QUEEN'S UNIVERSITY BELFAST | INTERNATIONAL STUDY CENTRE

NTO1068: Engineering Design Projects

HILL CLIMB MODEL CAR PROJECT

Post-Race Retrospective

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DESIGN INTENT & ENGINEERING RATIONALE

PROJECT OBJECTIVES	Design a single-motor model car that climbs **0° – 50° ramps** in the shortest possible time while still completing valid runs consistently. Steep-angle completion is a key scoring risk, because any stall or invalid run would impact overall performance.
DESIGN RULES	The car had to use kit components only, stay within the dimension and mass limits, run with a single motor, and use the supplied battery system. With limited available power, performance had to come from gearing, traction, mass placement, and structural efficiency.
ENGINEERING CHALLENGE	As incline angle increases, the downslope component of weight increases, so required wheel torque also rises. As motor power is finite, more torque usually means lower wheel speed.

ENGINEERING CHALLENGES

(1) $F_{//} = mg \sin(\theta)$

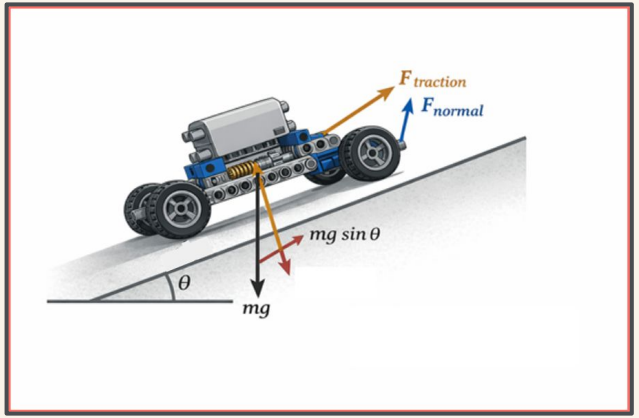
Steeper ramps increase the force that the wheels must overcome.

(2) $F_{traction} = \mu F_{normal}$

Traction is limited by tyre–surface friction and normal load at the driven wheels.

(3) $P = \tau\omega$

With roughly fixed motor power, torque gains tend to reduce angular velocity. That is why the final concept became slower as it became more climb-capable.



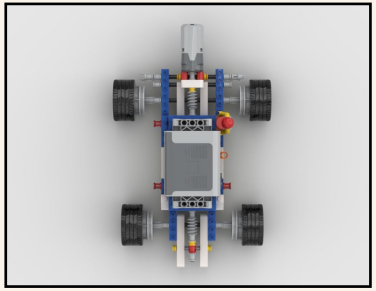
CONCEPT COMPARISON & FINAL CONCEPT SELECTION

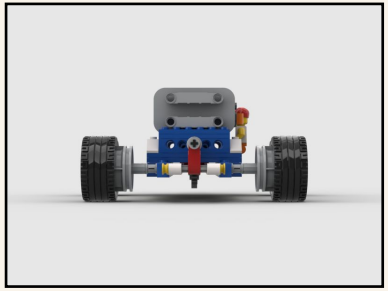
CONCEPT	LAYOUT/RATIO	DESIGN INTENT	MAIN LIMITATION
1	RWD 1:5 (gear on gear)	High speed, simple drivetrain	Stalled at higher inclines and front lift risk
2	FWD 1.4:1 (differential)	Better stability and front traction	Still torque-limited, differential added loss
3	AWD 24:1 (worm gear)	Maximum torque and reliability	Slow and less efficient due to worm friction

Concept 3 was selected because it best matched the project objective at the steepest inclines. Concepts A and B preserved more speed, but both remained **torque limited** as incline increased.

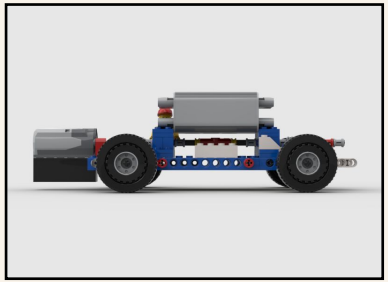
Concept 3 deliberately **traded speed and efficiency** for mechanical advantage, AWD traction, and a more failure-resistant chassis. The table reflects that logic where Concept C did not win on speed potential, but it dominated in **incline capability, slip resistance, and reliability under load**.

FINAL CONCEPT ARCHITECTURE: CONCEPT 3









FEATURE	DESIGN CHOICE
Drive layout	All-wheel drive
Main gearing	24:1 worm reduction
Battery location	Flat and central
Balance strategy	Added low mass below motor
Wheel strategy	Modified nested wheel/tyre arrangement
Structure	Locked gear geometry + heavy bracing
Final dimensions	24.5 × 13.8 × 7.3 cm
Mass	252 g dry / 437 g total

WHY THE FINAL CONCEPT WAS ENGINEERED THIS WAY

Torque strategy

Concepts 1 and 2 showed that wheel speed alone was not enough. Concept 3 therefore used a 24:1 worm reduction to maximise mechanical advantage and reduce the chance of motor stall at 40°–50°. The trade-off was intentionally lower angular velocity.

Traction and stability strategy

AWD distributed drive across four contact patches rather than relying on a single axle. The battery was placed low and centrally, and extra mass was added below the motor to reduce pitch-back and maintain usable normal force at the front wheels.

Reliability strategy

High torque loads can push gears apart if the frame flexes. The final chassis therefore locked the gear positions, widened the structure, and added bracing so the drivetrain would keep meshing under load instead of skipping or failing.

Testing programme

(The development process was staged by concept, target incline, and controlled configuration changes)

Weeks 1–2
Goal: fast, low-CG car on flat / shallow incline

3 logged runs

Week 3
Goal: climb 30° with improved stability

5 logged runs

Week 4
Goal: climb 50° with final torque concept

6 logged runs



VARIABLES TESTED

The team changed drivetrain layout, gear ratio, wheel construction, chassis width, and weight distribution. The raw log sheets also recorded validity, wheel slip, loss of control, rollback, drive failure, and structural failure for each run.

METHOD CONTROLS AND LIMITATION

The tests used the same kit, same motor class, same incline ramp type, and the same structured data sheet. Changes were documented between runs where possible, but sample sizes were small and some runs were affected by invalid attempts, time pressure, and setup error.

Concept 1 results: RWD, 1:5, speed-biased

Fast on flat ground, but the first concept exposed the torque limit immediately

CONFIGURATION & EVIDENCE

Layout: Rear-wheel drive, narrow front, wider rear, rear battery bias

Objective: Fast and agile car with stable base / low centre of gravity

Valid performance: 0° average = 1.745 s (from 3 logged runs in retro summary)

Failure point: Failed to climb 10°; motor stalled with no forward movement

Conclusion: Speed was not the problem; torque multiplication was too low

ENGINEERING INTERPRETATION

Concept 1 was mechanically efficient and very fast on shallow terrain, but the 1:5 reduction did not multiply torque enough to overcome the incline load. That means the limiting factor was wheel torque, not tyre grip. This was the first major design pivot: a successful race car could not be chosen on flat-speed performance alone.

DECISION TAKEN

Move away from pure speed bias. The next concept had to improve torque delivery and stability before higher-angle testing could be meaningful.

Concept 2 results: FWD, 1.4:1, stability-biased

CONFIGURATION CHANGES

- FWD layout
- Battery moved centrally
- Modified gear arrangement
- Extra rim support added
- *Result: Improved static stability and packaging, but low reduction cost useful torque.*

RAMP ANGLE	LOGGED RESULT	INTERPRETATION
10°	4.27 s	Climbed easily
20°	4.06 s	Still stable
30°	4.36 s	Good progress toward steeper goal
40°	Failed. (2 attempts)	Torque output became insufficient

KEY TAKEAWAY

Concept 2 proved that the project was not purely a traction problem. The car was more stable and showed no major wheel slip, yet it still failed once the incline demanded more torque. That evidence justified a more radical shift: all-wheel drive plus a much larger reduction ratio.



Concept 3 development: AWD, 24:1, final race direction

DEVELOPMENT CHANGE	REASON FOR CHANGE
2WD to AWD	Spread traction demand across four wheels
Wider chassis	Improve structural stiffness and stability
24:1 worm gearing	Increase torque and resist rollback
Wheel combination changed	Improve contact patch consistency

RAMP ANGLE & RESULTS		
20°:	4.287 s	(Valid run)
30°:	32.7 s	(Reached after problems)
40°:	31.8 s	(Valid but slow)
50°:	Failed in development	(Still sensitive)

INTERPRETATION

Concept 3 finally addressed the torque and reliability problem strongly enough to become the race concept. However, the data already showed the cost of that choice: the drivetrain was far slower than earlier concepts, and development still involved invalid runs before the final geometry was stabilised.

DATA DRIVEN DEVELOPMENT

Iteration 1

Claim: The car could be fast with a simple RWD 1:5 layout.

Evidence: It was quick on 0° but stalled at 10°.

Decision: Increase torque focus; speed alone is not enough.

Iteration 2

Claim: A more stable layout might solve the climb problem.

Evidence: Concept 2 improved stability and reached 30°, but still failed at 40°.

Decision: Move to AWD and a much larger reduction.

Iteration 3

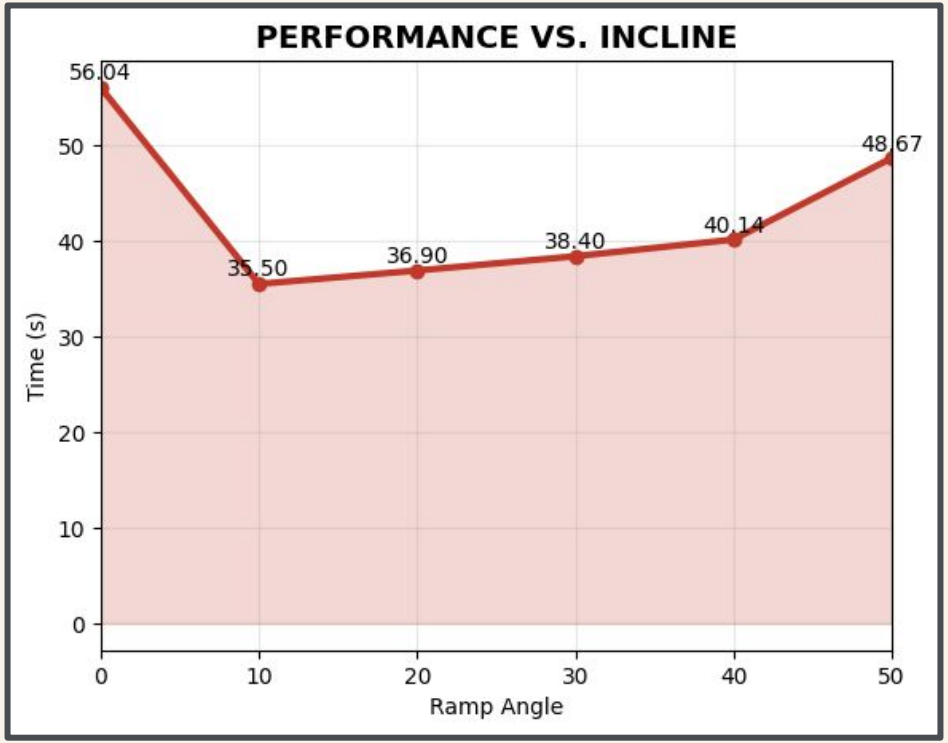
Claim: A torque-biased AWD concept can finish the event.

Evidence: Week 4 logs showed improved climb capability, but also slow times and some invalids.

Decision: Race Concept 3, then accept that speed optimisation becomes the next problem.

This progression is the strongest evidence of engineering iteration in the project. The team did not simply describe three cars; they used test results to identify the limiting mechanism, then changed architecture and gearing to target that mechanism directly.

RACE EVENT PERFORMANCE ANALYSIS



Incline	Official time (s)
0°	56.04
10°	35.5
20°	36.9
30°	38.40
40°	40.14
50°	48.67

What the result means

The car completed all race legs from 0° to 50°. According to the retro, only two groups achieved this, so the torque and structural reliability objective was met.

However, the time trend also shows the cost of the worm-drive trade-off: the design was consistently much slower than expected and the team finished with one of the lowest point totals.

WHY RACE PERFORMANCE DIFFERED FROM TESTING?

Observed Difference	Evidence	Likely cause
0° much slower than expected	Retro notes mention slow placement and failure to complete the three runs efficiently	Human setup error inflated the flat-leg time
10° slower than expected	Retro notes say the car went off track	Tracking / launch alignment issue, not only powertrain limitation
All legs slower than speed-biased concepts	Race line remains high even when no stall occurs	24:1 worm drive and extra mass traded speed for torque and reliability
Race more consistent than earlier tests	Completed every incline from 0° to 50°	Final bracing, AWD, and torque reserve improved completion robustness

Analytically, the most important point is that the race outcome was not “bad luck”. The final concept did exactly what it was designed to do (avoid stalling and complete the event) but the team learned that the torque-for-speed trade-off had been pushed too far, especially for the lower-angle legs.

TECHNICAL WEAKNESSES

Worm-drive inefficiency
High sliding friction reduced drivetrain efficiency and wheel speed, especially on low-angle legs where the torque reserve was not fully needed.

Mass and over-bracing
The reliability strategy added structure and ballast, but that increased the load the motor had to move and made the car slower overall.

Limited optimisation range
The team moved directly from low reductions to a 24:1 worm solution, leaving a broad mid-range of potentially better spur-driven ratios untested.

Launch / tracking sensitivity
Going off track at 10° and setup delays at 0° show that the car-race system included operator and alignment sensitivity, not only drivetrain performance.

Process reflection

What went well

Clear Division of Responsibilities: Team effectively split into concept development,
development, documentation/testing, and building roles. This preserved a usable evidence trail and facilitated justified design decisions.

Structured Decision-Making: The decision matrix and run logs prevented intuition-based choices, directly linking the final concept selection to observed test limitations.

What HIndered Progress



Initial Planning Challenges & Unknown Trade-offs: Difficulty in planning the first concept due to unclear speed, torque, and traction trade-offs. Later, time pressure limited intermediate gearing exploration and official-style preparation.



Race-Day Process Weaknesses: Staging and handling significantly impacted performance. Faster setup, better launch repeatability, and more official-condition rehearsal were needed to reduce human-error penalties.

IMPROVEMENTS FOR VERSION 2.0

KEEP

- Low, central battery position and a stiffness-focused chassis layout.
- AWD traction philosophy if steep-angle completion remains the priority.
- Evidence-based concept selection using logged runs and comparison tables Improve wheel concentricity / alignment so launch direction is more repeatable

CHANGE

- Replace the worm drive with a lower-loss multi-stage spur reduction in the mid-range
- Reduce unnecessary mass and remove any bracing that does not measurably improve reliability between 1:5 and 24:1.
- Improve wheel concentricity / alignment so launch direction is more repeatable

TEST DIFFERENTLY

- Run more repeats per configuration and include official-style staging in the test plan.
- Record additional data: battery voltage drop, setup time, off-track events, and per-run failure mode
- Test several intermediate ratios to find the best balance between torque reserve and wheel speed

KEY TAKEAWAYS

The team started with a speed-first mindset, but testing showed that the real design bottleneck was torque at steep inclines. Concept 3 solved that problem through AWD, 24:1 gearing, mass placement, and bracing, allowing the car to complete the full race

The downside is equally important, where the final design over-corrected toward reliability and gave away too much speed. That is why the race result is both a success and a warning. The engineering lesson is not merely that more torque helps, but that the best design balances torque reserve, traction, and efficiency.

