wheel efficiency (%)
 - Auxiliary power (P_{aux})
- Limitations:
 - physics based equations are meant to model equipment motion (transit and haul)
 - load and dump are modelled separately by average energy per activity
 - constant parameters are an approximation
 - only Transit activity was used as payload weight was unknown for Haul activity



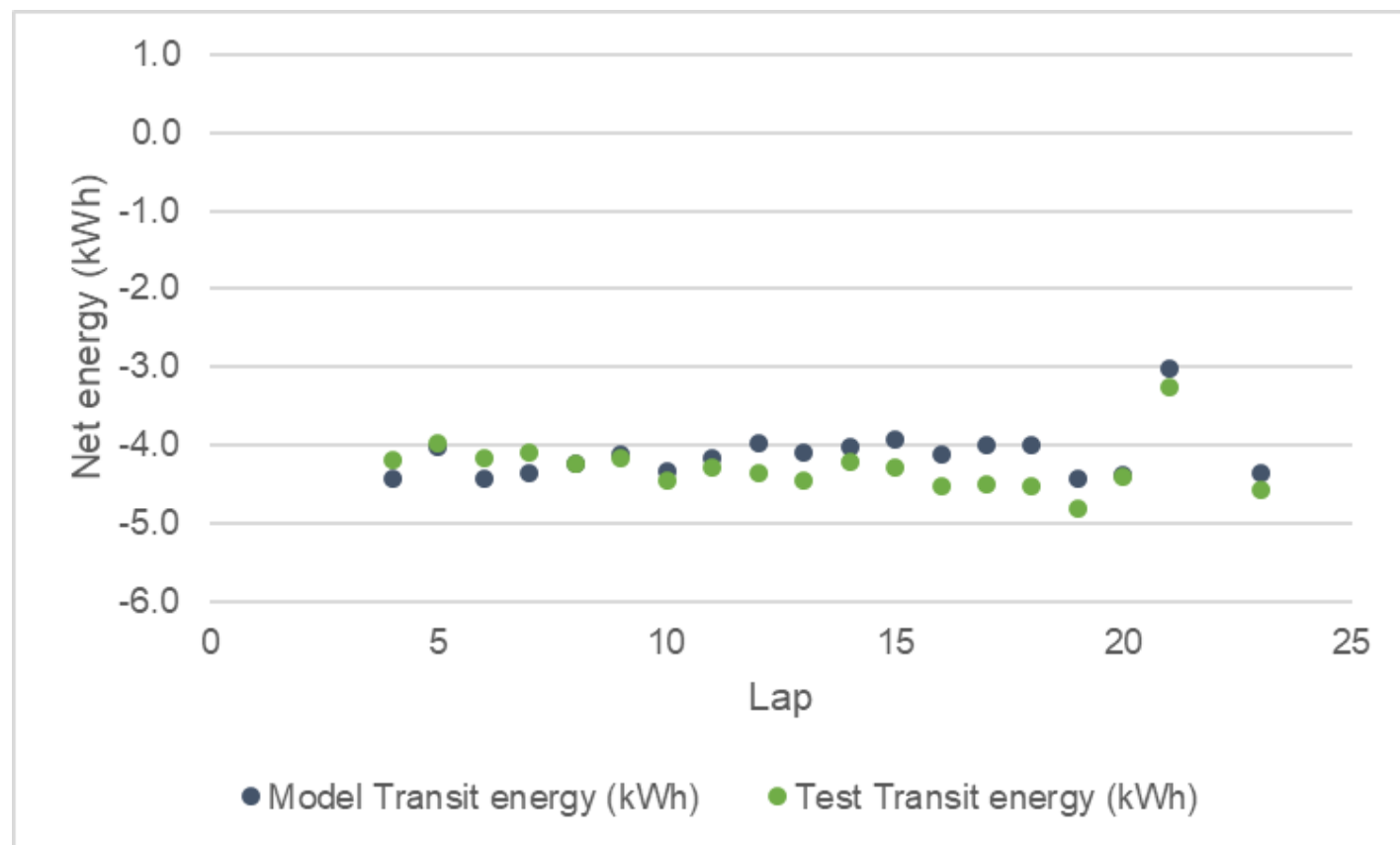
Energy consumption model – Transit

- Energy consumption model (ECM) calibration considering all laps resulted in:
 - Rolling resistance of 2.9%
 - Vehicle efficiency of 81.4%
 - Paux 0.0 kW
- Errors within -109% and +41% (test versus model)
- Largest errors for warm up laps (2 & 3) and the lap after battery swapping (22)
- Outliers removed for next ECM



Energy consumption model – Transit

- Including average Paux of 5.8 kW (0.2 kWh):
 - Rolling resistance of 2.9%
 - Vehicle efficiency of 85%
 - Paux 5.8 kW
 - Test and model error $\pm 12\%$ after removing outliers
- Battery energy averages:
 - Model Transit -4.1 kWh
 - Test Transit -4.3 kWh



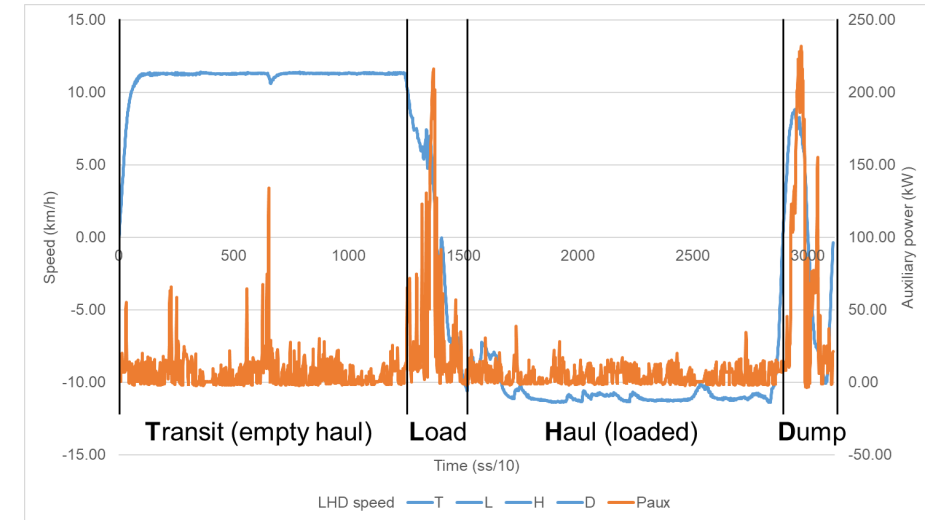
Energy consumption model – publications

- Li, G., Le, J., Acuña-Duhart, E., Levesque, M., Tomini, E., Mohsenimanesh, A., Ribberink, H. & Summers, P. (2024). CanmetMINING battery electric vehicle field test series: Relay utility vehicle. CIM Journal, 15(2), 75–85.
<https://doi.org/10.1080/19236026.2023.2258716>
- Acuña-Duhart, E. (2024). CanmetMINING mine electrification research: Goldex Railveyor study ECM. 2nd MVPC conference,
https://mdec.ca/2024/S5P1_Acuna.pdf
- Acuña-Duhart, E., Li, G., & Levesque, M. (2025). CanmetMINING BEV field test series: Energy consumption model and simulation. CIM Journal, 16(2), 127–134. <https://doi.org/10.1080/19236026.2025.2460127>
- Darcovich, K., Ribberink, H., Acuña-Duhart, E., Le, J., Levesque, M., & Loizeau, L. (2026). Simulation study comparing battery swapping to fast charging for electric underground mine haul trucks. CIM Journal, 17(2), 63–93.
<https://doi.org/10.1080/19236026.2025.2607763>



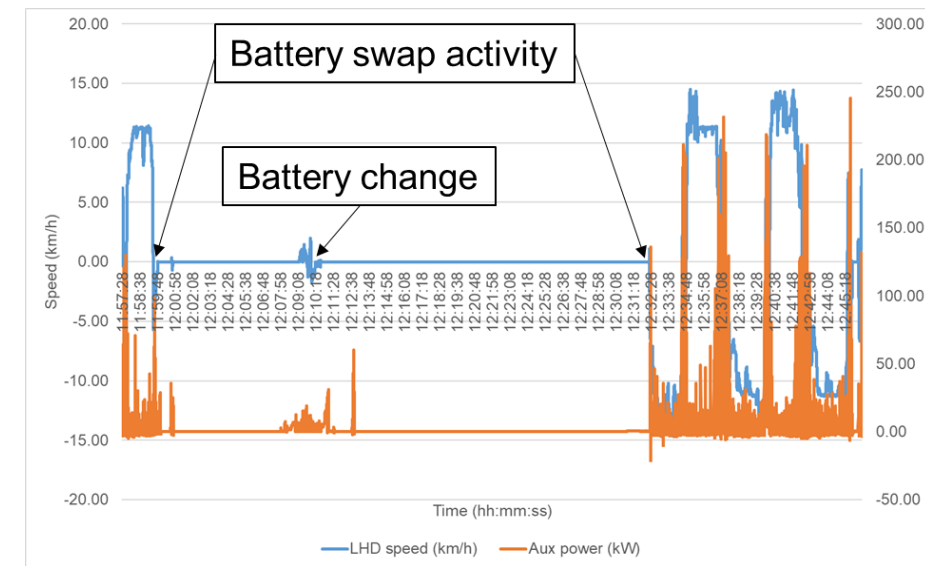
Summary – data exploring

- The LHD up ramp loaded test data was explored and divided to match the Transit, Load, Haul and Dump (TLHD) activities of the duty cycle
- Vehicle speed and auxiliary power allowed the classification



Summary – data exploring

- The LHD up ramp loaded test data was explored and divided to match the Transit, Load, Haul and Dump (TLHD) activities of the duty cycle (top figure)
- Vehicle speed and auxiliary power allowed the classification
- The battery swapping activity was also observed during the up ramp loaded test (bottom figure)
- Battery (total) power was used to calculate the total net energy consumed (consumed – captured) for each activity and per cycle (first objective of the study)



Summary – energy consumption model

- The payload weight was not measured during the test, as a result only the down ramp empty (Transit) data was used to calibrate the energy consumption model (ECM)
- The resulting ECM constant parameters are:
 - 2.9% rolling resistance
 - 85% vehicle efficiency
 - 5.8 kW auxiliary power
 - with a $\pm 12\%$ model error as compared to the test data (after removing outliers)
- The loading and dumping activities were estimated to consume 0.8 and 2.5 kWh each respectively
- The calibrated ECM could be used to simulate the LHD for similar operating conditions with the uncertainty (error) resulting from the calibration process.





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Thank you! Questions?

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