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Introduction to Engineering

Professor Molly Clark Carpenter

Final Report

"SafeSpread"

A remote-operated vehicle that applies liquid brine to driveways before a freeze, preventing ice from bonding to the surface.



Team 9

Mark Ghiu

George Bankoff

Mithun Rameshkumar

Khai Lockwood

TA: Ben Norton

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Executive Summary

Every winter, homeowners have to clear ice from their driveways, a task that requires physical effort many elderly and limited-mobility people cannot safely provide. SafeSpread is a small vehicle that applies liquid brine to a driveway before a freeze, preventing ice from bonding to the surface so that any accumulation can be removed with little effort. The design is scoped to walkways and single-car driveways of up to roughly 480 ft². The primary users are elderly and limited-mobility homeowners; the purchaser is often an adult child or caregiver buying on their behalf, and with enough optimization the product could see widespread use among general homeowners. No low-cost mobile anti-icing product currently exists: existing options are either expensive (embedded heating, heated mats, retrofit sprayers) or perform reactive snow removal rather than preventative treatment.

The prototype pairs an off-the-shelf RC chassis with a custom fluid system: a 1.5 L reservoir, a 12 V pump, an inline needle valve for flow control, a stop valve to prevent residual discharge, and a perforated spray bar that lays down parallel brine lines, all controlled by Arduino electronics. Testing showed that flow rate is set by the pump rather than by the spray holes (the pump is positive-displacement), and that a needle valve reduces flow from 88.2 mL/s to a repeatable 5.33 mL/s. A full-tank driving test covered roughly 764 ft² on one tank, exceeding the 480 ft² target, at a total weight of 14.91 lb (under the 25 lb limit) and an estimated bill-of-materials cost of about $345 (under the $400 target). After the final presentation we also got automation working: an iPhone mounted on the rover supplies its position through ARKit visual-inertial odometry, and in a field test the rover treated a taped 40 ft × 12 ft rectangle (480 ft²) on its own in about six minutes. Survey responses and feedback from target users confirmed the need for the product. Next steps are real-world winter trials, durability testing, a custom chassis, and obstacle detection.

1. Problem and User

1.1 Problem statement

Removing ice from a driveway requires physical effort that a significant share of homeowners cannot safely provide. For many people the task is merely unpleasant, but for elderly individuals and people with physical disabilities it is frequently painful or altogether impossible, so the need is to remove the physical labor entirely rather than to make it easier. SafeSpread addresses this by treating the surface preventatively: liquid brine applied before a freeze keeps ice from bonding to the pavement, so any accumulation can be cleared with minimal force. This is anti-icing (applied before the freeze), not de-icing (applied after).

SafeSpread treats ice, not snow. Deep accumulation is still a job for a plow or snow blower; SafeSpread prevents the icy glaze underneath, which is what actually causes falls. In response to

design-review feedback we scoped the design to walkways and single-car driveways of up to approximately 480 ft² (about 16 ft × 30 ft), with larger driveways as a next step once coverage is proven.

1.2 Magnitude and frequency

Hanover, NH receives roughly 70 in of average annual snowfall, producing repeated freeze events each winter (Western Regional Climate Center, n.d.). About 1 million ice- and snow-related fall injuries are treated annually in the U.S. (Rothman Orthopaedics, n.d.), and roughly one in four adults 65 and older reports falling each year; falls are the leading cause of injury in this age group (Centers for Disease Control and Prevention, 2026). The population least able to treat an icy driveway is also the population most vulnerable to the falls that untreated ice causes. Treating the surface before the freeze keeps that ice from forming at all.

1.3 User and purchaser

Primary user: elderly and limited-mobility homeowners. They own a driveway but cannot safely treat it. They need the physical task removed, not reduced.

Buyer-on-behalf: adult children and caregivers. Frequently the purchaser rather than the operator, buying for a parent living alone.

Secondary market: general homeowners. The roughly half of respondents who currently take no action; reachable without changes to the product.

A user survey of 27 respondents informed these definitions (answered counts vary by question because some fields were left blank):

- 92.6% (25/27) rate ice as at least an inconvenience and report having slipped; within that group, 22.2% (6/27) find it really annoying and slip a lot. Only 7.4% (2/27) never think about it.
- 52.2% (12/23) take no action and accept the risk; 47.8% (11/23) manually dump or chip ice. No respondent uses a heated driveway (prohibitively expensive).
- 76.0% (19/25) sometimes skip treating ice because the task is too much work; 40.0% (10/25) do so often.

These responses establish that the hazard is widely recognized and that effort is the main barrier to treating it. The respondent pool included both elderly individuals and college-aged students, so the survey speaks to the general population as well as our target demographic.

2. State of the Art

2.1 Existing solutions and their limitations

Commercial snow and ice-management products generally take one of four approaches: embedded heating, portable heating, autonomous snow removal, or fixed chemical application. Each approach demonstrates useful capabilities, but none fully satisfies SafeSpread's goals of affordability, low user effort, and preventative treatment at residential scale:

Solution	Cost / scale	Limitation
Embedded driveway heating	$6k to $12k	Fully automatic but requires removing and repouring the driveway surface to install.
HeatTrak heated mats	$1,075 / 20 ft²	Surface-laid strips; cost scales linearly with area and is prohibitive at driveway scale.
Yarbo snow robot	$4,999	Autonomous but mechanically complex; performs reactive snow removal, not preventative treatment.
KlearWay sprayer	Up to 1,000 ft²	Closest functional competitor; fixed retrofit plumbing and frequent saline refills.

Table 1. Existing commercial solutions and their limitations.

At municipal scale, the Capra Urban robot shows that mobile precision brine application is technically feasible, but it is marketed to municipalities and facility managers and publishes no consumer price (Capra Robotics, n.d.), which leaves the residential niche open.

2.2 Patent search

Relevant patents reviewed: US6102306A, fixed flush-mounted nozzles that apply a liquid freezing-point depressant (2000); US20210164181A1, a stationary motorized salt dispenser with remote activation (2021); and US11635760B2, autonomous path-treatment machines that follow mapped routes (2023). Together they show that installed spraying, remotely controlled dispensing, and autonomous path treatment have each been explored individually. None of them claims a low-cost, mobile, preventative brine applicator sized for a residential driveway.

2.3 Gap

No low-cost mobile anti-icing product exists. Existing systems are either fixed infrastructure, cost-prohibitive at driveway scale, or reactive rather than preventative. SafeSpread occupies this gap.

3. Specifications and Problem-Solving Method

3.1 Performance specifications

Specification	Justification	Quantified target	Method of evaluation
Flow control	Metering the brine is the core function; the uncontrolled pump empties the tank in seconds	Repeatable flow rate low enough to treat a full driveway on one 1.5 L tank	Timed dispense tests; volume collected over a fixed interval

Specification	Justification	Quantified target	Method of evaluation
Coverage	Must treat a full walkway or single-car driveway without user intervention	100 ft² minimum, up to 480 ft² in a single run	Distance travelled × spray width, from measured flow rate and drive speed
Autonomy	Must remove the physical task from the user entirely	No manual spreading motions; under 2 min of user setup	All spreading performed by the vehicle's fluid system
Battery life	A run that ends mid-driveway leaves the surface partly untreated	Dispenses a full 1.5 L tank and completes one 480 ft² run on a single charge	Continuous drive-and-pump discharge over a complete route
Durability	Must work outdoors in freezing weather, and salt is strongly corrosive	Operates to 10 °F; enclosure at least IP54; wetted parts corrosion-resistant	Freezer, dry-ice and moisture exposure; salt-soak inspection

Table 2. Performance specifications.

The 480 ft² coverage target corresponds to the scoped single-car driveway (about 12 ft × 40 ft); the 100 ft² minimum corresponds to a typical walkway.

3.2 Constraint specifications

Specification	Justification	Quantified target	Method of evaluation
Weight and portability	Must be liftable and storable by an elderly or mobility-limited user without strain	Under 25 lb; stores within 2 ft × 2 ft	Weigh unit; lift and storage test with target users
Cost	Must be affordable for an individual homeowner, not an institutional buyer	Total unit cost under $400	Bill-of-materials costing against commercial alternatives
Safety	Must not injure people or pets or damage property during operation	Zero safety incidents in testing; halts within 15 cm of a detected obstacle	Supervised trials with obstacle-detection stress tests
Environmental	De-icing chemicals can harm soil, waterways, pets, and plants	Minimum effective dose; runoff within EPA and state guidance	Compare applied volume and runoff against published guidelines
Legal	Must have clear design ownership and comply with regulations on robotic devices and chemical use	No patent infringement; complies with local codes for outdoor robotics and de-icer use	Patent search; review of municipal and state codes

Table 3. Constraint specifications.

3.3 Concept selection

Five concepts spanning fixed infrastructure, hand-pushed tools, and mobile robots were scored 1 to 5 against the specification categories:

Concept	Eth.	Leg.	Safe	Eff.	Cov.	Wt.	Aut.	Dur.	Cost	Total
Sensor robot (bottom-dispense)	4	4	4	3	3	4	5	3	4	34
Saline liner (backup)	4	5	4	3	4	2	5	4	2	33
Push spreader cart / cane	4	5	4	3	3	4	1	4	5	33
Heated coil grid	5	3	5	4	4	1	5	4	1	32
Camera robot (top-launch)	3	4	3	4	4	3	5	3	2	31

Table 4. Concept-selection matrix, scored 1 (poor) to 5 (excellent) against the specification categories (Eth. = ethical, Leg. = legal, Eff. = effective, Cov. = coverage, Wt. = weight, Aut. = autonomy, Dur. = durable).

The bottom-dispensing sensor robot scored highest (34/45) and became our selected solution, driven by strong autonomy and cost scores. The saline liner (33/45) was retained as a backup rather than rejected: it fails only on weight and portability, but otherwise removes all physical spreading from the user with no moving vehicle to fail. The push spreader cart scores well on cost and legality but fails the core autonomy requirement, since the user must still walk the icy driveway. The heated coil grid is the safest and most effective option but is far too heavy and expensive, and the camera robot adds software complexity we were not confident we could deliver reliably within the term.

3.4 Key design decisions and justification

We made three major design decisions early. First, liquid brine over granular salt: a liquid can be pumped and metered while a solid can only be broadcast, and metering is what allows the application rate to be controlled, so the reservoir-and-pump architecture followed from this choice. Second, parallel spray lines over a solid sheet or mist: dry gaps preserve traction until the brine spreads and dissolves outward, discrete streams resist wind drift better than an atomized mist, and the pattern gives even coverage with minimal fluid. Anti-icing before a storm also costs roughly 50% less than reactive de-icing after one (Federal Highway Administration, 1996). Third, buying and customizing an RC base rather than building a vehicle: instructor and TA feedback was that a fully custom vehicle was out of scope for an eight-week project, so we concentrated our effort on the fluid system and used an off-the-shelf RC chassis as the platform.

4. Prototype and Testing

This section describes the prototype and our testing, roughly in the order the work happened. We started from a dimensioned drawing and a bare fluid loop, and each round of testing exposed the next problem to fix: the flow rate was far too high, the pump did not respond the way we first expected, fluid leaked and drained when it should not have, and the loaded chassis did not drive straight. The calibrated driving run in Section 4.11 is the benchmark comparison against our specifications, and Sections 4.12 and 4.13 cover the automation we added after the final presentation.

4.1 Starting point: architecture and first build

The prototype is built from four subassemblies defined in the initial dimensioned drawing (Figure 1):

Donor chassis. Off-the-shelf RC car, 52.1 × 24.1 × 23 cm; wheelbase 32.5 cm; wheels 11.5 cm diameter × 4.5 cm wide.

Deck. 12 × 18 in sheet-metal plate bolted above the chassis to carry the fluid system.

Reservoir. 7.08 × 3.54 × 4.7 in windshield-washer tank (≈1.5 L) with an integrated 12 V pump (≈8 psi) at the outlet.

Spray bar. Transverse perforated tube (a "T-bar") with a row of 1/8 in holes, mounted at the rear and discharging downward. The bar was welded in the machine shop from aluminum tube stock (Figure 2).

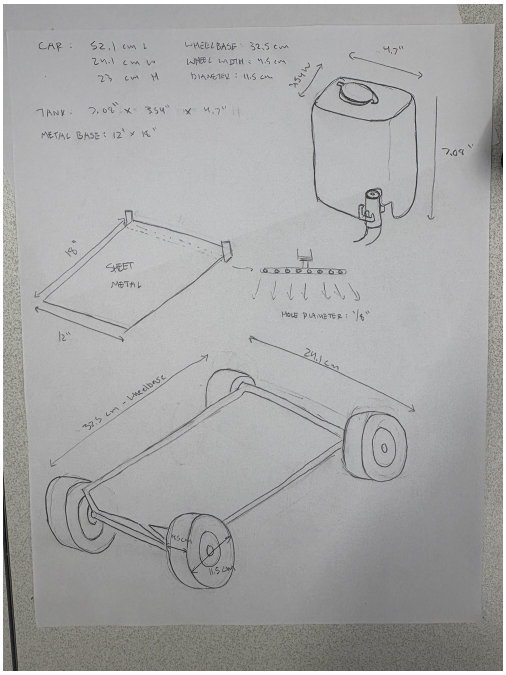


Figure 1. Initial dimensioned prototype drawing defining the four subassemblies.



Figure 2. Welded perforated spray bar (T-bar) fabricated in the machine shop.

4.2 Fluid system and first flow test

Flow path: tank → 12 V pump → tubing → needle valve → stop valve → perforated T-bar → discharge. The first build had no flow control at all; the pump discharged directly to the bar (Figure 3). The objective was to confirm that the pump could draw from the tank and produce an even discharge across the full width of the bar, which it did. This confirmed the core loop worked, and it also exposed the first major problem: the flow rate was far too high to treat a driveway on a single tank. The needle valve and stop valve were added later in response to specific problems found in the testing below.

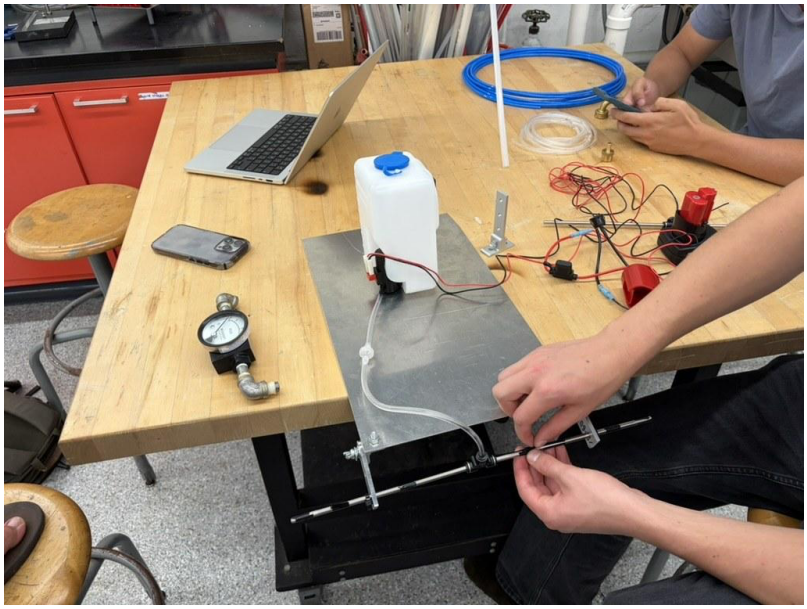


Figure 3. First fluid-system build: tank, pump, and tubing discharging directly to the bar.

4.3 Choosing the spray pattern

Before refining flow rate, we settled the discharge pattern: parallel brine lines rather than a solid sheet or an atomized mist. Dry gaps between lines preserve traction until the brine spreads and dissolves outward, discrete streams resist wind drift better than a mist, and the pattern gives even, repeatable coverage using the least fluid, which matters directly for the one-tank coverage target.

We validated the pattern on pavement. Figure 4 shows the discharge test that reached the desired spray pattern: discrete parallel lines with dry gaps between them, laid down across the bar's full width as the vehicle drives. The same testing showed the tank emptying far too quickly, which became the focus of the flow testing in Section 4.4.

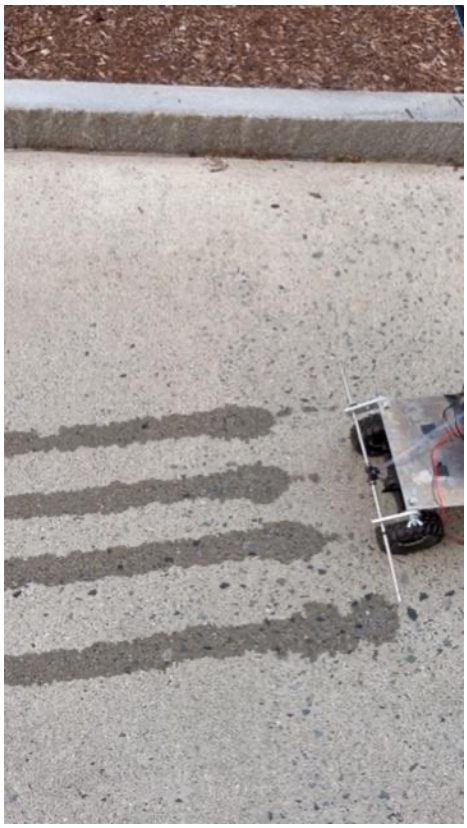


Figure 4. Spray-pattern test on pavement: parallel lines with dry gaps, discharged across the bar's full width.

4.4 Flow rate testing

We measured flow rate as Q = V/t, where V is the volume of water released and t is the time to release it, by timing how long the pump took to empty a full 1.5 L tank under each configuration. Our first thought was that the eight 0.07 in holes in the bar set the flow, so, with a check valve installed, we taped holes shut to vary the number of open outlets and measured the effect on Q.

Configuration	Time to empty 1.5 L	Flow rate Q
Pump direct to bar (8 holes, no valve)	17 s	88.2 mL/s

Configuration	Time to empty 1.5 L	Flow rate Q
Check valve added (8 holes)	28 s	53.6 mL/s
6 holes (check valve)	27 s	55.6 mL/s
4 holes (check valve)	26 s	57.7 mL/s
1 hole (check valve)	30 s	50.0 mL/s

Table 5. Tank-emptying time and flow rate versus number of open holes.

Closing holes had essentially no effect: going from six open holes to one changed Q by under 8 mL/s, within experimental error. The check valve, however, reduced flow by about 39% (88.2 to 53.6 mL/s) on its own.

This matches the behavior of a positive-displacement (peristaltic) pump. The pump delivers a fixed volume per revolution, so total flow is set by pump speed, not by downstream restriction. By conservation of mass, the volume leaving the holes each second equals what the pump forces in, so closing holes only forces the same flow through fewer openings at higher velocity; it does not lower Q. The check valve differs because it raises the pressure the pump must overcome, loading the pump against its torque limit and reducing Q at the source. The holes act only on distribution and the valve acts on flow, so to lower the flow rate we had to act on the pump side.

4.5 Flow control: needle valve

Acting on the pump side, we installed a needle valve downstream of the pump as an adjustable restriction, with an inline pressure gauge to read the back-pressure while setting it (Figure 5). Closing the valve raises the back-pressure the pump works against, which lowers the flow. We searched for a working setting by gauge reading: 1.0 psi ran too fast and 0.1 psi too slow, and the working value settled near 0.3 psi.



Figure 5. Inline pressure gauge used to read back-pressure while setting the needle valve.

The needle valve provides a fine, repeatable restriction. The gauge readings got us close, and the final setting was calibrated by timed dispensing, measured as 160 mL in 30 s, giving 5.33 mL/s. Time to empty the 1.5 L tank rose from 17 s (pump direct) to 281 s with the needle valve, roughly a 16-fold increase in run time on the same tank volume.

Configuration	Flow rate
Pump direct to bar	88.2 mL/s
With check valve	53.6 mL/s
With needle valve	5.33 mL/s

Table 6. Measured flow rate by configuration.

4.6 Residual discharge and joint leakage

Two smaller problems showed up during flow testing, and each got a targeted fix:

Residual discharge. Fluid remaining in the line kept draining through the bar after the pump was switched off, so the vehicle dribbled with the pump off. Fix: a stop valve immediately upstream of the T-bar (Figure 6).

Joint leakage. The tube outer diameter was marginally undersized for the fittings, causing leaks at the needle-valve and stop-valve connections. Fix: tube ends wrapped in tape to increase diameter and create firmer fittings.

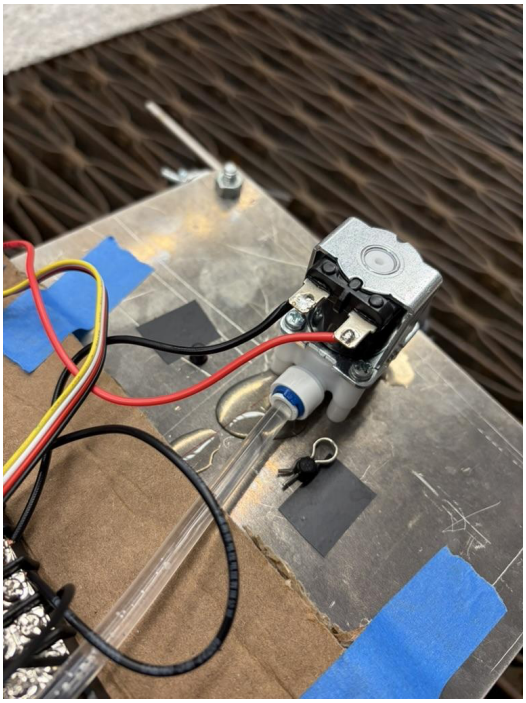


Figure 6. Stop valve installed immediately upstream of the T-bar to prevent residual discharge.

4.7 Electronics and control

In parallel with the fluid work, the drivetrain and control electronics were assembled (Figure 7). The board houses an Arduino (ESP32-S3) driving a Redcat ESC and steering servo for the drivetrain, plus relays for the pump and the shutoff valve. A 12 V → 5 V converter and a PWM controller complete the board. Two battery packs are used: a 7.4 V NiMH for the ESC and drivetrain and a 12 V NiMH for the pump and valve. An earlier build used a salvaged lithium-ion drill battery as a temporary 12 V source. All electronics and the battery sit in a NEMA enclosure on the deck (Figure 8).

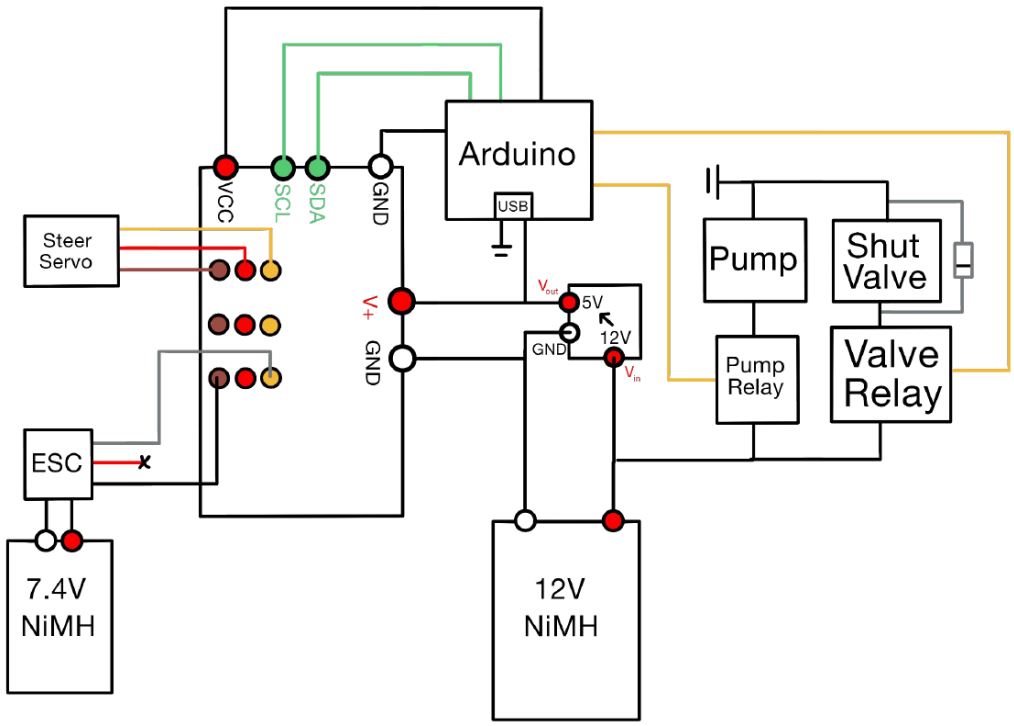


Figure 7. Control-electronics schematic: ESP32-S3 Arduino, ESC and steering servo, pump and valve relays, and dual battery packs.

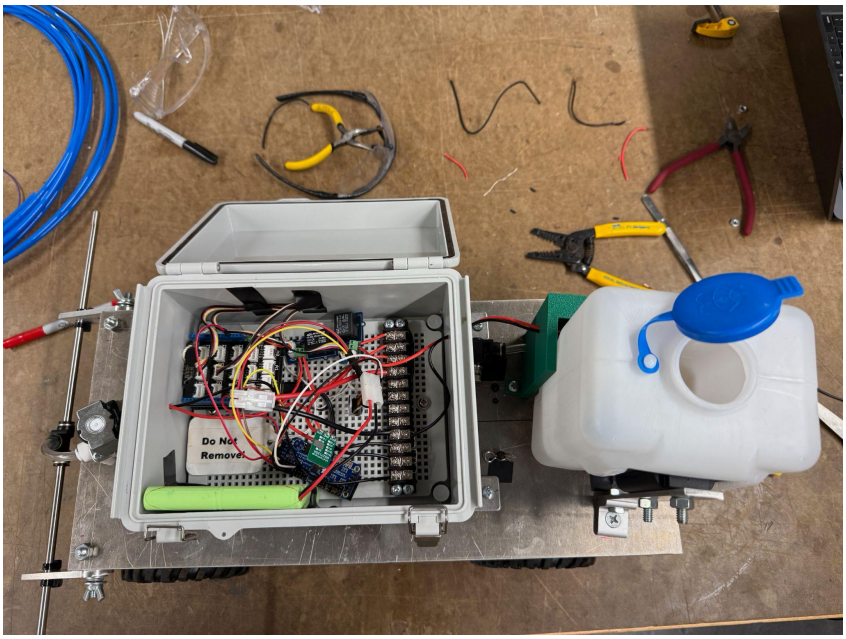


Figure 8. Electronics and battery housed in the NEMA enclosure beside the reservoir.

4.8 Loaded chassis instability

We mounted and drove the empty sheet-metal deck first (Figure 9), then added the fluid system on top. This exposed the next problem: with a full tank the suspension had too much give and the whole base swayed, which would ruin straight-line coverage. The solution was measured, 3D-printed cylinders inserted inside the springs to stiffen the suspension (Figure 10). This is also why later speed calibration had to be done with the tank full, since the load changes how the vehicle drives.



Figure 9. Sheet-metal deck mounted on the RC chassis, tested empty before the fluid system was added.

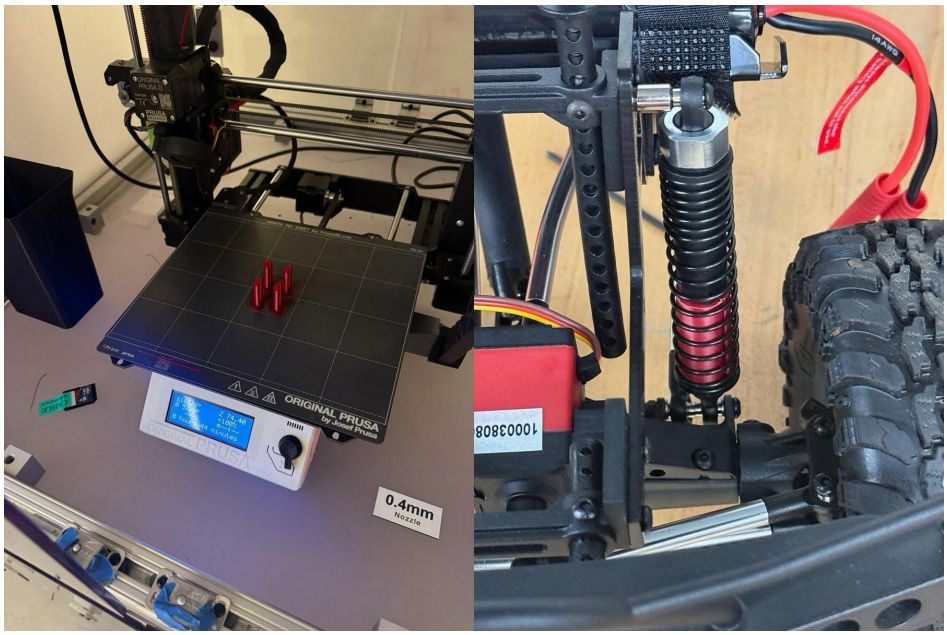


Figure 10. Measured 3D-printed cylinders (left) installed inside the suspension springs (right) to stiffen the loaded chassis.

4.9 Turning flow into coverage: the application-rate model

With a repeatable flow rate in hand, we could predict coverage. The area a run can treat depends on flow rate, spray width, and vehicle speed:

$$\textit{liquid applied per area} = Q / (\textit{vehicle speed} \times \textit{spray width})$$

At a constant pump flow rate, increasing vehicle speed spreads the same amount of liquid over a larger area and decreases the amount applied per square foot, so vehicle speed must be matched to the pump's flow rate and the width of the spray pattern.

Working the target backwards: treating 480 ft² with an 18 in (1.5 ft) spray width requires covering 480 / 1.5 = 320 ft of path. At 2 mph (2.93 ft/s) that takes 320 / 2.93 = 109 s, so emptying exactly one 1.5 L tank over that path would require a flow rate of about 13.7 mL/s. Since our final controllable flow rate of 5.33 mL/s is below this, one tank lasts longer than the 480 ft² path requires, and coverage is limited by the driven route rather than by tank volume.

Theoretical upper bound (level ground, constant 1.5 ft width, continuous discharge, constant speed): at 1.5 mph the 281 s tank life yields ≈619 ft of path and ≈928 ft² of coverage. This is a calculated figure; the driving tests below were used to confirm actual treated area.

4.10 Speed and steering calibration

Before a benchmark run we had to get the loaded vehicle to drive straight at a known speed. Settings were timed over a fixed 35 ft distance to find the combination that produced the straightest line and best coverage. A consistent left drift turned out to be reversed left/right trim values. Loading the full tank also reduced speed by about 19% (2.03 mph unloaded to 1.65 mph

loaded on an earlier setup), confirming that calibration had to be done with the tank full. On the final setup, settings converged as follows:

Speed setting	Steer setting	Time for 35 ft	Speed	Result
1600	1290	13.64 s	1.75 mph	Veering right
1590	1450	19.72 s	1.21 mph	Veering left
1590	1380	19.67 s	1.21 mph	Better, slight left
1590	1400	19.25 s	1.24 mph	Straight (final calibrated setting)

Table 7. Speed and steering calibration over a fixed 35 ft distance, full tank.

4.11 Final driving tests and benchmark comparison

With flow, coverage model, suspension, and steering all resolved, we ran the vehicle end-to-end. Figure 11 shows the SolidWorks drawing of the final assembly, and Figure 12 the completed prototype. Two full-tank driving runs were performed (Figure 13); both exceeded the 480 ft² coverage target, and the final calibrated run is the benchmark comparison.

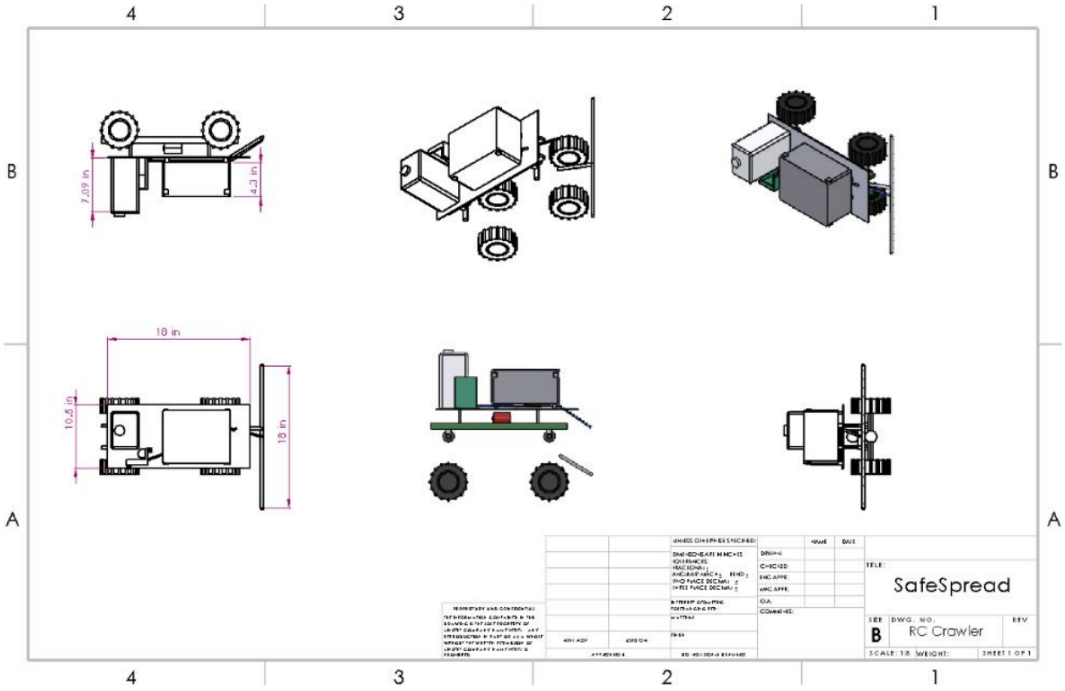


Figure 11. SolidWorks drawing of the final assembly.

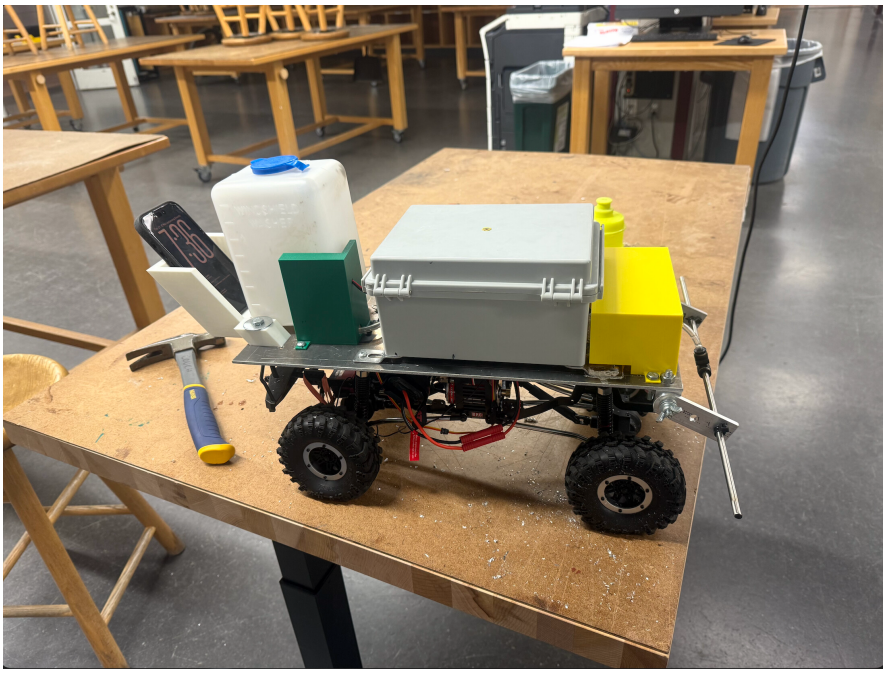


Figure 12. Completed prototype: reservoir, needle and stop valves, rear T-bar, NEMA electronics enclosure, and phone holder on the stiffened RC chassis.

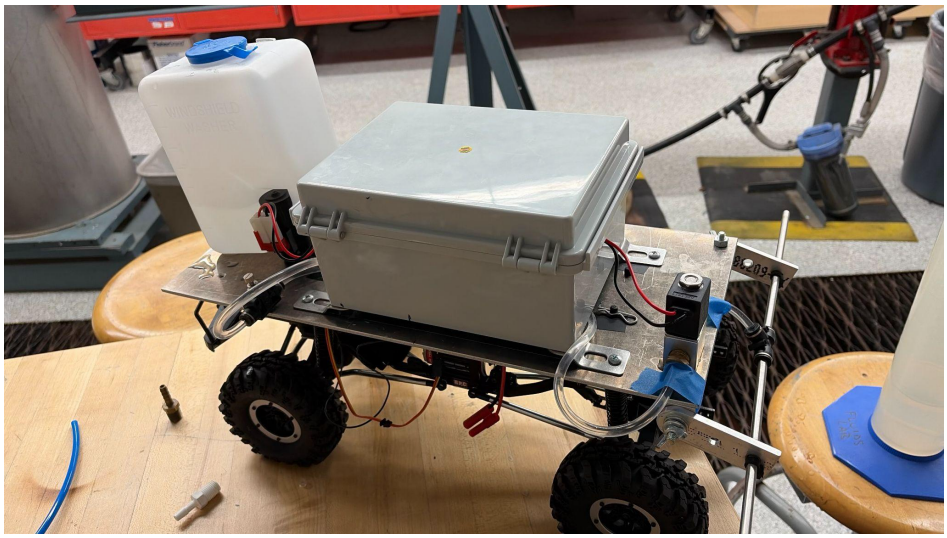


Figure 13. Final full-tank driving test of the completed prototype.

Run	Speed	Tank life	Path length	Coverage (× 1.5 ft)	vs 480 ft²
Initial driving run	1.02 mph (1.50 ft/s)	281 s	≈422 ft	≈632 ft²	Pass
Final calibrated run	1.24 mph (1.82 ft/s)	280 s	≈509 ft	≈764 ft²	Pass

Table 8. Full-tank driving runs against the 480 ft² coverage target.

The final run emptied a full 1.5 L tank in 4 min 40 s (280 s) while driving at 1.82 ft/s, covering about 509 ft of path and 764 ft² of treated area: roughly 1.6 times the 480 ft² requirement, on one tank and one battery charge. The flow rate measured in that run (1500 mL / 280 s ≈ 5.36 mL/s) agrees with the 5.33 mL/s bench value, so the bench flow tests carried over to real driving. Total weight with a full tank was 14.91 lb, under the 25 lb limit.

Against the state of the art, SafeSpread requires no installation (unlike embedded heating and HeatTrak), costs far less at driveway scale, and treats the surface before ice forms rather than removing snow afterward (unlike the Yarbo robot). Its closest functional match is the KlearWay sprayer, which is a fixed retrofit rather than a mobile unit. Against our own specifications:

Specification	Target	Result	Status
Weight	< 25 lb	14.91 lb (full tank)	Met
Coverage	100 to 480 ft² per tank	≈764 ft² per tank	Met
Flow control	Repeatable; treats full driveway on one tank	5.33 mL/s, repeatable	Met
Autonomy	No manual spreading; < 2 min setup	Full mission driven autonomously (Section 4.13)	Met
Battery life	Full tank + one 480 ft² run per charge	Full tank emptied on one charge in final run	Met
Cost	< $400 unit cost	≈$345 estimated BOM (Section 6.2)	Met (estimate)
Durability	10 °F, IP54, corrosion-resistant	Freezer, IP and salt-soak tests not yet run	Not yet tested
Safety	Halts within 15 cm of obstacle	Faults stop the rover; no obstacle sensing yet	Partially met; see note
Environmental	Minimum dose; runoff within EPA/state guidance	Low controlled dose; runoff not quantified	Partially met

Table 9. Performance against specifications.

The autonomy and safety rows reflect the field test in Section 4.13, added after the final presentation: the rover now drives its route on its own and stops itself on any internal fault, but it has no dedicated obstacle sensing, so the 15 cm obstacle-halt target is still open. Durability verification (cold, ingress, and salt-soak testing) was specified but not reached within the term. Both are future work (Section 7).

4.12 Automation

The final presentation listed complete automation as future work. After the presentation we kept working and got it running: the finished prototype drives a complete coverage mission on its own. The operator enters the rectangle's dimensions in a phone app, sets the rover at a corner, and presses Start.

Position and heading come from an iPhone mounted on the rover in a 3D-printed holder, with its camera pitched 45 degrees down at the pavement. We wrote a companion app (React Native with a native ARKit module) that reads ARKit's visual-inertial odometry, which fuses camera tracking with the phone's inertial sensors and works on plain pavement with no GPS or added sensors on the rover. The app checks each pose before it is used (tracking state, sequence and timestamp, age, and limits on speed, acceleration, and yaw rate) and streams accepted poses over Bluetooth to the ESP32-S3. The rover does not calculate position on its own.

The route for the whole mission is computed once when Start is pressed and is only followed after that; tracking error steers the rover back onto the plan instead of producing a different plan. (An earlier version re-decided its route from its own tracking error and oscillated between maneuvers.) The route covers the rectangle in back-and-forth passes at the spray bar's 21 in lane spacing, joined by three-point turns in the headlands. Turns are planned from the rover's two turning radii, which are measured separately for each direction (5.5 ft left, 5.1 ft right) by a one-button calibration routine. Steering uses a measured map of pulse width to curvature, because the pulse at which the wheels actually point straight is not the midpoint of the servo's travel; assuming it was put every outbound pass off to one side and every return pass off to the other. A PI speed loop holds ground speed rather than a fixed throttle setting, since the rover gets lighter as the tank drains. Passes run at 1.5 ft/s and turns at 0.7 ft/s.

The pump and stop valve follow spray flags carried by the route, so fluid is only dispensed inside the rectangle, and spraying cuts off if the rover strays more than 1.5 ft from its line. The app controls the mission through a Configure, Arm, Start state machine, and a safety layer stops the rover on any fault: lost Bluetooth, stale pose, stall, wrong direction, excessive tracking error, or an invalid route. The app and firmware have a test suite covering the route planner, turns, safety transitions, and the wire protocol. Much of this was debugged during practice runs on a taped course in a parking garage (Figure 14) before the outdoor test.

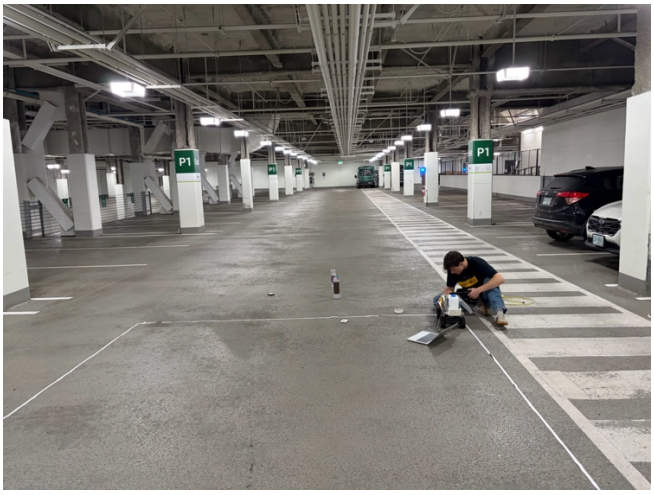


Figure 14. Practice and debugging runs on a taped course in a parking garage on test day, before the outdoor test.

4.13 Autonomous coverage test

On August 28 we taped out a 40 ft × 12 ft rectangle (480 ft², the full single-car-driveway area from our coverage specification) on outdoor brick pavers, entered the dimensions in the app, set the rover at a corner, and started the mission. We made two runs (Table 10).

Run	Duration	Passes sprayed	Outcome
Run 1	5 min 50 s	5 of 7	Route fault in the far headland; the rover stopped in place
Run 2	6 min 17 s	7 of 7	Complete: ≈390 ft route driven, mean cross-track error 0.45 ft

Table 10. Autonomous coverage runs on the 40 ft × 12 ft test rectangle.

The first run ended about five minutes and fifty seconds in, with five of the seven passes sprayed, when the firmware raised a route fault in the far headland and stopped the rover in place. This is the intended failure behavior: a fault stops the rover rather than letting it wander. We restarted, and the second run completed.

Figures 15 through 18 show the second run. The rover covered the full rectangle on its own in 6 minutes 17 seconds, driving seven passes joined by six three-point turns along a planned route of about 390 ft, and finished in the COMPLETE state back at the near headland. Cross-track error logged by the firmware averaged 0.45 ft over the mission, with a 95th percentile of 1.9 ft; the largest errors occur during the three-point turns. Pass speed held near the 1.5 ft/s target. The app accepted 22,408 poses and rejected 63, and one ARKit relocalization shifted the world frame by 0.8 ft mid-run without causing a fault.

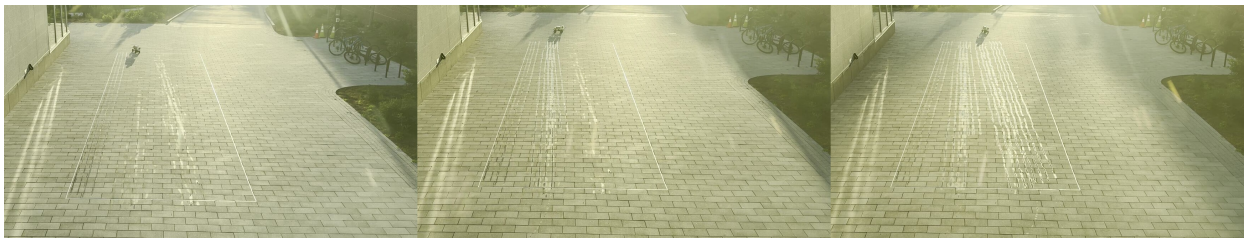


Figure 15. Autonomous coverage in progress at roughly 1, 3, and 5.5 minutes into the run; sprayed passes accumulate across the taped rectangle.



Figure 16. Three-point turn in the headland between passes. The phone that supplies the rover's position is visible in its mount.

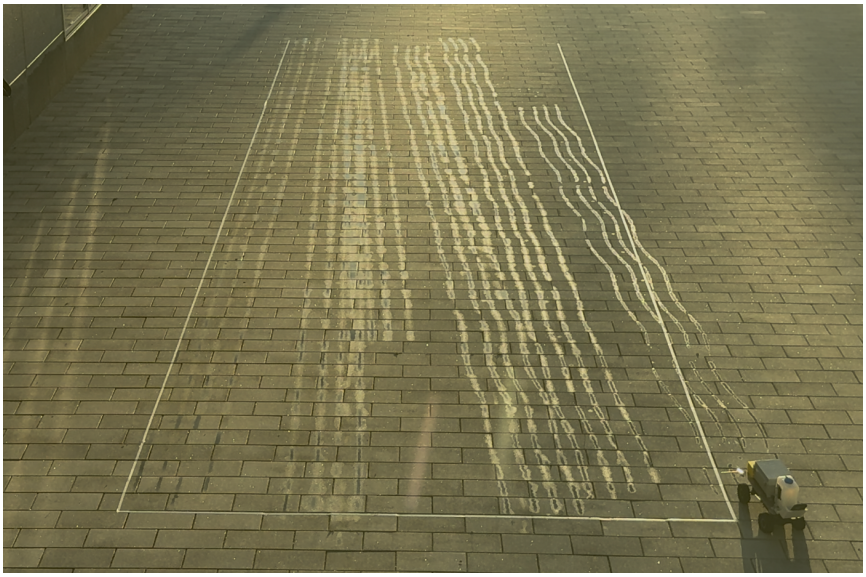


Figure 17. Final frame of the test video: the full 40 ft × 12 ft rectangle treated, with the rover parked at the end of its route.

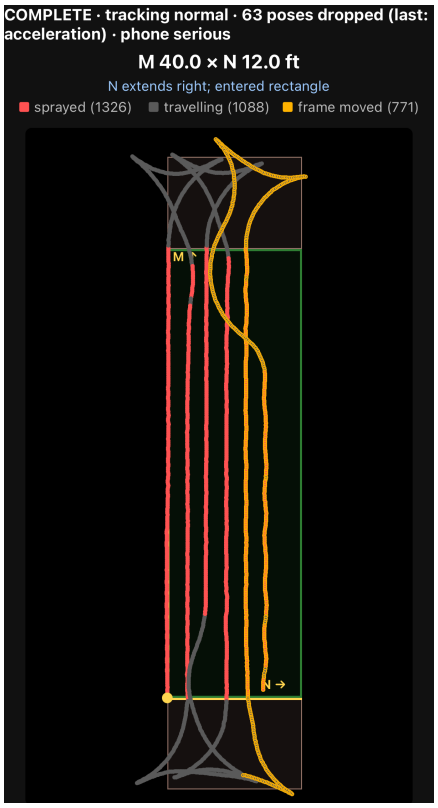


Figure 18. The app's mission map at completion: sprayed passes (red) inside the rectangle, headland travel (grey), and poses re-plotted after the mid-run relocalization (orange).

This test satisfies the autonomy specification: no manual spreading motions, and setup consists of entering two numbers and pressing two buttons. Run 1 also demonstrated the controlled-stop behavior our safety specification calls for. The test does not demonstrate obstacle detection; the rover stops for its own faults, not for a pedestrian, so we kept the test area clear of people, and the 15 cm obstacle-halt target remains future work.

4.14 User and stakeholder feedback

Source	Feedback	Decision made
Survey respondents	Ice is widely recognized as a hazard, but about half take no action and 76% sometimes skip treating it; effort is the main barrier.	Confirmed the autonomy specification (remove the task entirely, rather than reducing) and the need for the product.
Target users (elderly individuals)	Agreed on both the need and the assumed habits.	Confirmed target-user assumptions and the need.
Instructor / TA	From the initial presentation: a fully bottom-up system is too much for eight weeks; focus on the fluid system.	Bought and customized an off-the-shelf RC base instead of building a vehicle; prioritized the fluid system.
Machine shop staff	Recommended fabricating the spray bar as a welded transverse T-bar and advised on hole drilling and welding technique.	Spray bar built as a welded T-bar with uniformly drilled holes in the machine

Source	Feedback	Decision made
		shop; fabrication plans reviewed with shop staff before each build.

Table 11. Feedback received and the resulting design decisions.

5. Ethics and Sustainability

5.1 Ethical considerations

Several ethical questions come up once the device moves from concept to something that operates around people.

Safety. A self-propelled vehicle dispensing fluid creates collision and slip hazards for bystanders, pets, and operators. The prototype now drives its route autonomously and stops itself on internal faults, but it cannot yet detect a person or pet in its path, so autonomous runs were made with the test area kept clear; the obstacle-halting behavior in the safety specification is still to be implemented.

Component reliability. The salvaged components (a repurposed drill battery, scavenged tubing, and hand-cut sheet metal) raise reliability questions, since parts not rated for this application could leak, short, or fail in ways a purpose-built system would not.

Environmental impact. Saline is corrosive and ecologically disruptive, so runoff or over-application could damage soil, vegetation, groundwater, and nearby infrastructure. The design therefore has to keep dosing precise and account for where excess brine goes.

Dual use. Because the platform is essentially a mobile fluid-delivery system, the same mechanism could be adapted to dispense substances that are not benign; this calls for responsibility in how the design is documented and shared.

Accountability. As remote or autonomous control is added, if the system misjudges speed or flow and causes harm, it should be clear who is responsible, and a human should retain the ability to intervene or shut it down.

Considering these issues early let the team build safeguards into the design instead of adding them at the end.

5.2 Sustainability

In the design process. Rather than sweeping through arbitrary pressure and flow-rate values, the team tested only settings it had reason to believe would be productive, converging on a target through deliberate, bisection-style steps rather than brute force: after 1 psi ran too fast and 0.1 psi too slow, 0.5 psi was tested and the working value settled near 0.3 psi. This directed search minimized the number of trials and the water, energy, and time each trial consumed. The team was equally deliberate with materials. The first prototype was built from a scrap piece of cut

sheet metal and a length of tubing found in the Couch, and the tank's pump was powered by a battery from an existing drill instead of a new component; the current design reuses the base of an off-the-shelf RC car driven by an Arduino. Reusing what was on hand avoided fabricating parts that already existed in usable form. The team also sketched extensively before any physical build, so design problems could be caught on paper instead of by burning through materials in trial-and-error assembly.

In operation. By synchronizing the vehicle's driving speed with the pump's flow rate, the system applies saline evenly and only in the amount each area needs. This eliminates the flooding and over-application that waste material and can damage the treated surface, and it means less saline is consumed per unit area, which reduces both resource use and runoff. Preventative anti-icing is also more efficient than reactive de-icing, which needs far more chemical to break an already-bonded layer. The design uses widely available components, so the product is easy to maintain and repair without depending on custom or disposable parts. Because the core mechanism is mechanical and modular, worn or damaged pieces (spray bar, valves, tank) can be swapped out individually instead of scrapping the whole unit, which extends its service life and keeps it out of the waste stream.

In manufacture. The prototype's reuse of salvaged parts does not carry into production, so sustainability at scale depends on the design itself: standard components instead of custom or proprietary parts, recyclable materials in the largest pieces (an HDPE tank, an aluminum spray bar and deck), and a production chassis that can be taken apart so the NiMH battery packs and electronics can be separated for recycling at end of life. Because the device dispenses the minimum effective dose, it also uses less chemical over its lifetime than the manual salting it replaces.

6. Economics and Business Plan

6.1 Business model canvas (summary)

Value proposition. Removes the physical strain and injury risk of manually spreading salt; far less effort and time than manual treatment and a fraction of the cost of a heated driveway; light and easy for elderly or limited-mobility users to handle.

Customer segments. Primarily elderly homeowners and people with physical disabilities in snowy regions; buyers-on-behalf (adult children, caregivers); secondarily general homeowners who want to skip the task.

Channels. Direct-to-consumer web store; online marketplaces (Amazon); home-improvement and hardware retailers.

Customer relationships. Onboarding and seasonal support; safety and how-to content on correct brine use and coverage; warranty.

Key activities. Product design and iterative prototyping across mechanical, electrical, and firmware; cold-condition testing.

Key resources. The prototype and design IP; bill of materials (sheet metal, tubing, pump, controller); prototyping tools (CAD, electronics, machine shop); funding.

Key partners. Component suppliers (pumps, microcontrollers, motors, batteries, tubing, tanks); a contract manufacturer/assembler; magnesium-chloride and de-icer suppliers; retail and distribution partners; senior-care and disability organizations for credibility and referrals.

Cost structure. R&D and engineering labor (largest early cost); per-unit bill of materials; manufacturing, assembly, and logistics; testing and certification; software development and maintenance; marketing and warranty/returns.

Revenue streams. One-time hardware sales (primary); accessories and replacement parts (spray bars, batteries, larger tanks); optional recurring brine-concentrate refills or subscription, kept modest since efficient dosing is a selling point rather than a dependency; extended warranty and seasonal service plans.

6.2 Cost estimates and breakeven

Unit cost. The cost specification is a total unit cost under $400, evaluated by bill-of-materials costing against commercial alternatives (which range from roughly $1,075 to $12,000). Table 12 itemizes the prototype bill of materials at approximate new-component retail prices. Several components were salvaged at no cost (the drill battery, tubing, and scrap sheet metal), so the team's actual outlay was lower; the estimate below conservatively prices every component new.

Component	Approximate cost
Off-the-shelf RC crawler chassis (incl. ESC, steering servo, 7.4 V NiMH pack)	$150
Windshield-washer reservoir with integrated 12 V pump	$25
12 V NiMH battery pack (pump and valve)	$35
ESP32-S3 microcontroller board	$15
Relays (×2), 12 V → 5 V converter, PWM controller	$20
NEMA-style enclosure	$25
Sheet-metal deck (12 × 18 in)	$15
Aluminum spray-bar stock and fittings	$10
Needle valve	$12
Stop valve	$18
Tubing, fasteners, tape, and 3D-printed suspension stiffeners	$20
Total estimated unit cost	≈$345

Table 12. Estimated bill of materials at new-component retail prices.

Fixed costs. Bringing SafeSpread to market would require engineering development beyond the prototype: design refinement of a custom integrated chassis, cold-weather validation, safety and IP-rating certification, and control firmware. A rough estimate is $150,000: approximately $120,000 of engineering labor, $15,000 of tooling for the custom chassis and enclosure, $10,000 of testing and certification, and $5,000 of software development.

Breakeven. At a retail price of $449, below each automated alternative in Section 2, and a production variable cost of about $250 per unit (component prices fall at volume, but assembly, packaging, logistics, and warranty reserves are added), each sale contributes $199 toward fixed costs. Breakeven volume = fixed costs / (price − variable cost) = $150,000 / $199 ≈ 750 units. Selling roughly 750 units over the product's first winters is a plausible target for a niche accessibility product sold through senior-care networks and home-improvement channels, and every unit past that point earns a margin. These are planning estimates, but they suggest the product can undercut its competitors and still recover its development cost at modest volume.

7. Reflections

What we learned. The most useful result from testing was diagnostic: flow rate is set by the pump, not by spray-hole geometry, because the pump is positive-displacement. Shrinking or closing holes changes the spray pattern but not the flow rate, so controlling flow required acting on the pump side with a downstream restriction. This finding redirected the whole flow-control effort and led to the needle valve. We also learned to search parameters deliberately, bisecting toward a target instead of sweeping blindly, which got us to working values in far fewer trials, and that buying an RC base let us spend our effort on the fluid system, which is the part of the product that is actually new. The automation work taught us multiple lessons: plan once, then follow the plan. Our first navigator re-planned from its own tracking error and oscillated between maneuvers; planning the whole route at Start and treating tracking error as something to steer away made the behavior repeatable. Furthermore, it is important to have proper version history when coding. Many times, we attempted to add new features, which broke things previously working. We lost many hours trying to recover and return to the working version.

What could be improved. While the prototype proves the core mechanism, the items below are what we would work on next.

- **Real-world winter trials.** Test on actual driveways in freezing conditions to confirm treated area, spray uniformity, and anti-icing performance under real weather.
- **Custom, integrated components.** A refined or custom chassis and purpose-built fluid parts rather than repurposed ones, improving reliability and consistency.
- **Battery charging port.** For easy reuse without disassembly.
- **Single unified enclosure.** A sealed, protected housing that conceals internals.

- **Obstacle detection.** Time-of-flight sensors and a halting behavior, which would satisfy the 15 cm obstacle-halt safety specification that autonomous operation now makes pressing.
- **Durability verification.** Run the planned freezer, dry-ice, moisture, and salt-soak tests to confirm the 10 °F, IP54, and corrosion-resistance targets.

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