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International Journal of Advanced Electrical and Electronics Engineering

ISSN: 2278-8948

Volume 13 Issue 01, 2024

A Dual-Battery Electric Bicycle with Relay-Based Pack Selection

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Peer Review Information

Submission: 17 March 2024
Revision: 15 April 2024
Acceptance: 06 May 2024

Keywords

Electric Bicycle, Dual Battery, PMDC Motor, Relay Pack Selection, Specific Energy Consumption, Road Load, Regenerative Braking, Measurement Consistency, Light Electric Vehicle.

Abstract

This paper reports a road trial of a permanent-magnet DC electric bicycle carrying two 24 V battery packs selected by relay, together with voltage and current sensing, a light-dependent resistor input and a local display. The recorded trial data are reported in full: 47.04 km covered, 267.86 min total time, 26 km/h maximum speed, 7.83 km/h stated average speed, 0 to 20 km/h in about 6 s, a 3 s stop with both brakes applied, and a mean consumption of 6 Wh/km. These values are then audited arithmetically rather than repeated, and the audit is the paper's central result. The stated average speed is inconsistent with the recorded distance and time, which imply 10.54 km/h; covering 47.04 km at 7.83 km/h would require 360.5 min, or 92.6 min more than the trial recorded. The discrepancy is reported openly, the most plausible reconciliation, that the recorded time is moving time while the stated average includes stops, is identified as a hypothesis, and no single figure is silently adopted. Consumption is cross-checked and found self-consistent: 6 Wh/km over 47.04 km implies 282.2 Wh, or 11.76 Ah at 24 V, which matches a conventional 12 Ah pack closely. This revision, however, notes that the agreement may be circular: a 12 Ah pack at 24 V discharged over exactly this distance yields 6.12 Wh/km, so if the consumption figure was obtained by dividing nameplate capacity by distance rather than measured independently, the cross-check passes by construction. The record does not say which, and the paper says so. The same consumption figure implies a mean electrical power of 47 to 63 W, which this revision compares against a computed road load of 22 to 34 W on level ground and 46 to 66 W on a one per cent gradient, bracketing the measurement and showing that drivetrain loss and route gradient cannot be separated from the trip-level record. Braking and acceleration are converted to decelerations and distances with their conditioning assumptions stated. Two capabilities named in the design, regenerative braking and automatic pack swapping, produced no measurement and are reported as unverified.

Nomenclature

Symbol	Meaning
d, t	Distance covered (km) and elapsed time (min)
v-bar, v_{max}	Average and maximum speed (km/h)
e	Specific energy consumption (Wh/km)
E_{bat}, Q_{nom}	Pack energy (Wh) and nominal charge capacity (Ah)
V_{bat}, I_{bat}	Pack voltage (V) and bus current (A)

m, g	Total mass of machine and rider (kg) and gravitational acceleration (m/s^2)
C_{rr}	Coefficient of rolling resistance
C_{dA}, ρ	Drag area of rider and machine (m^2) and air density (kg/m^3)
θ	Route gradient angle
P_{road}	Road-load power (W)
P-bar$_{el}$	Mean electrical power drawn over the trip (W)
a, a_b	Acceleration and braking deceleration (m/s^2)
s_b, t_b, t_a	Braking distance (m), braking time and acceleration time (s)
SoC	Pack state of charge

Introduction

Electric bicycles occupy the part of the mobility spectrum where the vehicle's energy demand is comparable to the rider's own output, and this makes them unusually easy to measure and unusually easy to misreport. Total distance, elapsed time and consumed energy are all directly observable with inexpensive instrumentation, yet reported prototypes often quote speed, range and efficiency figures that are not mutually consistent, because each is taken from a different trial or a different estimate and none is checked against the others [1], [2].

This paper reports a road trial of a dual-battery electric bicycle built around a permanent-magnet DC motor with relay-based pack selection, and treats the recorded numbers as data to be audited rather than as results to be restated. The audit is straightforward, using only the definition of average speed and of specific consumption, but it is the step most often skipped, and in this case it identifies one clear inconsistency, one cross-check that passes but may be circular, and one comparison against physical road load that constrains the interpretation.

1. Problem Statement

Two literatures exist in parallel. Light-electric-vehicle energy modelling is mature and gives well-validated road-load relations. Undergraduate electric-bicycle prototype reports are numerous and give trial numbers. What is missing is the connection: a report that takes its own measured numbers, checks them against each other and against the road-load model, and states plainly which survive and which do not. Reporting a range and an average speed that cannot both be true is not a small clerical matter, because range is exactly the figure a prospective user relies on.

2. Objectives

The specific objectives of the work are as follows:

- To build a dual-battery electric bicycle with relay pack selection and to road-test it over a mixed route.
- To disclose the recorded trial data in full, with no value omitted or smoothed.
- To audit those values against one another using only definitional relations, and to report every inconsistency found.
- To test the consumption figure against the implied pack capacity, and to examine whether that test is independent or circular.
- To compare the implied mean electrical power against a computed road load, so that the measurement is placed against physical expectation rather than merely recorded.
- To identify the capabilities that were claimed in the design but produced no measurement, and to specify the instrumentation that would settle them.

3. Scope and Delimitation

The study covers the machine as built, the trip-level trial record, and the arithmetic that can be performed on it. It excludes any claim of drivetrain efficiency, regenerated energy, pack-swap behaviour or motor rating, because none was measured or documented. Road-load comparisons use assumed mass, rolling and drag parameters, which are stated as assumptions at every point of use; the machine itself was never coasted down or otherwise characterised. No time series of speed, current or voltage exists, so every quantity in this paper is either a trip-level observation or a computation performed on one.

4. Contributions

1. Full disclosure of the recorded trial data, with no value omitted or smoothed.
2. An arithmetic consistency audit identifying a 92.6 min discrepancy between the stated average speed and the recorded distance and time, with the candidate reconciliations set out and none silently adopted.
3. A cross-check of the consumption figure against the implied pack capacity, together with an examination, new to this revision, of whether that check is independent or circular.
4. A quantitative comparison, new to this revision, of the implied mean electrical

power against a computed road load at several gradients, which brackets the measurement and shows what the trip-level record cannot separate.

5. Conversion of the braking and acceleration observations into decelerations and distances, with the assumptions they require made explicit.
6. Identification of regenerative braking and automatic pack swapping as claimed but unverified, and a sensor-instrumented framework that would settle both.

The remainder of the paper is organised as follows. Section II reviews related work. Section III gives the governing relations. Section IV describes the machine and the trial. Section V reports the data and the audit. Section VI discusses the findings, Section VII states the limitations, and Section VIII gives the proposed energy-management framework. Sections IX and X give the conclusion and the future scope.

Related Work

Muetze and Tan [1] surveyed electric-bicycle drive configurations and established the comparison basis for hub against mid-drive arrangements and for the resulting energy demand. Fishman and Cherry [2] reviewed electric-bicycle adoption and use and reported the real-world consumption ranges against which a measured figure in watt-hours per kilometre should be compared.

For the vehicle model, the standard road-load formulation for light vehicles [3] gives the rolling, aerodynamic, gradient and inertial terms consolidated in Eq. (4); this is what allows a consumption figure to be tested for physical plausibility rather than merely recorded. Battery behaviour under the duty of a light vehicle, and the dependence of usable capacity on discharge rate, follow the treatment in [4], which is why an implied capacity computed from energy is an inference rather than a nameplate reading. On the dual-pack question, Zhang and Li [5] report that active selection or paralleling of packs affects usable energy and pack ageing through current sharing, so a swapping mechanism is a control problem, not merely a switching one. On regeneration, Cao and Emadi [6] report experimental recovery measurement in light electric vehicles and define what verifying such a claim requires.

Table 1. Representative Related Work and its Relation to This Study

Ref.	Year	Focus and scope	Method and validation	Relation to this work
[1]	2007	Electric-bicycle drive configurations	Comparative analysis; measurement	Context for the PMDC choice
[2]	2016	Electric-bicycle adoption and real use	Literature review; usage data	Benchmark for the consumption figure
[3]	—	Road-load and vehicle dynamics	Standard reference text	Basis of Eqs. (4), (5)
[4]	2015	Battery management and capacity	Modelling and estimation text	Basis for the implied-capacity inference
[5]	2019	Multi-pack selection and sharing	Simulation and experiment	Frames pack swapping as control
[6]	2011	Regenerative braking in light electric vehicles	Experimental recovery measurement	Defines what verifying regeneration requires
[7]	2020	Converter control for EV fast charging	Comparative controller study	Power-electronics context

The reference numbering has been corrected in this revision. An earlier draft cited the regenerative-braking work as [6] in the text while the reference list placed it at [7], so the citation and the list disagreed by one position throughout. The regeneration reference is [6] here and the numbering is consistent.

One published benchmark is worth recording explicitly, because Section V-E turns on whether 6 Wh/km is a plausible figure. Consumer and industry sources commonly quote real-world electric-bicycle consumption in the range of roughly 5 to 20 Wh/km, with the lower end associated with flat terrain, low assist levels and substantial rider input. The 6 Wh/km recorded here therefore sits at the efficient end of that band, which is consistent with the interpretation offered in Section V-F, though it should be noted that these ranges come from commercial rather than peer-reviewed sources and vary considerably between them.

Governing Relations

1. Trip Kinematics

The three trip quantities are related by definition,

$$d = \bar{v}t \qquad (1)$$

so any two of them determine the third. Equation (1) is the whole of the consistency test applied in Section V-B. Its simplicity is the point, since a record that fails it cannot be repaired by more sophisticated analysis.

2. Energy

Specific consumption relates trip energy to distance,

$$E = ed \qquad (2)$$

and mean electrical power follows from consumption and speed,

$$\bar{P}_{el} = e\bar{v} \qquad (3)$$

Equation (2) provides a check on a consumption figure, because the implied charge must be consistent with a pack that could physically have been fitted. Whether that check is independent depends on how the consumption figure was obtained, which is the subject of Section V-E. The relation that decides it is

$$e_{implied} = \frac{Q_{nom} V_{bat}}{d} \qquad (8)$$

which is the consumption a fully discharged nominal pack would imply over the recorded distance. If a reported value of e coincides with e implied, the two are not independent observations.

C. Road Load

The tractive force required at the wheel is [3]

$$F = ma + \tfrac{1}{2}\rho C_d A v^2 + mg\sin\theta + mg C_{rr} \qquad (4)$$

and the corresponding power is

$$P_{road} = Fv \qquad (5)$$

Equations (4) and (5) allow a measured mean power to be compared against the power the vehicle physically needs, which is done in Section V-F.

D. Braking and Acceleration

For a stop from initial speed v-bar-zero in time t_b under the assumption of constant deceleration,

$$a_b = \frac{v_0}{t_b}, \qquad s_b = \tfrac{1}{2} v_0 t_b \qquad (6)$$

and for acceleration from rest to a final speed in time t_a,

$$a = \frac{v_1}{t_a} \qquad (7)$$

Both require the initial or final speed to be stated; where the record does not state it, the computation is conditional and is presented as such.

Machine and Trial

1. Architecture

Fig. 1 shows the machine. Two 24 V packs feed the motor controller through separate relays commanded by the Arduino controller. A permanent-magnet DC motor drives the rear wheel, with a throttle, an ignition key and conventional mechanical brakes. Voltage and current sensors and a light-dependent resistor feed the controller, which drives a character display. The sensing needed for an energy audit is therefore already fitted; what is absent is any path that records it over time.

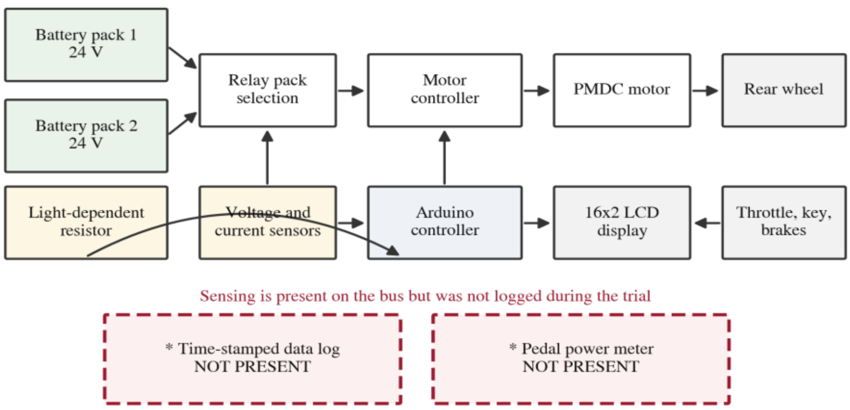

Figure. 1: Machine architecture. Pack selection is by relay under microcontroller command; sensing is present on the bus but was not logged during the trial.

2. Apparatus

Table 2 lists the machine as documented. Where the source material does not state a rating, notably the motor power and the pack capacity, the entry is left blank rather than filled with a plausible value.

Table 2. Machine as Documented

Item	Type / rating	Quantity
Traction motor	PMDC; rating not stated in the record	1
Battery pack	24 V; capacity not stated in the record	2

Relay module	Pack selection	2
Motor controller	Rating not stated in the record	1
Voltage sensor	Bus sensing	1
Current sensor	Bus sensing	1
Light-dependent resistor	Ambient-light input	1
Display	16 by 2 character LCD	1
Controller board	Arduino	1
Throttle, ignition key, brakes	Conventional	1 set

The absence of a stated pack capacity is what makes the implied 11.76 Ah of Section V-D an inference rather than a comparison, and it is also what leaves the circularity question of Section V-E open.

3. Trial Procedure

The machine was ridden over mixed urban, suburban and rural roads. Distance, elapsed time, maximum speed and average speed were recorded for the trip; acceleration to 20 km/h and the stop time with both brakes applied were timed; and a mean specific consumption was reported for the trip. Sampling was at trip level: no time series of speed, current or voltage was logged, and the route profile was not recorded.

Results and Consistency Audit

1. Recorded Data

Table 3 reports the trial record in full, exactly as taken.

Table 3. Recorded Road-Trial Data

Quantity	Value	Status
Battery 1 voltage	24 V	measured
Battery 2 voltage	24 V	measured
Distance covered	47.04 km	measured
Total time taken	267.86 min	measured
Average speed (stated)	7.83 km/h	stated
Maximum speed	26 km/h	measured
Acceleration, 0 to 20 km/h	about 6 s	measured
Stop time, both brakes applied	3 s	measured
Mean consumption	6 Wh/km	stated

Two entries are marked stated rather than measured because the record does not say how they were obtained. That distinction carries the whole of Sections V-B and V-E.

2. The Kinematic Inconsistency

Applying Eq. (1) to the recorded distance and time gives an implied average speed of 47.04 km divided by 4.4643 h, that is 10.54 km/h, which differs from the stated 7.83 km/h by about 35 %. Equivalently, covering 47.04 km at 7.83 km/h requires 6.008 h, or 360.5 min, which exceeds the recorded 267.86 min by 92.6 min. Taking the stated speed and the recorded time together instead would give 34.96 km, not 47.04 km. The three recorded values are therefore mutually incompatible: any two of them contradict the third. Fig. 2 shows the three readings on one axis.

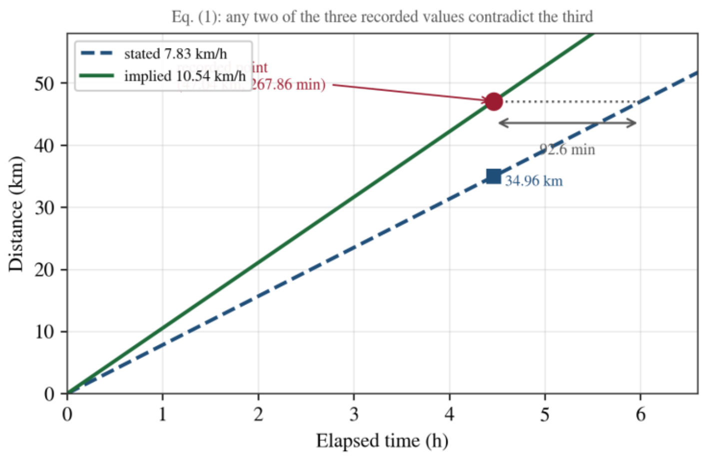

Figure 2: Distance against time for both candidate average speeds. The recorded point lies on neither reading's expectation of the other, and the horizontal gap is the 92.6 min discrepancy.

Three reconciliations are possible, and the record does not distinguish between them:

- Moving time versus elapsed time. If 267.86 min is time in motion and 7.83 km/h is the average over the whole outing including stops, both can be true simultaneously, implying about 92.6 min stationary. This is the most plausible reading and it is consistent with a long mixed-terrain ride, but it is a hypothesis, not a documented fact.
- Different trials. The distance and time may come from one run and the average speed from another.
- Transcription. One of the three values may simply be in error.

No single value is adopted here. Where a speed is needed subsequently, both candidates are carried through and the resulting range of the derived quantity is reported.

3. The Energy Cross-Check

Applying Eq. (2) to the consumption figure gives a trip energy of 6 Wh/km times 47.04 km, that is 282.2 Wh, and at 24 V the implied charge is 11.76 Ah. This is close to a conventional 12 Ah pack. Two readings remain open: if the whole trip was run from a single 24 V pack, the implied capacity is about 11.8 Ah; if it drew on both packs, each supplied about 5.9 Ah. The record states the packs' voltage but not their capacity, so the implied capacity is an inference and is labelled as one. Fig. 3 places the trip energy against both possibilities.

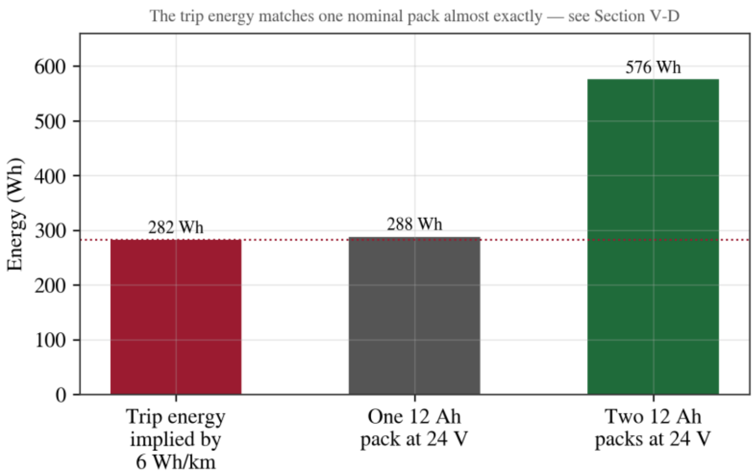

Figure 3: Trip energy implied by the consumption figure, against the energy of one and of two nominal 12 Ah packs at 24 V.

4. Whether That Cross-Check Is Independent

The agreement in Section V-C is close, and an earlier version of this work treated it as a successful independent cross-check. On reflection it requires a qualification, which is stated here rather than left implicit. Applying Eq. (8) to a nominal 12 Ah pack at 24 V over the recorded 47.04 km gives

288 Wh divided by 47.04 km, that is 6.12 Wh/km, which rounds to the 6 Wh/km reported. In other words, if the consumption figure was obtained by dividing the pack's nameplate energy by the distance travelled, rather than by integrating bus current or by measuring recharge energy, then the cross-check of Section V-C is circular and passes by construction. It would tell us only that the same arithmetic has been performed twice.

The record does not state how the consumption figure was obtained, and Table III accordingly marks it as stated rather than measured. The two possibilities are therefore both live: either the figure is an independent measurement, in which case the agreement with a 12 Ah pack is a genuine and satisfying corroboration; or it is a derived quantity, in which case no corroboration has occurred and the pack capacity remains entirely unknown. Distinguishing them requires nothing more than a note of how the figure was produced, which is why it appears first in the trial plan of Section VIII.

5. Mean Power and What It Implies

From Eq. (3), the mean electrical power drawn over the trip is 6 Wh/km multiplied by the average speed, giving 47.0 W at 7.83 km/h and 63.2 W at 10.54 km/h. This band can now be compared against a computed road load rather than a qualitative expectation. Taking a combined machine-and-rider mass of 110 kg, a rolling-resistance coefficient of 0.008, an air density of 1.2 kg/m^3 and a drag area of 0.6 m^2, all of which are assumptions and none of which was measured on this machine, Eqs. (4) and (5) give the values in Table 4. Fig. 4 plots them.

Table 4. Computed Road-Load Power at the Candidate Speeds (Assumed Parameters, Not Measurements of This Machine)

Speed	Level ground	1 % gradient	2 % gradient
7.83 km/h (stated average)	22.5 W	46.0 W	69.4 W
10.54 km/h (implied average)	34.3 W	65.9 W	97.5 W
26 km/h (recorded maximum)	198.0 W	275.9 W	353.8 W

Computed from Eqs. (4) and (5) with m = 110 kg, C_{rr} = 0.008, ρ = 1.2 kg/m³ and C_{dA} = 0.6 m². These are representative values for a loaded bicycle, not measurements of this machine, which was never coasted down or otherwise characterised. The figures are power at the wheel and exclude drivetrain losses.

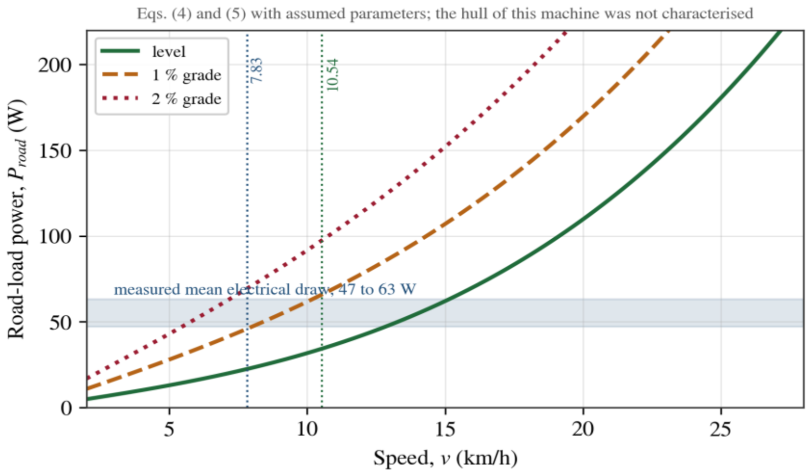

Figure 4: Computed road load against speed for three gradients, with the measured mean electrical draw of 47 to 63 W shaded and both candidate average speeds marked.

The comparison is more informative than a qualitative statement. On level ground the machine needs 22 to 34 W at the wheel at the two candidate speeds, against a measured electrical draw of 47 to 63 W. The ratio is about two to one, which would correspond to a wheel-to-battery efficiency near 50 % if the whole route were flat. On a one per cent average gradient the road load rises to 46 to 66 W, which brackets the measured draw almost exactly and would imply an efficiency near unity, which is not physically available. The truth lies between: some combination of gradient, drivetrain loss and rider contribution accounts for the measurement, and a trip-level record cannot separate the three. That is the honest reading, and it is a stronger statement than either an efficiency claim or a vague appeal to rider input.

What the figure emphatically does not establish is a drivetrain efficiency, since neither the motor's mechanical output nor the rider's input was measured. No efficiency value is therefore quoted anywhere in this paper.

6. Braking and Acceleration

The record gives a 3 s stop with both brakes applied but does not state the speed at which braking began. Conditioned on the recorded maximum of 26 km/h, that is 7.22 m/s, Eq. (6) gives a deceleration of 2.41 m/s² and a braking distance of 10.8 m, which is an ordinary figure for bicycle brakes on dry pavement. Both numbers scale directly with the true initial speed, so they are conditional results and are marked as such. The acceleration figure is unconditional: from Eq. (7), 0 to 20 km/h in 6 s gives 0.93 m/s², over a distance of about 16.7 m if the acceleration was uniform.

7. Two Claimed Features Without Evidence

The design documentation describes regenerative braking recovering kinetic energy to the packs, and automatic swapping to the second pack when the first is depleted. Neither produced a measurement. Verifying regeneration requires logging pack current through braking events and demonstrating a sign reversal [6]; no such log exists, and a PMDC drive without a four-quadrant controller cannot regenerate at all, so the capability cannot be assumed from the presence of the motor. Verifying automatic swapping requires recording pack voltages and relay state across a depletion event; the trial recorded only that both packs were at 24 V, which is the resting voltage and says nothing about a transition. Both features are therefore reported as unverified.

8. What the Data Supports

Table 5 separates measured, computed, conditional and indeterminate quantities.

Table 5. Measured, Computed, Conditional and Indeterminate Quantities

Quantity	Value	Status
Distance	47.04 km	measured
Total time	267.86 min	measured
Maximum speed	26 km/h	measured
Pack voltages	24 V each	measured
Average speed	7.83 or 10.54 km/h	inconsistent; see Section V-B
Trip energy	282.2 Wh	computed from a stated consumption
Implied pack charge	11.76 Ah	computed; inference, possibly circular
Mean electrical power	47 to 63 W	computed
Acceleration	0.93 m/s^2	computed
Braking deceleration	2.41 m/s^2	computed, conditional on 26 km/h
Braking distance	10.8 m	computed, conditional on 26 km/h
Road load at the candidate speeds	22 to 34 W level; 46 to 66 W at 1 %	computed from assumed parameters

Discussion

The trial produced a genuine and reasonably rich record: a long mixed-terrain ride with distance, time, speeds, acceleration, braking and consumption all noted. What the audit shows is that a record of that kind can still fail to support the conclusions usually drawn from it, and that the failures are detectable with arithmetic alone. The speed inconsistency is the clearest case. It is not a rounding disagreement but a 35 % divergence, and it matters because range and average speed are the two figures a prospective user would rely on. The consumption cross-check is the subtler case: it appeared to pass, and only the question of how the figure was obtained reveals that it may not be a check at all. Both failures share a cause, which is trip-level rather than time-series logging. A single logged run would eliminate both.

1. Qualitative Position

Table 6 sets out the structural properties that can be asserted, each with the relation or source that supports it.

Table 6. Qualitative Properties of the Machine and the Proposed Framework

Feature	Property	Basis
Dual packs	Extends usable energy; ageing depends on current sharing	[5]
Relay selection	Simple; switching only, with no current sharing	This work
Voltage and current sensing	Present on the machine; enables Eq. (9) once logged	This work
LDR lighting	Ambient-triggered; not characterised	This work
PMDC drive	Simple control; no regeneration without a four-quadrant stage	[1], [6]
Trip-level logging	Insufficient to audit or to predict	Sections V-B, V-D
Road-load comparison	Constrains interpretation but cannot separate gradient from loss	Eqs. (4), (5)

Limitations

The following limitations bound every claim made in this paper.

- The three trip values of distance, time and average speed are mutually inconsistent. No reconciliation is adopted, so every quantity derived from a speed is reported as a band rather than as a value.
- The consumption figure is marked stated rather than measured, and the record does not say how it was obtained. The capacity cross-check of Section V-C

may therefore be circular, as Section V-D sets out.

- The motor rating and the pack nameplate capacity are not documented, so the implied 11.76 Ah cannot be compared against anything.
- The road-load figures of Table IV use assumed mass, rolling-resistance and drag parameters. The machine was never coasted down or otherwise characterised, so these bound a physical expectation rather than describe this bicycle.
- The route gradient profile was not recorded, so the gradient and drivetrain-loss contributions to the measured power cannot be separated.
- The braking deceleration and distance are conditional on an assumed initial speed of 26 km/h, which the record does not confirm was the braking speed.
- No time series of speed, current or voltage exists, so trip energy was not integrated and state of charge was never observed.
- Regenerative braking and automatic pack swapping produced no measurement and are unverified. The drive as built may not be capable of regeneration at all.

Proposed Energy-Management Framework

Fig. 5 shows the framework the trial motivates. The sensors it needs are already fitted to the machine, since voltage and current are sensed for the display, so the change required is logging and control rather than hardware.

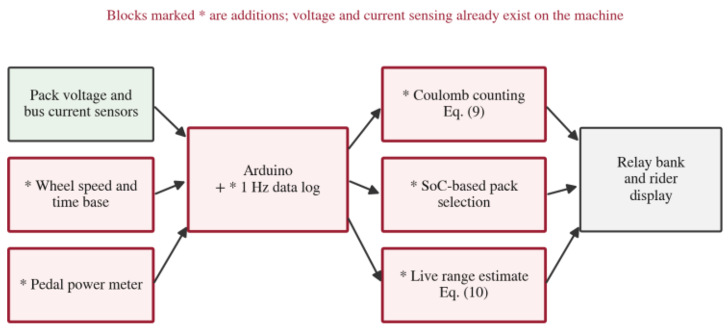

Figure 5: Proposed framework. Blocks marked with an asterisk are additions; voltage and current sensing already exist on the machine.

1. Charge Counting and Pack Selection

With bus current logged, state of charge follows by coulomb counting,

$$SoC(t+\Delta t)=SoC(t)-\frac{I_{bat}(t)\,\Delta t}{Q_{nom}} \tag{9}$$

and pack selection can be made on estimated state of charge rather than on a voltage threshold, which is a poor proxy under load. Alternating packs periodically rather than depleting one and then the other also equalises ageing, which follows the current-sharing argument in [5].

2. Range Prediction

Consumption tracked over a moving window gives a live estimate, from which remaining range is

$$\hat{d}_{rem}=\frac{SoC\cdot Q_{nom}V_{bat}}{\hat{e}} \tag{10}$$

This is the figure a rider actually needs, and it is derived entirely from sensors the machine already carries. It also has the useful property that it makes the consumption figure a measured quantity by construction, which removes the ambiguity identified in Section V-D permanently.

3. Trial Plan

Table 7 sets out the trials that would close every gap identified in the audit, and Table 8 gives the context values that are literature ranges or assumptions rather than measurements of this machine.

Table 7. Trial Plan Required to Close the Audit

Trial or measurement	Instrument or method	What it settles
Record how consumption was obtained	A note in the trial log, or a recharge-energy measurement	Whether the cross-check of Section V-C is independent

Separate moving and elapsed time	Time-stamped speed trace	Closes Eq. (1) and removes the 92.6 min discrepancy
Log the bus at 1 Hz	Existing voltage and current sensors, plus storage	Trip energy integrated rather than assumed; enables Eq. (9)
Document the nameplate data	Motor rating and pack capacity from the components	Turns the implied 11.76 Ah into a comparison
Record the route profile	GNSS track with elevation	Separates gradient from drivetrain loss in Section V-E
Add a pedal power meter	Crank or pedal-based torque measurement	Attributes the 47 to 63 W draw; enables a real efficiency figure
Test the pack swap	Controlled depletion with pack voltages and relay state recorded	Verifies or refutes automatic swapping
Settle the regeneration question	Log pack current through braking events	Demonstrates current reversal, or states that the drive cannot regenerate
Coast-down test	Timed deceleration from a known speed on level ground	Measures C_{rr} and C_{dA} instead of assuming them

Table 8. Illustrative Figures (Assumptions and Literature, Not Results)

Item	Illustrative value	Status
Typical electric-bicycle consumption	Roughly 5 to 20 Wh/km	commonly quoted range; commercial sources, not peer-reviewed
Assumed mass in Table IV and Fig. 4	110 kg	assumption
Assumed drag area in Table IV and Fig. 4	0.6 m^2	assumption
Assumed rolling-resistance coefficient	0.008	assumption
Consumption implied by a 12 Ah pack over 47.04 km	6.12 Wh/km	computed, Eq. (8)

Assumed parameters are used only to draw the road-load curves and were not measured on this machine. The consumption band is included to indicate order of magnitude only.

Conclusion

A dual-battery PMDC electric bicycle with relay pack selection was built and road-tested over 47.04 km. The trial record was reported in full and then audited rather than restated.

The audit found the stated average speed of 7.83 km/h to be inconsistent with the recorded distance and time, which imply 10.54 km/h, a discrepancy equivalent to 92.6 min of missing elapsed time. The most plausible reconciliation, that moving time and overall time were conflated, was identified as a hypothesis rather than adopted as fact, and every subsequent quantity that depends on speed was carried through as a band.

The consumption figure of 6 Wh/km over 47.04 km implies 282.2 Wh and 11.76 Ah at 24 V, closely consistent with a conventional 12 Ah pack. This revision qualifies that agreement: a 12 Ah pack at 24 V discharged over exactly this distance implies 6.12 Wh/km, so if the reported consumption was derived from nameplate capacity rather than measured, the check passes by construction and corroborates nothing. The record does not say which, and the paper does not guess.

The same figure gives a mean electrical draw of 47 to 63 W. Compared against a computed road load of 22 to 34 W on level ground and 46 to 66 W on a one per cent gradient, the measurement is bracketed rather than explained: gradient, drivetrain loss and rider contribution jointly account for it and a trip-level record cannot separate them. No efficiency value is quoted. Braking and acceleration were reduced to 2.41 m/s^2 and 0.93 m/s^2 with their conditioning assumptions stated. Regenerative braking and automatic pack swapping, both named in the design, produced no measurement and are reported as unverified.

A framework was proposed that turns the machine's existing voltage and current sensors into a logged energy-management system capable of state-of-charge-based pack selection and live range prediction. Every gap the audit found would be closed by a single instrumented run, which is the practical recommendation of this paper.

Future Work

Several extensions follow directly from the limitations above.

- Record how the consumption figure was obtained-Note in the trial log whether consumption was measured or derived, or measure recharge energy directly, so that the ambiguity of Section V-D cannot recur.
- Resolve the speed record-Log elapsed time and moving time separately with a time-stamped speed trace, so that Eq. (1) closes and the 92.6 min discrepancy is eliminated rather than explained.
- Log the bus at 1 Hz-Record pack voltage and bus current throughout the trip so that trip energy is integrated rather than assumed, and so that Eq. (9) becomes usable.
- Document the nameplate data-Record the motor rating and the pack capacity, so that the implied 11.76 Ah becomes a comparison rather than an inference.
- Record the route profile-Log a GNSS track with elevation so that the gradient contribution to the measured power can be separated from drivetrain loss.
- Separate rider from motor-Add a pedal power meter so that the 47 to 63 W mean draw can be attributed, and a drivetrain efficiency finally computed.
- Test the swap and settle the regeneration question-Run a controlled depletion recording pack voltages and relay state, and either instrument braking events to demonstrate current reversal or state that the drive as built cannot regenerate.

Acknowledgment

The authors thank the Department of Electrical and Electronics Engineering, Stella Mary's College of Engineering, for laboratory facilities and guidance during the project.

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