

Surface mobility, rover fleets and logistics operations



Conceptual visualization — fleet logistics is a system problem involving payload, distance, energy, maintenance, navigation, rescue and dispatch priorities.

Treat Martian vehicles as a fleet: range, energy, availability, rescue, routes, cargo and autonomy.

Before starting — review power systems, autonomy and Mars logistics because fleet dispatch couples energy, rescue coverage, route geometry and maintenance state. Every important symbol is defined at first use.

Mastery objectives

- dispatch a rover fleet using energy, rescue coverage, terrain, communications and maintenance state together
- protect return reserve and rescue capacity instead of consuming nominal range on outward travel
- separate vehicle availability, mission availability and fleet resilience under concurrent demand
- decide when two individually acceptable surface missions become collectively unsafe

1. Mobility is infrastructure

A rover is not an isolated machine. It connects the habitat, science sites, ISRU, workshop, depot and landing zone. Its availability therefore shapes the entire settlement. A colony that depends on one multipurpose vehicle has a major single point of failure. Fleet design separates functions such as crew transport, cargo, towing, excavation, reconnaissance and rescue.

Johnson Space Center rover capabilities connect mobility, testing and surface operations.

[NASA JSC — Rovers](#)

2. Range and return reserve

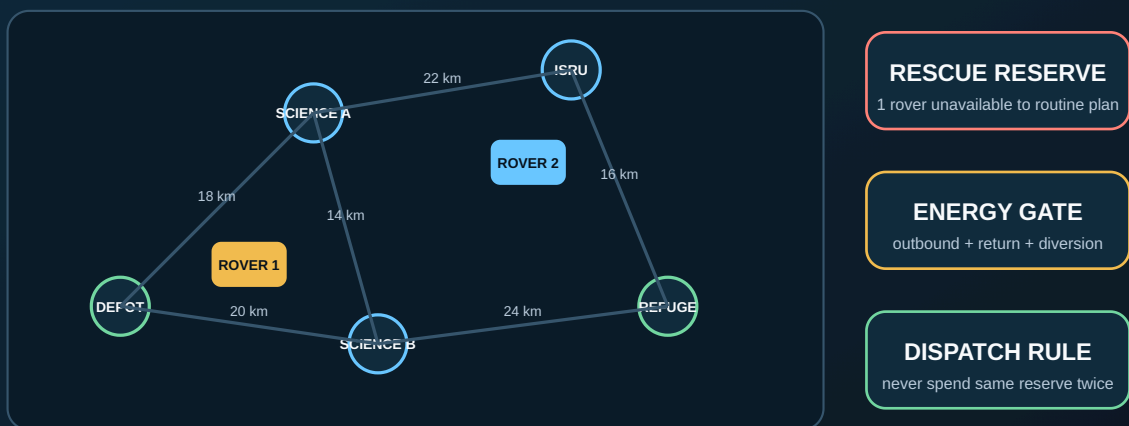
Maximum distance cannot be calculated from all stored energy. Reserve is kept for diversion, slower travel and degraded return. For crew operations, safe radius may be limited by suit endurance or rescue capability before battery energy becomes the limiting factor. The return case is therefore designed first, not added after the nominal route.

3. Traction, slope and terrain

Mobility depends on wheel-soil interaction. Slope raises required force, soft ground increases slip and obstacles can force detours. Energy models should use terrain-dependent consumption rather than one kWh/km number. Mobility maps become living operational products updated from vehicle data and field observations.

Rover-fleet dispatch map

Route graph, distance labels, rescue reserve and energy gates for concurrent surface missions



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Two individually acceptable missions can become unsafe when they consume the same rescue, charging or maintenance reserve. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

4. Fleet availability

A fleet is managed by availability, not nominal vehicle count. Three vehicles can mean only one schedulable asset if one is waiting for a part and another is reserved for rescue. Track maintenance due, battery state, wheel condition, onboard tools and restrictions. Fleet status belongs on the daily operations board beside energy, water and atmosphere.

5. Move cargo without consuming crew time

Autonomous or supervised rovers can move water, parts and samples while crew perform higher-value work. Autonomy introduces navigation, obstacle detection, communications and recovery needs. A cargo mission is successful when it arrives with little supervision and predictable risk, not merely when it moves fast.

6. Rescue and recovery

Every distant route asks what happens if the rover cannot restart. Options include redundant vehicles, towing, emergency shelter, a ready rescue vehicle and limited operational radius. Injury has to be included: a plan that assumes the crew will simply walk 20 km in suits is generally not credible.

7. Distributed charging

A fleet can charge at the habitat, remote depots or mobile power trailers. Depots reduce onboard battery mass but add new dependencies. Their state, connectors, dust protection and simultaneous power capability matter. An empty or failed depot can make a geographically reachable region operationally unreachable.

8. Data and predictive maintenance

Every drive produces current, slip, temperature, vibration, consumption and navigation data. Trends can expose a wheel drawing more current or a bearing heating up. Predictive maintenance begins with reliable measurements and a preserved history, not with a magical AI model.

Deepening: true cost of a kilometer

Trip cost includes energy, wear, crew time, risk and future maintenance. A longer smooth road may be preferable to a rocky shortcut that accelerates wheel damage. Fleet history gradually provides cost estimates by route segment. That model can influence depot and industrial-site placement using real logistics rather than map distance alone.

Deepening: multi-vehicle scheduling

When vehicles share roads, chargers and workshop support, scheduling becomes a resource-allocation problem. Two missions can each be feasible yet conflict because they require the same power trailer or technician. Planning therefore represents support dependencies as well as the rover itself. A fleet board shows assignments, charging windows, due maintenance and the rescue capability that must remain free.

Deepening: grounding criteria

A rover should not automatically operate until complete failure. Temporary grounding criteria protect crews: abnormal energy use, brake faults, lost communication redundancy or wheel damage. This discipline may appear to reduce available fleet size, but it prevents an already degraded vehicle from becoming the cause of a rescue operation. Return to service requires understood cause, repair and a suitable functional test.

9. Worked example: range with reserve

A rover has 120 kWh usable energy and must retain 25% final reserve. Expected terrain requires 3.2 kWh/km. Planned energy is $120 \times 0.75 = 90$ kWh, so total out-and-back distance is about $90 \div 3.2 = 28.1$ km. For a symmetric route, theoretical radius is roughly 14 km before weather, detour and battery-aging margins.

Calculated case study: minimum energy for a two-rover mission

TEACHING ASSUMPTION — A logistics route is 42 km long. Each rover averages 0.9 kWh/km and must carry a 25% energy reserve above the calculated need.

Let d be distance in km; c consumption in kWh/km; E energy without reserve in kWh; r reserve, dimensionless; and E_r per-rover energy including reserve.

$E = d \times c = 42 \times 0.9 = 37.8$ kWh. $E_r = 37.8 \times 1.25 = 47.25$ kWh per rover. For two rovers:
 $E_2 = 2 \times 47.25 = 94.5$ kWh.

The 94.5 kWh total does not mean that this battery capacity is sufficient in reality: temperature, terrain, ageing and rescue requirements can change demand. The calculation makes the reserve explicit before departure.

10. Exercise

Compare two routes to a depot 9 km away: route A is 9 km at 3 kWh/km, route B is 12 km at 2.1 kWh/km. Calculate round-trip energy and add 20% planning margin. Then compare time and rescue complexity.

11. Reasoned solution

Route A uses $18 \times 3 = 54$ kWh. Route B uses $24 \times 2.1 = 50.4$ kWh. The longer route is slightly better energetically but may expose the crew longer. The final choice is multi-constraint, not a shortest-distance calculation.

12. Validation project

Define a fleet for a 30-person base: crew, cargo, rescue and construction vehicles, availability rules, maintenance, batteries, roads, remote charging, immobilization policy and daily status board.

Surface mobility is a settlement network, not a collection of vehicles

A rover is useful only when the entire chain around it works: a known route, enough energy, a charged reserve, communications, navigation, maintenance, cargo interfaces, rescue capability and a place to park or repair the vehicle. On Mars, mobility connects habitats, landing zones, science sites, construction areas, power fields and emergency shelters. The correct design question is therefore not “how far can this rover drive?” but “what missions can the settlement complete safely and repeatedly when one or more vehicles are unavailable?”

That change of viewpoint matters because a nominal range figure hides the variables that dominate operations. Soft regolith, slopes, wheel slip, low temperatures, cabin heating, payload mass and detours can all increase energy consumption. A vehicle that can complete a route once under favorable conditions may still be unsuitable for scheduled logistics. Operational planning must use measured consumption distributions and explicit return reserves rather than a single optimistic kilometer number.

A Mars fleet also has to separate crew transport from freight whenever practical. Moving supplies autonomously or teleoperating cargo vehicles can reduce crew exposure and free human time for tasks that truly require people. Crew-rated mobility, however, needs more conservative reliability, life-support interfaces and rescue rules because a vehicle failure can become a survival problem rather than merely a delivery delay.

Ten system-level principles for a rover fleet

1. Design missions before choosing vehicles

Start with recurring mission types: crew transfer, pallet delivery, science sortie, construction support, emergency recovery, inspection and long-range reconnaissance. Each mission has distance, payload, speed, environmental exposure, communications and time constraints. Vehicle specifications follow from those mission envelopes. This avoids buying or designing one impressive platform that is mediocre at every daily task.

For each mission, record what must still happen if the preferred rover is unavailable. A second crew rover, a tow-capable cargo vehicle, a cached shelter or a route with intermediate charging may provide resilience. The alternative should be operationally rehearsed rather than existing

only as a drawing.

2. Range is an energy budget with a return obligation

Distance alone does not determine usable range. Mission energy includes traction, steering losses, thermal control, avionics, communications, lighting and payload-specific loads. The planned reserve must cover uncertainty and a credible diversion or recovery action. A return reserve is not “unused battery”; it is a safety resource intentionally protected from routine consumption.

When terrain is poorly characterized, planners can divide the route into energy gates. At each gate, the vehicle compares actual state of charge and distance remaining against a return threshold. If consumption is worse than planned, the correct result may be an early turn-back even when the destination looks close.

3. Terrain changes both energy and controllability

Loose soil, rocks, slopes and wheel sinkage can increase slip. Slip means the wheels rotate farther than the vehicle advances, so energy per useful kilometer rises and navigation based on wheel odometry becomes less reliable. Route surveys should therefore record not only geometry but also observed traction and repeatability.

Heavy vehicles may damage routes and create ruts that make later journeys worse. Fleet operations and civil engineering are coupled: grading, compaction and maintenance of critical corridors can save energy across thousands of future trips. A route improvement should be evaluated over its lifetime traffic, not only by the energy used to build it.

4. Availability matters more than fleet count

A settlement with six rovers does not have six useful rovers if two await parts, one is under inspection and one has a degraded battery. The operational variable is the number ready for assigned missions. Daily dispatch should show which vehicles are mission-ready, restricted, in maintenance or held in emergency reserve.

Availability targets should differ by function. A unique rescue rover deserves stronger redundancy and parts support than a non-critical survey cart. This is a consequence-based maintenance policy: scarce technician time and spares are allocated where loss of function has the greatest impact.

5. Cargo logistics should minimize crew hours

Routine freight can often tolerate lower speed and greater scheduling flexibility than crew transport. Autonomous convoys, supervised teleoperation and pre-positioned cargo runs can move water, food, regolith, samples and spare parts without placing people outside the habitat for every transfer. The fleet can be designed around standardized cargo interfaces so pallets move between lander, depot and rover with minimal handling.

Logistics planning should count human touches. Every manual coupling, lift, repacking operation or suit-dependent inspection consumes crew time and introduces an error opportunity. A good Martian logistics system moves more useful mass while requiring fewer exposed human interventions.

6. Rescue capability defines the practical edge of the map

A crew sortie should remain inside a rescue envelope that reflects response time, energy, communications and life-support duration. The rescue vehicle itself must be ready, not merely theoretically available. If the only recovery rover is assigned to another distant task, the safe radius of simultaneous missions shrinks.

For long routes, intermediate shelters, cached consumables or charging points can change the rescue geometry. They do not eliminate risk, but they can break one long unsupported leg into several shorter survivable legs. The map of the settlement should therefore show rescue time contours as well as roads.

7. Charging is a network-capacity problem

A charger with sufficient peak power may still be poorly placed, while a well-placed charger may overload the local microgrid at the wrong time. Fleet energy planning must align departure schedules with power generation, storage state, habitat loads and thermal constraints. Charging several large rovers simultaneously can become one of the settlement's major discretionary loads.

Distributed charging at industrial or science outposts can extend operations, but it adds hardware, maintenance and cable or connector standards. The value of a remote charger should be measured by missions enabled and rescue margin created, not by geographic coverage alone.

8. Battery condition must be tracked as capacity, not age

Calendar age is only a weak proxy for usable energy. Thermal history, depth of discharge, charge rate and cell imbalance influence battery condition. Fleet planning should use measured available capacity and internal diagnostics so the dispatch system does not assume that every nominally identical battery can deliver the same mission.

A degraded pack can remain useful for short cargo tasks even after it is removed from crew-critical service. This creates a controlled second-life policy while protecting safety margins. Reassignment should be based on measured performance and clearly labelled limits.

9. Data logs turn repeated missions into better planning

Every trip can improve the route model. Energy per kilometer, slip, wheel torque, temperature, vibration, stops, communication dropouts and maintenance observations create a history of actual operating conditions. Over time, this allows planners to replace large generic margins with evidence-based margins that remain conservative where uncertainty is high.

Logs also support predictive maintenance, but prediction should not replace inspection. A model can identify unusual trends; technicians still need clear criteria for when a vehicle is safe to dispatch, restricted to low-consequence work or removed from service.

10. Common interfaces make the fleet resilient

Shared charging connectors, tow points, cargo locks, diagnostic protocols and wheel or suspension modules reduce the number of unique spares. Standardization also makes recovery easier because one vehicle can assist another without improvised adapters. The design goal is not absolute sameness but a deliberate reduction of unnecessary variety.

Interfaces should be tested in dust, cold and gloved operation. A connector that is convenient in a laboratory may be difficult to clean or impossible to manipulate during an EVA. Human factors and contamination control are therefore part of mechanical standardization.

Calculation laboratory: energy, reserve, charging and availability

Mission traction and fixed-load energy

$$E_{\text{mission}} = d \times c + E_{\text{fixed}}$$

Read aloud: mission energy equals distance times average energy consumption per distance plus fixed-load energy. Here d is travelled distance, c is measured energy per kilometer under the relevant route condition, and E_{fixed} represents loads that depend more on time than distance, such as cabin thermal control or scientific equipment.

If a 42 km sortie averages 0.9 kWh/km and fixed systems consume 6 kWh during the mission, traction contributes 37.8 kWh and total mission energy is 43.8 kWh. This is not yet the dispatch requirement because a reserve still has to be protected.

Planning reserve

$$E_{\text{dispatch}} = E_{\text{mission}} \times (1 + m)$$

The symbol m is the planning margin written as a fraction. With a 25% margin, 43.8 kWh becomes 54.75 kWh. The margin is not universal: a well-characterized paved route can justify a different policy from a first traverse across uncertain regolith. The important point is that the rule is stated before departure and checked against actual state of charge.

Fleet readiness

$$A_{\text{fleet}} = N_{\text{ready}} / N_{\text{total}}$$

If eight vehicles exist but only six are ready for unrestricted dispatch, readiness is $6/8 = 0.75$, or 75%. That number is more operationally useful than saying “the base owns eight rovers.” A fleet can also publish readiness by class, because losing one of two crew rovers is more significant than losing one of five cargo carts.

Average charging power

$$P_{\text{avg}} = E_{\text{charge}} / t_{\text{charge}}$$

Restoring 60 kWh in three hours requires an average 20 kW delivered to the battery. The electrical system must then account for charger losses and simultaneous loads. If two rovers charge together while the habitat is near peak demand, the dispatch plan may need to stagger charging rather than oversize every part of the microgrid.

Integrated worked case: two-rover science sortie

A science team plans a 42 km total route. Measured consumption on a representative route is 0.9 kWh/km per rover. The plan requires a 25% reserve, and two rovers travel together so that one can support the other. Ignoring fixed loads for the first calculation, one rover requires $42 \times 0.9 = 37.8$ kWh for the nominal drive. Applying the reserve gives $37.8 \times 1.25 = 47.25$ kWh per rover. Two rovers therefore need 94.5 kWh of dispatchable traction energy.

Now add a 5 kWh fixed mission load per rover for thermal control and instruments. The nominal energy becomes 42.8 kWh per rover. With the same 25% planning reserve, dispatch energy becomes 53.5 kWh per rover, or 107 kWh for the pair. This shows why “kilometers $\times$ kWh/km” can understate the real mission if time-dependent loads are ignored.

The plan should still ask what happens if consumption rises after the outbound half of the route. The correct gate compares actual remaining energy with the energy needed to return by the conservative route plus reserve. If the gate fails, the crew turns back or diverts to a safe node. The reserve is meaningful only when operational rules protect it.

Failure-mode drill: one rover becomes immobile 14 km from base

The first decision is not automatically to tow. The crew confirms life-support status, communications, weather, power and the mobility failure. If the second rover can carry both people safely, transferring crew may be preferable to an immediate heavy tow. The disabled rover can be secured for later recovery if leaving it does not create a hazard.

If towing is required, the team recalculates energy because rolling resistance, speed and route choice change. A recovery mission should have pre-defined tow points, compatible hardware and tested procedures. Improvisation under EVA conditions is a poor substitute for a standardized fleet interface.

The incident also feeds the reliability system. Was the failure detectable earlier? Did a sensor trend change? Was the route unusually damaging? Did maintenance miss a precursor? The goal of the post-mission review is not merely to repair one rover but to reduce recurrence across the fleet.

Progressive exercises with solutions

- ▶ Exercise 1 - Compare two routes
- ▶ Exercise 2 - Add a reserve
- ▶ Exercise 3 - Charging schedule
- ▶ Exercise 4 - Readiness

Interactive beginner glossary

- operational range - distance or mission envelope that remains safe after margins are protected.
- return reserve - protected energy for return or contingency.
- wheel slip - wheel rotation lost to poor traction.
- fleet readiness - mission-ready vehicles divided by relevant fleet size.
- rescue envelope - region in which credible recovery remains possible.
- decision gate - continue/return checkpoint based on measured conditions.
- common interface - shared connector, tow, cargo or diagnostic standard.
- derating - deliberate reduction of allowable capability.

Rover-logistics calculation laboratory: distance and payload turn vehicles into a transport network

A rover fleet must be sized around missions, route length, payload, energy, turnaround, maintenance and rescue availability rather than vehicle count alone.

Payload-distance workload

$$W = \sum(m_i \times d_i)$$

Question. How can different hauling jobs be compared with one simple workload indicator?

For two teaching jobs, 2.5 t moved 12 km contributes 30 tonne-kilometres, and 1.2 t moved 20 km contributes 24 tonne-kilometres. Total workload is 54 t·km. This does not predict energy directly because terrain, speed, vehicle efficiency and empty return legs matter, but it reveals that a light distant job can rival a heavy nearby job.

Fleet-hour coverage

$$A_{\text{hours}} = H_{\text{available}} / H_{\text{required}}$$

If planned missions require 80 rover-hours in a week but maintenance, charging and crew constraints leave 64 rover-hours available, coverage is $64/80 = 0.80$. The 16-hour deficit must be removed by rescheduling, added capacity, shorter routes or lower demand; calling the fleet “80% available” does not make the missing missions disappear.

► Exercise — transport workload

Mission-control studio: dispatch a rover without spending the return reserve

A rover mission is safe only if the vehicle can perform the task, return, and still retain the reserve needed for uncertainty and contingency. “Maximum range” is therefore not a distance printed on a brochure; it is the result of an energy budget that changes with payload, terrain,

temperature, stops, detours and battery condition.

1. Build the outbound-and-return distance

$$d_{\text{total}} = d_{\text{out}} + d_{\text{return}} + d_{\text{detour}}$$

All three terms use kilometres. A site 18 km from base with an 18 km nominal return and 4 km planning allowance gives 40 km total planned travel. The detour term is not a promise that four kilometres are sufficient; it makes the planning allowance visible instead of burying it.

2. Convert distance into traction energy

$$E_{\text{drive}} = c_E \times d_{\text{total}}$$

c_E is modeled energy consumption per kilometre in kWh/km. If a teaching model uses 1.6 kWh/km, $E_{\text{drive}} = 1.6 \times 40 = 64$ kWh. The unit check is $(\text{kWh/km}) \times \text{km} = \text{kWh}$. Real c_E is route- and vehicle-specific and must come from tests or validated models.

3. Add non-driving loads

$$E_{\text{mission}} = E_{\text{drive}} + P_{\text{aux}} \times t_{\text{mission}}$$

P_{aux} is average auxiliary electrical power in kW and t_{mission} is mission time in hours. If thermal control, computing, communications and instruments average 1.2 kW for 6 h, auxiliary energy is 7.2 kWh; total modeled energy becomes 71.2 kWh.

4. Protect a dispatch reserve

$$E_{\text{required}} = E_{\text{mission}} \times (1 + f_{\text{uncertainty}}) + E_{\text{emergency}}$$

If uncertainty margin is 20% and a separate 12 kWh emergency reserve must remain protected, $E_{\text{required}} = 71.2 \times 1.20 + 12 = 97.44$ kWh. This equation intentionally separates uncertainty from emergency energy; using the emergency reserve to make the nominal plan fit defeats its purpose.

5. Correct usable battery energy for current state

$$E_{\text{usable}} = E_{\text{nominal}} \times f_{\text{SOC_dispatch}} \times f_{\text{health}} \times f_{\text{operating_window}}$$

Suppose a battery is nominally 140 kWh, dispatch state of charge is 95%, measured health factor is 0.88, and operations intentionally use 85% of that adjusted energy window. $E_{\text{usable}} = 140 \times 0.95 \times 0.88 \times 0.85 \approx 99.5$ kWh. The 97.44 kWh requirement fits, but with little margin. A small deterioration in terrain or battery state could make the mission unacceptable.

6. Use an explicit abort threshold

$$E_{\text{abort}} = E_{\text{return_estimate}} + E_{\text{emergency}} + E_{\text{uncertainty_return}}$$

This threshold is recalculated using the vehicle's current position and observed consumption. When remaining usable energy approaches the threshold, continuing the outbound task should require an explicit operational justification rather than optimism.

► Integrated exercise — go, modify or no-go?

Mission decision. The correct question is not “Can the rover reach the target?” It is “Can the fleet complete the objective, preserve a credible return and rescue strategy, and recover from the failure modes that remain plausible?”

First-Man fieldbook: dispatch is a promise to bring the crew home

A settlement does not own mobility merely because several rovers are parked outside. It owns mobility only when a crew can request a mission, the dispatcher can prove that a suitable vehicle and rescue path exist, the energy and thermal budgets are acceptable, the route is understood, communications are adequate, and the vehicle can be returned to service without stealing critical capability from another mission. The operational unit is therefore the *mission chain*, not the rover. A single weak link can make a technically healthy vehicle unavailable.

Start with the route as a graph rather than a straight line on a map. Nodes are places where the crew can obtain something useful: the main habitat, a charger, a communications relay, a pressurised refuge, a maintenance bay, a science site or a cached emergency kit. Edges are traversable route segments with their own length, slope, roughness, navigation uncertainty and rescue difficulty. Two sites at the same geometric distance can have very different operational accessibility because one route contains a steep field of blocks, poor line-of-sight communications or no safe turnaround point.

Habitat

crew, workshop, main charging

Support node

relay, cache, charger or refuge

Work site

science, construction or logistics

Recovery path

return, tow, shelter or rescue rover

Build the dispatch budget from worst credible legs, not brochure range

$$E_{\text{dispatch}} = (d_{\text{out}}c_{\text{out}} + d_{\text{back}}c_{\text{back}} + E_{\text{aux}}) \times k_{\text{unc}}$$

Starting question

How much energy must the dispatcher allocate before the vehicle leaves, when outbound and return terrain may consume different energy and the crew still needs heating, communications and instruments?

Read aloud

Read: “dispatch energy equals outbound distance times outbound consumption, plus return distance times return consumption, plus auxiliary energy, all multiplied by an uncertainty factor.”

Symbols, pronunciation and meaning

d_{out} and d_{back} are route distances; c_{out} and c_{back} are measured energy use per kilometre for the expected terrain and loading; E_{aux} covers non-driving loads; k_{unc} is a dimensionless planning multiplier greater than or equal to one.

Units

Distance in km multiplied by kWh/km gives kWh. Auxiliary energy is also kWh. Multiplying the sum by a dimensionless

uncertainty factor leaves the result in kWh.

Origin and status of values

Distance comes from the approved route; consumption should come from fleet history or conservative test data for comparable payload, temperature and terrain. Auxiliary demand comes from the mission timeline. The uncertainty factor is a planning policy, not a physical constant.

Why this operation

Energy from each leg is added because the battery must supply all of it. Outbound and return coefficients are kept separate so a loaded climb and an unloaded descent are not falsely treated as identical. The final multiplier reserves margin for deviations that have not been modelled explicitly.

Substitution and calculation

Teaching case: 18 km outbound at 3.4 kWh/km, 18 km return at 2.7 kWh/km, 9 kWh of auxiliary demand and $k_{unc}=1.15$. Driving energy is $61.2 + 48.6 = 109.8$ kWh. Add auxiliaries: 118.8 kWh. Apply uncertainty: $118.8 \times 1.15 = 136.62$ kWh.

Calculator entry

Enter $(18 \times 3.4 + 18 \times 2.7 + 9) \times 1.15$. Keep the entire mission sum inside parentheses before applying the uncertainty factor.

Mental estimate

The two driving legs are about 110 kWh; adding about 10 gives about 120; fifteen percent of 120 is about 18. A result near 138 kWh is therefore plausible.

Independent check

Recalculate by applying the 15% margin separately: $118.8 + 0.15 \times 118.8 = 118.8 + 17.82 = 136.62$ kWh.

Physical or operational interpretation

If usable battery energy at dispatch is only 145 kWh, this mission leaves less than 9 kWh beyond the planning budget.

That may be inadequate if the settlement also requires a protected final reserve that must never be consumed in normal dispatch.

Plain-English translation

A vehicle may be able to reach the site and still be unfit for the mission because a safe dispatch must pay for the return, the crew's non-driving loads and uncertainty before departure.

Variation / sensitivity

If return consumption rises from 2.7 to 3.2 kWh/km because of dust or a detour, the pre-margin mission rises by 9 kWh. The same change can erase most of a small reserve.

Limit / assumption

The equation does not model battery temperature, power limits, regenerative braking, wheel slip transients or state-of-charge-dependent performance. Those effects belong in a higher-fidelity model or demonstrated operating envelope.

What this does not prove

Enough energy does not prove that the rover is safe. Steering, braking, wheels, navigation, communications, medical condition of the crew and the rescue system remain independent dispatch gates.

Boundary case to test

If the approved recovery route disappears because the rescue rover is unavailable, the correct operational response may be to cancel the mission even when E_{dispatch} is comfortably below the battery capacity. Energy feasibility and mission authorization are different questions.

A rescue rover is not “another rover”

The reserve vehicle must be protected from routine scheduling. If it is simultaneously carrying cargo on the opposite side of the settlement, it is not rescue capability. Define a maximum time to dispatch, a maximum time to reach each route sector, towing or crew-transfer interfaces, medical equipment, spare oxygen and power, and who is allowed to release the rescue asset for non-emergency work. This turns rescue from a comforting label into a measurable service.

Consider a crew immobilised 14 km from the habitat. A rescue vehicle averaging 12 km/h cannot arrive in “about an hour” once preparation, suit-up, route confirmation and safe docking are included. The time-to-consequence of the stranded crew must exceed the full detection-to-recovery chain with margin. That chain can become the real limit on exploration radius long before battery range is reached.

Maintenance capacity controls fleet size

Adding vehicles without workshop capacity can reduce effective availability. Every additional rover creates tyres or wheels to inspect, bearings and seals to monitor, batteries to condition, software configurations to manage, contamination to remove and spares to stock. Track mean downtime by failure class, not only kilometres driven. A fleet with six vehicles and two long-duration repairs may offer less guaranteed service than a smaller fleet with standardised modules, proven diagnostics and interchangeable parts.

Practice ladder: three dispatch decisions

1. **Beginner.** A 10 km round trip consumes 2.8 kWh/km and auxiliaries need 4 kWh. Compute nominal mission energy.
2. **Intermediate.** Repeat with a 20% planning margin and only 38 kWh usable battery energy. Decide whether a protected 15% final reserve can still be preserved.
3. **Operations review.** The energy gate passes, but the only rescue rover is under brake maintenance and the route has no pressurised refuge. State the dispatch decision and identify what must change before approval.

Reasoned answer. The first energy is 32 kWh. With a 20% margin it becomes 38.4 kWh, already above the available 38 kWh before protecting any final reserve, so the intermediate mission fails. In the final case, a positive energy budget still does not authorize departure

because the recovery architecture is unavailable. Restore a credible rescue path or change the mission geometry.

Range is not nameplate endurance; dispatch protects a return path and a separate rescue reserve under realistic terrain and temperature. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Operational qualification lab: plan a rover mission around the return, not the destination

A surface mobility system is safe only if it can return—or reach another safe haven—after a credible degradation. Range therefore cannot be calculated from nominal battery capacity alone. Terrain, thermal control, communications, crew life support, payload, wheel slip, dust, detours and rescue capability all consume margin. The outbound plan should be built backwards from the return requirement.

Reserve energy before committing distance

Separate battery state of charge from usable mission energy. Some energy may be unavailable because of battery protection limits, temperature, ageing or a reserve policy. Then protect energy for return and contingency before assigning the remainder to outbound travel and science. If the architecture relies on a second rover for rescue, that rover's availability and compatible route must be part of the same plan.

One-way safe radius from a simple energy budget

$$R_{\text{safe}} = (E_{\text{usable}} - E_{\text{fixed}} - E_{\text{reserve}}) / (2 e_{\text{travel}})$$

1 – Concrete question

With a defined usable energy inventory, what one-way travel distance leaves enough energy for the return and protected reserve?

2 – Intuition

Remove fixed mission energy and emergency reserve, then split the remaining travel energy between outbound and return legs.

3 – Quantities

Estimate usable energy, fixed non-propulsion energy, protected reserve and travel energy per kilometre.

4 – Formula

Safe radius equals available travel energy divided by twice the energy used per kilometre.

5 – Read aloud

“R safe equals E usable minus E fixed minus E reserve, divided by two times e travel.”

6 – Symbols

R is distance; E terms are energy; e_{travel} is energy per unit distance.

7 – Pronunciation

Lowercase e here is a specific travel-energy rate, not the mathematical constant e.

8 – Units

kWh divided by kWh/km gives kilometres.

9 – Convention

The factor two assumes similar outbound and return energy rates. If terrain is asymmetric, calculate the legs separately.

10 – Why this relationship

Only energy left after fixed loads and reserve can move the rover; round-trip travel requires energy for two legs.

11 – Assumptions

Travel energy per kilometre is treated as approximately constant for the teaching case.

12 – Unit check

$\text{kWh} \div (\text{kWh/km}) = \text{km}.$

13 – Numerical case

Usable rover energy: $E_{\text{usable}} = 150 \text{ kWh}.$

Fixed mission loads: $E_{\text{fixed}} = 20 \text{ kWh}.$

Protected return reserve: $E_{\text{reserve}} = 30 \text{ kWh}.$

Energy available for round-trip travel = $150 - 20 - 30 = 100 \text{ kWh}.$

Specific travel energy = 2.5 kWh/km each way.

Round-trip energy per kilometre of one-way radius = $2 \times 2.5 = 5$ kWh/km.

$R_{\text{safe}} = 100 \div 5 = 20$ km.

14 – Operations

First remove 60 kWh that cannot be assigned to nominal travel. The remaining 120 kWh supports 60 km of round-trip travel, or 30 km one way.

15 – Algebra check

30 km out + 30 km back at 2 kWh/km uses 120 kWh; adding 24 and 36 returns the 180 kWh usable inventory.

16 – Mental estimate

About two thirds of the battery is available for motion; at 2 kWh/km that is about 60 total kilometres.

17 – Interpretation

Thirty kilometres is the teaching-case radius before adding route-specific slope, slip and weather derating.

18 – What it does not prove

It does not prove the rover has enough oxygen, cooling, tyre/wheel life, communications or rescue coverage for that radius.

19 – Sensitivity

If rough terrain raises travel demand to 2.6 kWh/km, the same budget gives about 23 km.

20 – Practice

Guided exercise. Recompute one-way safe radius with 150 kWh usable energy, 20 kWh fixed loads, 30 kWh protected reserve and 2.5 kWh/km travel demand.

Detailed guided correction.

1. Travel energy after fixed loads and reserve = $150 - 20 - 30 = 100$ kWh.
2. Round-trip travel uses $2 \times 2.5 = 5$ kWh per kilometre of one-way radius.
3. $R_{\text{safe}} = 100 \div 5 = 20$ km.
4. The 20 km result is a planning radius under the assumed specific energy; it must be reduced for

terrain, temperature, battery degradation, navigation detours and rescue policy.

Autonomous exercise. Model a route with 3.0 kWh/km outbound and 2.0 kWh/km inbound. Usable energy is 170 kWh, fixed loads are 25 kWh and protected reserve is 35 kWh. Find the energy-limited one-way distance.

► Autonomous correction – open after attempting the exercise

21 – Mission decision

Publish a route-specific turn-back threshold based on measured consumption. If actual e_{travel} exceeds the planning value, reduce the destination radius before the reserve is spent.

A fleet needs rescue geometry

Fleet planning should map safe havens, tow capability, spare wheels or mobility units, charging points and communications shadows. One rover may be nominally available but unsuitable as a rescue asset because it lacks range, seats or compatible towing interfaces. Maintenance status should therefore include mission capability, not only “serviceable/unserviceable.”

Qualification drill

Plan a 25 km traverse with three rovers in the settlement fleet, one of which is undergoing maintenance. Inject 30% higher-than-planned energy use halfway outbound. Decide whether to continue, turn back or divert to a safe haven. Then explain how the decision changes if the second operational rover cannot depart for two hours.

Source context. NASA rover development and Moon-to-Mars architecture material provide operational context. The energy values are pedagogical assumptions. [NASA JSC — Rovers](#).

R61 rover-fleet dispatch: route assurance, rescue depth, charging

and maintenance as one mission system

Surface mobility should be operated as a fleet rather than as independent vehicles. A science sortie consumes energy, vehicle health, charging capacity, crew time, rescue coverage and route knowledge. Dispatch therefore needs an integrated release decision: a rover can be mechanically healthy yet still be unavailable because the rescue fleet, charging window or qualified crew is not sufficient for the route.

Define dispatch status with more than “green / red”

For each rover record propulsion and steering health, pressure integrity if pressurised, energy state, navigation status, communications, critical spares carried, overdue maintenance and any restrictions. A rover with a degraded wheel can be released for a short support mission but prohibited from becoming the rescue asset for a long traverse. Restrictions should follow the vehicle into the dispatch board so they are not lost at shift handover.

Primary-source bridge — JSC Rovers. NASA JSC rover work is a primary bridge for human surface mobility concepts. R61 applies that operational context to fleet dispatch, rescue and sustainment rather than treating a rover as a standalone vehicle. [Official source](#).

Route assurance combines terrain, energy and communications

A route should include known slopes, difficult terrain, navigation landmarks, communications gaps, turn-back points, safe waiting areas and alternate paths. Energy predictions should be updated from actual consumption on similar terrain. If a planned route crosses an area where communications and navigation are simultaneously weak, that common exposure belongs in the risk assessment even if each subsystem is individually redundant.

Rescue depth is a fleet property

Do not dispatch the nominal rescue rover on a mission that leaves no second recovery option unless the risk is explicitly accepted. For long sorties, consider whether another rover can reach the route, whether it carries compatible towing or transfer equipment, and whether the habitat has enough trained crew to operate the rescue while maintaining essential systems. Fleet resilience depends on preserved reserve capability, not the number of parked vehicles.

Primary-source bridge — Moon to Mars Architecture. NASA Moon-to-Mars architecture material provides primary context for surface mobility as one component of a broader exploration architecture. R61 makes the dependency on power, crew, communications and rescue explicit in the training model. [Official source](#).

Charging is a scheduling constraint, not a background service

Two rovers returning together can create a peak electrical load that competes with life support or industry. Dispatch planning should reserve charge windows, account for charger availability and include expected battery conditioning. A sortie that is energy-feasible in isolation may be operationally unacceptable if it prevents the rescue rover from being recharged before the next risk window.

Use maintenance trends to change mission assignment before failure

Track repeated wheel-motor temperature anomalies, suspension play, seal leakage, battery imbalance and communication dropouts. A weak trend can justify moving a rover from long independent sorties to local logistics while maintenance investigates. This is not wasteful conservatism: mission assignment should reflect confidence in the machine, not merely whether it can still move today.

Dispatch drill — two missions compete for the same rescue reserve

A science team requests a 30 km traverse while a construction team needs the second long-range rover at a remote site. Each mission is individually acceptable, but running both simultaneously eliminates mutual rescue and leaves only a short-range utility rover. The dispatch board should either stagger the missions, provide another qualified recovery method or explicitly reject one mission. Fleet risk is created by combinations of missions, not only by each route separately.

Route libraries should learn from every sortie

After each mission, update actual energy use, wheel slip, communication gaps, dust conditions, navigation difficulty and maintenance findings. A route should become better characterised over time. This allows dispatch to replace generic reserve factors with evidence while still preserving conservatism for new terrain or changed vehicle condition.

Crew endurance can be the limiting rover resource

Long traverses impose cognitive load, vibration, suit or cabin constraints, navigation work and delayed return. A rover with abundant battery may still need to turn back because the crew is approaching a fatigue or duty limit. Dispatch should therefore combine machine endurance with human endurance and the staffing needs waiting at the settlement.

Towing and passenger transfer need practiced envelopes

A disabled rover may be movable only on certain slopes or surfaces, and transferring crew can change occupancy, life-support and mass constraints in the rescue vehicle. Define and rehearse the conditions under which towing, parts delivery, crew transfer or shelter-in-place is preferred. Rescue capability is credible only when the team knows the boundary between these options.

Mission availability requires the rover, crew, communications, route and rescue architecture to be ready at the same time. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Primary sources and bridges

- [NASA JSC — Rovers](#)
- [NASA — Moon to Mars Architecture Components](#)