1

2

Outline

- Background
- Test site and vehicle
- Test approach
- Energy consumption and generation by load, speed and terrain grades
- Calibration of energy model parameters using field test data
- Estimate of energy consumption using energy model
- Summary

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2

3

Background

- Mobile electric vehicles have the advantages of zero emission, high efficiency and less maintenance, and have been used increasingly in Canadian mines to replace diesel fuel equipment.
- A series of mine vehicles, including MacLean and Kovatera diesel and electric trucks, Rokion and Relay battery electric utility vehicles, were tested by CanmetMINING and CanmetENERGY. More vehicles and field tests are planned for next two years.
- Main objective of the project was to gather information on energy consumption, generation and battery charging; and to assess how these parameters were affected by terrain grade, speed and load.
- An energy model was developed to simulate the energy demand of mine vehicles. The energy model parameters were calibrated with the field test data, then the model was used to estimate the energy consumption of a duty cycle for a utility vehicle in an underground mine.
- This presentation covers the results of the Relay testing and associated model calibration.

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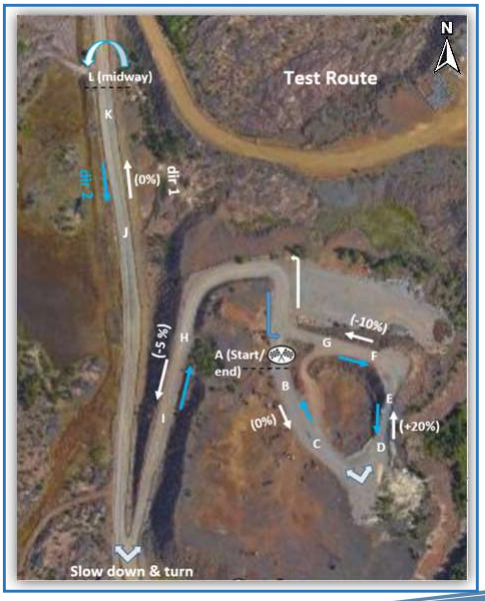
3

4

Test site

- Vale's North mine site in Sudbury, Ontario; average temperature 3.5°C during the test.
- The 1.25 km surface mine route included a range of terrain grades from 0% to 20% incline.
- The vehicle needed to travel along the route in both directions to complete one lap (2.5 km).

Grade (%)	Distance (km)	% of lap distance
+20	0.08	3
+10	0.09	4
+5	0.36	14
0 (flat)	1.45	58
-5	0.36	14
-10	0.09	4
-20	0.08	3
Total	2.50	100



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Test Vehicle

- Relay electric light utility vehicle by Miller Technology Inc.
- Equipped with 48 kWh battery package (nominal) with 43 kWh of usable energy
- Allowed for both off-board DC fast charging and on-board AC opportunity charging
- Total weights tested (vehicle, driver, passenger, and counterweights) were 6.23, 5.29 and 4.12 tonnes respectively for full, mid and empty load conditions.
- Vehicle's heat, air conditioning and user controllable auxiliary devices were turned OFF during the test.

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5

6

Test Approach

- Test plan included driving the BEV to complete four laps (each 2.5 km) at 5 km/h and 15 km/h under three load conditions.
- Test started at full load, then weights were removed to test the vehicle at mid and empty loads. Battery was charged before the empty load test started.
- A portable data logging system was used to collect vehicle's speed, incline, and ambient temperature at 10 samples per second.
- CANbus signals for power draw, RPM, torque, charging power, and other parameters were collected through the vehicle control system.

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6

7

Test Results by Speed and Load

- Compared to empty load, full and mid load weights increased by 51% and 28%.
- Net energy consumption increased by 39% and 13% at 5 km/h; and 25% and 14% at 15 km/h

Energy and Run Time	Full Load		Mid Load		Empty Load	
	5 km/h	15 km/h	5 km/h	15 km/h	5 km/h	15 km/h
Energy level at start of test (SoC)	94%	72%	49%	31%	66%	50%
Energy level after 4 laps (SoC)	73%	56%	31%	16%	50%	38%
Test run time (minutes)	120	40	120	40	120	40
Energy consumed for 4 laps (kWh)	8.8	7.2	7.3	6.4	6.2	5.3
Energy captured for 4 laps (kWh)	1.1	1.6	0.9	1.3	0.6	0.9
Net energy used for 4 laps (kWh)*	7.7	5.6	6.4	5.1	5.6	4.4

* Net energy consumption includes energy generated through regenerative braking and excludes energy used to set up the vehicle in position at the beginning and turning points of the lap. Battery SoC represents the nominal state of charge (%) from vehicle control system.

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7

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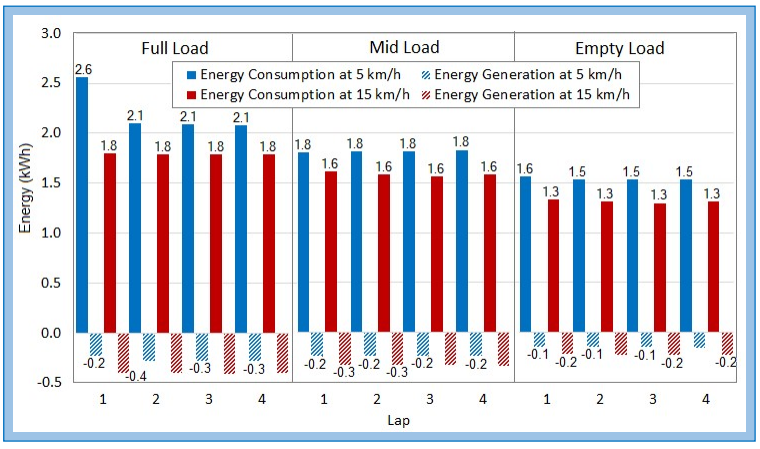
Lap Results by Speed and Load

- Full load lap1 at 5 km/h used more energy due to the cab heater turned on.
- Lap consumption and generation were consistent for other laps and loads.
- Vehicle consumed less and generated more energy at higher speed
- Energy consumption and generation by inclination grades were then examined.



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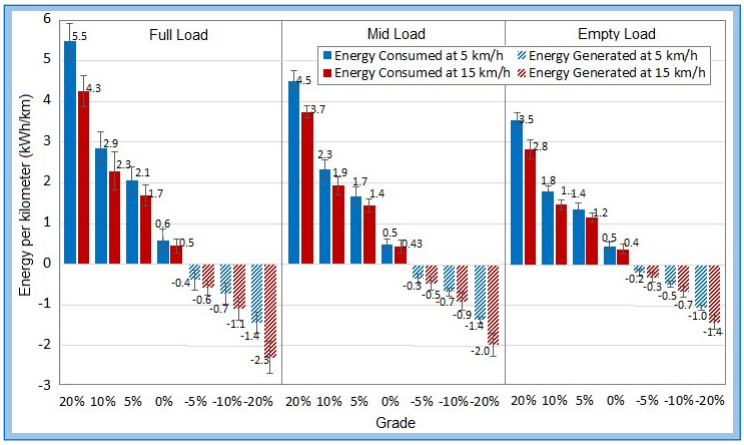
8

9

Energy per km by Grade, Speed and Load

- Average energy value for each grade, speed and load was normalized by distance.
- Energy values consumed and generated per kilometer differ by grade, speed and load.
- Vehicle consumed more energy on steeper uphill grade, at lower speed and with heavier load.
- Vehicle generated more energy on steeper downhill grade, at higher speed and with heavier load.



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Charging Data

- The BEV was driven for 5 hours and 20 minutes with full and mid loads before it was recharged.
- Average ambient temperature was 15°C.
- The off-board charge system can provide a maximum charge power of 50 kW.
- Battery was charged in low power mode to bring the SoC from 6% to 65% after 144 minutes.
- Charger was reset to high power mode (45 kW) until SoC reached 74%, then charging was stopped since there was sufficient energy to complete the test.
- Energy gain rates were 0.17 and 0.76 kWh/min during the low and high power charging periods.

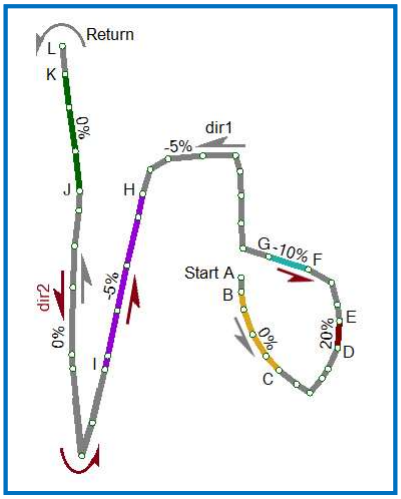
Part of charging session	Low power	High power
Max. charge power (kW)	8 - 11	45
Charging time (min)	144	5
Start energy level (SoC)	6%	65%
End energy level (SoC)	65%	74%
Energy gain rate (kWh/min)	0.17	0.76

10

11

Vehicle Energy Model

- A simulation tool was developed to assess the energy consumption and battery SoC of mine vehicles.
- Model parameters included 2% rolling resistance, 82% vehicle efficiency, and 1.0 kW auxiliary power.
- Vehicle and load weight was 5.29 tonnes for simulating the mid load test.
- Travel speed was 5 km/h and the vehicle spent 30.6 minutes to complete a whole lap of 2.5 km.



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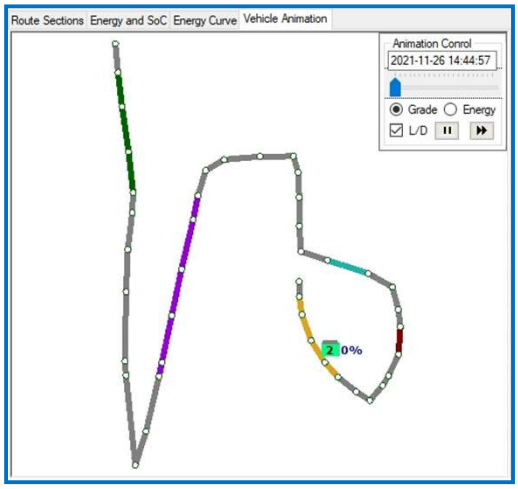
Vehicle Energy Model cont.

- Graphic interface of the energy model
- Animation of vehicle traveling along the test route
- Tabs for viewing route sections, energy data, and energy and SoC curves



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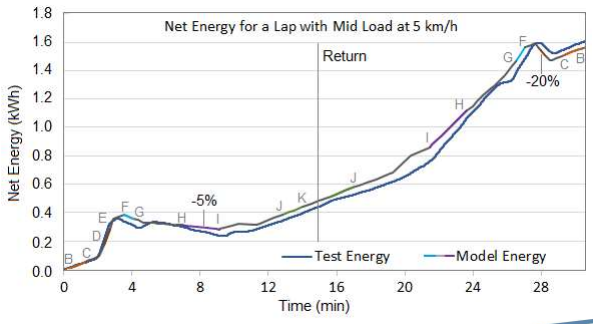
13

Calibration of Energy Model using Test Data

- Model energy values per km for each grade close to test results, except on 5% and 20% downhill grades where large discrepancies (52% and 39%) were observed.
- Total energy values consumed and captured were 1.81 kWh and 0.25 kWh from energy model.
- Total lap consumption and generation from the model were within 4% of the mid load test results.

Grade	Test Energy kWh/km	Model Energy kWh/km	Differ. kWh/km	Differ. (%)	Differ.* Range (%)
20%	4.50	4.00	0.50	11	9
10%	2.33	2.31	0.02	1	0
5%	1.67	1.44	0.23	14	4
0%	0.49	0.56	-0.07	14	1
-5%	-0.33	-0.16	-0.17	52	3
-10%	-0.67	-0.74	0.07	10	1
-20%	-1.36	-1.89	0.53	39	9

* Discrepancy based on max. range 5.86 (from -1.36 to 4.5) kWh/km



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13

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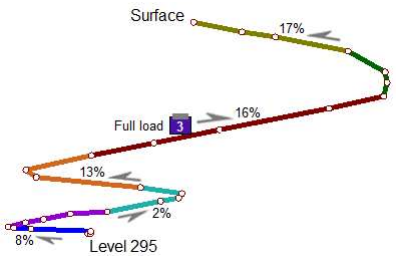
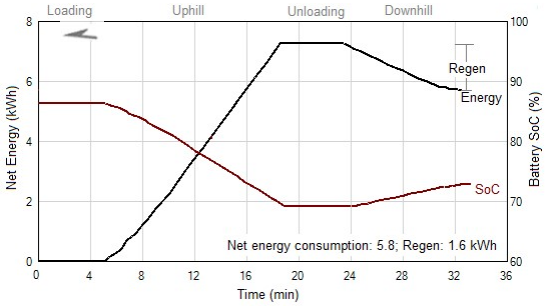
Hypothetical Example in Underground Mine

- Simulated light utility vehicle operating in the main ramp of an underground mine.
- Travel route distance was 1.83 km; average grade 14% ranging from 2.4% to 19%.
- The BEV started at Level 295 with 86% SoC; battery package 43 kWh and charging power 45 kW.
- Vehicle traveled uphill with full load (6.23 t) at 8 km/h; downhill empty (4.12 t) at 12 km/h; loading and unloading times were 5 minutes. Net energy consumption was 5.8 kWh for the first-round trip (33 min).





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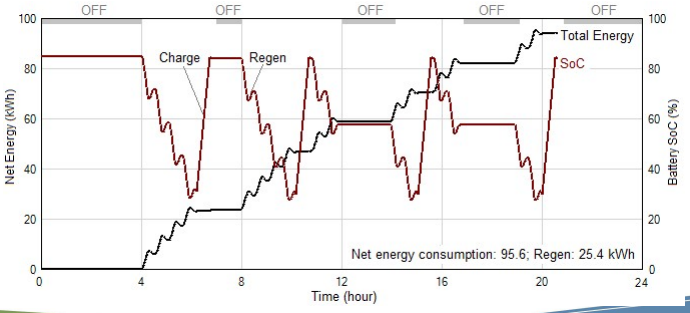
14

15

Energy Consumption for a Duty Cycle

- Assumed the vehicle was used 12 hours per day following a planned schedule.
- Battery was charged 4 times as needed (SoC < 30%), each charging session taking 39 minutes for every 4 trips, to bring the SoC from 31.4% to 86% (full).
- BEV consumed 95.6 kWh, including 25.4 kWh captured, to complete 16 trips (58.6 km) during the day.
- Total charging time of 155 minutes, plus 32 minutes traveling to/from charging station, was needed during the work shifts.

No.	Time (hh:mm)	Duration (min)	Start SoC	End SoC
1	06:11	38	32%	86%
2	10:11	39	31%	86%
3	15:05	39	31%	86%
4	20:05	39	31%	86%



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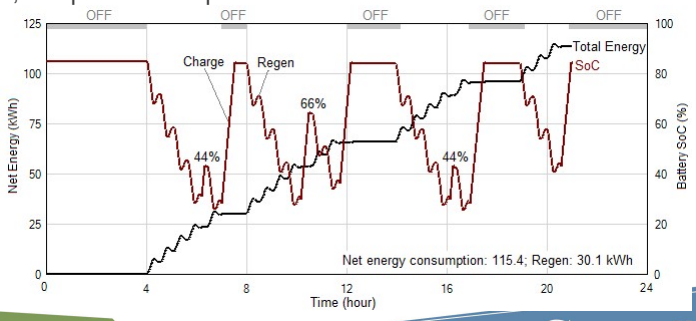
15

16

Charging Strategy for Increasing Productivity

- Opportunity charge: charge battery during OFF time between work shifts when SoC < certain level (70%).
- If battery must be charged during a shift, the SoC level is decided based on the time left within the shift (e.g., 66% SoC for 2 more trips); and the full charge is conducted during OFF time at the end of shift.
- Battery was charged 7 times and 111 minutes (of total 202 min or 55%) were conducted during OFF times.
- The vehicle completed 19 trips (69.5 km, added 3 more trips) and consumed 115.4 kWh during the day.
- Total productivity (trips) increased by 19%, compared to the previous scenario.

No.	Time	Dura. (min)	Start SoC	End SoC	OFF T (min)
1	06:11	14	32%	44%	0
2	06:59	40	30%	86%	40
3	10:11	27	31%	66%	0
4	11:45	35	38%	86%	21
5	16:11	15	31%	44%	0
6	16:59	40	30%	86%	40
7	20:38	31	45%	86%	10



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16

17

Summary

- Relay electric utility vehicle was tested to assess the energy demand and energy generation through regenerative braking, under 3 loads, 2 speeds and 10 route sections with different grades ranging from -20% to 20%.
- The vehicle was able to run 5 hours and 20 minutes and cover 16 laps (40 km) for full and mid load tests at two target speeds, before it was recharged to complete the empty load test.
- Energy amounts consumed and captured per kilometer differ by grade, speed and load. The use of an average value could over or underestimate the energy demand from a BEV if operating conditions are not considered.
- A vehicle energy model was developed to assess energy consumption, generation, and battery SoC for mine equipment. Model parameters were calibrated using field test data.
- The energy model was used to estimate the energy consumption of a utility vehicle in an underground mine. An opportunity charge strategy implemented in the model simulation enabled a 19% increase in the vehicle's productivity.

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17

18

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18

19

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20