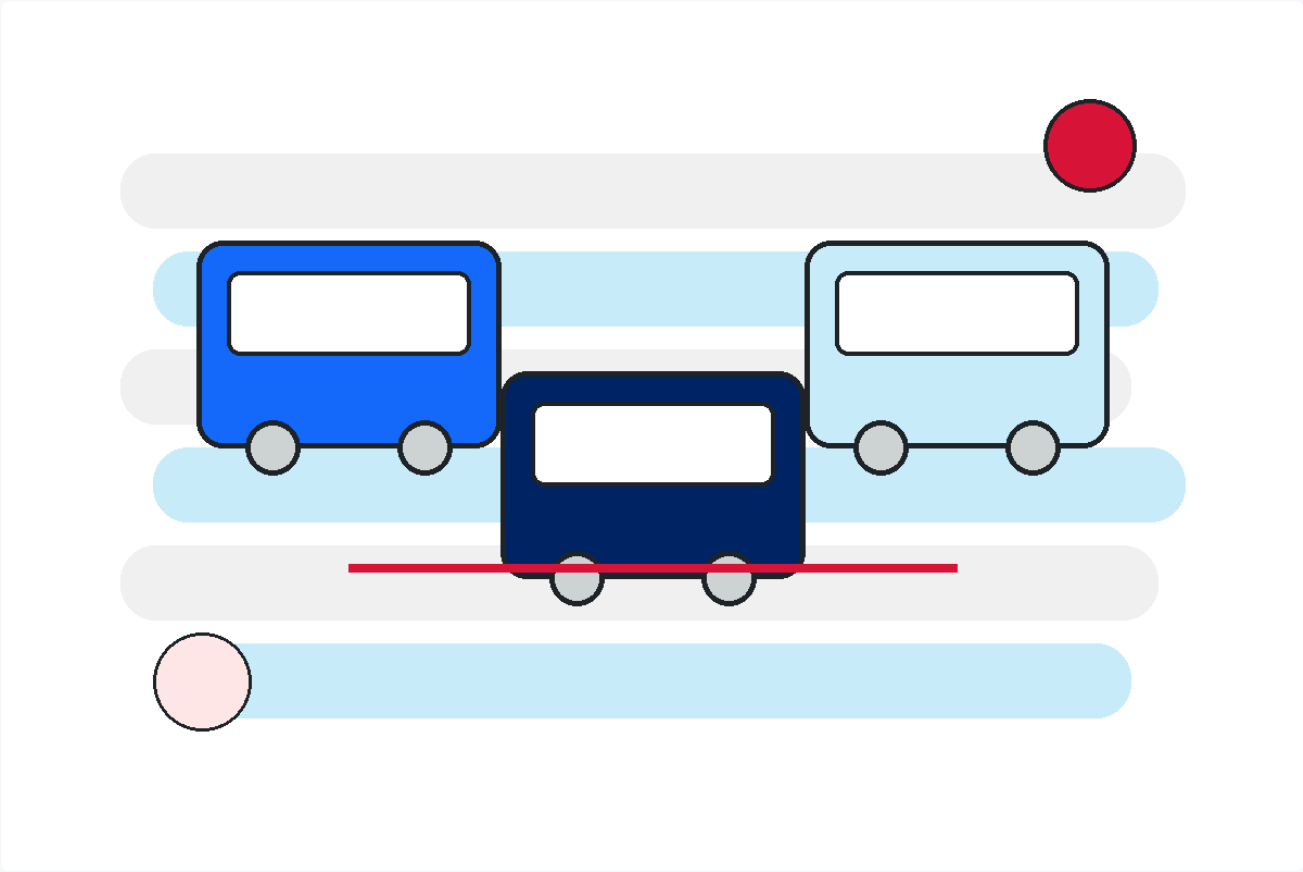
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Core Transport Assets Software & Hardware Tech Playbook: Roads, Trains & Ferries

SCATS 7 DRL, 5G NR-V2X, Compass IoT, GoA4 CBTC, ETCS L2/L3, FRMCS 5G-R, RailBAM, Candela/Artemis Hydrofoils & COLREGs Autonomy

04. Roads & Motorways Software & Hardware Tech Stack Playbook

Prepared for the Architect of Tech — Transport for NSW (TfNSW)



Asset Software & Tech Matrix: Roads, Trains & Ferries

1. Next-Generation Traffic Management & Signal Orchestration

1.1 SCATS Evolution: From Inductive Loops to SCATS 7 & Deep Reinforcement Learning (DRL)

- **Sovereign Heritage:** Invented in NSW (DMR/RTA, now TfNSW) in the 1970s, **SCATS (Sydney Coordinated Adaptive Traffic System)** controls **>65,000 intersections across 180+ cities in 28+ countries** (`https://www.scats.nsw.gov.au/`).
- **Classic SCATS Mechanics:** Sub-surface inductive loop detectors at the stop-line measure *Degree of Saturation (DS)*—the ratio of effectively used green time to total available green time—alongside *reconstituted traffic volume* to dynamically adjust **Cycle Length (C)**, **Phase Splits (g/C)**, and **Subsystem Offsets** between adjacent intersections.
- **SCATS 7 & Multi-Agent Deep Reinforcement Learning (MARL):**

- Next-gen SCATS decouples physical roadside traffic signal controllers from cloud and edge AI optimization engines via open, low-latency APIs.
- Through **iMOVE CRC** and UNSW/USyd research pilots, **Deep Reinforcement Learning (DRL)** agents ingest continuous spatial-temporal trajectories from Connected Vehicles (CAV probes), radar, and computer-vision cameras—seeing approaching platoons *300–500 meters upstream* rather than only at the stop-line loop.
- **Multi-Objective Reward Function:**

$$R_t = -\left(w_1 \sum ext{QueueLength} + w_2 \sum ext{VehicleDelay} + w_3 \sum ext{BusDelay}_{ ext{priority}} + w_4 \sum ext{PedestrianWait} + w_5 \sum ext{CO}_2 ight)$$

- **Verified Metrics:** Classic SCATS reduces travel times by **15–28%**, stops by **20–40%**, and fuel use by **12–15%**; fusing even low-penetration (5–15%) CAV trajectory data with DRL signal control delivers an **additional 10–20% reduction in intersection delay** and **30%+ queue length reduction** during non-recurring incidents.



Hangzhou & Global AI Traffic Orchestration

1.2 Edge-Compute Computer Vision & Surrogate Safety Analytics

- **Roadside Edge Architecture:** Ruggedized industrial AI nodes (**NVIDIA Jetson Orin / Hailo-8**) inside traffic signal cabinets process CCTV, uncooled thermal LWIR, and 4D millimeter-wave (mmWave) radar streams locally (sub-100ms inference, zero cloud video backhaul cost, GDPR/privacy-compliant edge anonymization such as **VivaCity** sensors deployed across NSW).
- **Capabilities:**
- **Proactive Near-Miss Detection:** Instead of waiting 5 years for fatal crashes to accumulate at an intersection to identify a blackspot, edge vision calculates continuous **Surrogate Safety Measures (SSMs)**—specifically **Time-to-Collision ($ ext{TTC} < 1.5 ext{ s}$)** and **Post-Encroachment Time ($ ext{PET} < 1.0 ext{ s}$)** between turning vehicles, cyclists, and pedestrians.

- **Dynamic VRU & Freight Phase Extension:** Automatically extends pedestrian walk phases when an elderly person or wheelchair user (`8-to-80 Cities` design) is still in the crosswalk, or holds a green phase for an approaching 68-tonne B-double freight truck to prevent dangerous hard-braking or red-light running.
- **Tunnel Incident Detection:** Instantaneous detection of stopped vehicles, wrong-way drivers, smoke, or spilled cargo inside **WestConnex, NorthConnex, Sydney Harbour Tunnel, and Western Harbour Tunnel**.

1.3 C-ITS / V2X (5G NR-V2X PC5 Sidelink) & Smart Motorway Algorithms

- **Protocol Evolution:** Moving from IEEE 802.11p / DSRC in the $5.9 ext{ GHz}$ ITS band toward **3GPP Release 16+ 5G NR-V2X**:
- **PC5 Direct Sidelink:** Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) direct radio link with **$<5 ext{ ms}$ latency** that operates even without cellular tower coverage.
- **Uu Cellular Interface:** Long-range Vehicle-to-Network (V2N) cloud broadcasts for regional hazard warnings.
- **Standard Messages:** ETSI ITS-G5 **CAM** (Cooperative Awareness Message), **DENM** (Decentralized Environmental Notification Message), **SPaT** (Signal Phase and Timing — telling the car's dashboard or ADAS the exact countdown to green), and **MAP** (digital intersection topology).
- **NSW Deployment:** TfNSW's **CITI (Cooperative Intelligent Transport Initiative)** in the Illawarra equipped heavy trucks and traffic signals with **Cohda Wireless** V2X units (`https://www.cohdawireless.com/`), backed by Austroads' National C-ITS Public Key Infrastructure (PKI).
- **Smart Motorway Shockwave Damping (M1, M4, M7):**
- Combines **Coordinated Ramp Metering (HERO algorithm)** with **Dynamic Variable Speed Limits (VSL)** to keep mainline density below the critical breakdown threshold ($\sim 28 ext{ veh/km/lane}$ or $\sim 2,000 ext{ veh/hr/lane}$), preventing "phantom traffic jams" (stop-and-go kinematic shockwaves).

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2. Predictive Road Asset Maintenance, Robotics & Smart Pavements

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Highway 15-Second Solar Drone-in-a-Box

2.1 Crowdsourced Connected Vehicle Telemetry (Compass IoT) & Mobile LiDAR

- **Compass IoT (`Pavepoint`) — Sydney Sovereign Innovation:**
- Rather than relying solely on specialized laser survey trucks (**NTRO iPAVE**) that inspect regional roads once every 1–2 years, **Compass IoT** (`https://www.compassiot.com.au/`) ingests high-frequency (1–10 Hz) vertical acceleration (a_z), pitch/roll rates, ABS/ESC activations, and GPS trajectories from hundreds of thousands of everyday connected cars and commercial fleets.
- Normalizing across vehicle suspension classes estimates the **International Roughness Index (IRI, in m/km)** continuously—detecting pothole formation and flood damage within hours of heavy rain across the entire NSW road network.
- **High-Speed Mobile LiDAR & Vision Transformers:**

- Survey vehicles equipped with dual laser scanners (**Riegl VMX / Trimble MX9**, $>2 ext{ million points/sec}$) and downward-facing 4K line-scan cameras run **Mask R-CNN / Vision Transformer** models to classify sub-millimeter alligator cracking, rutting, ravelling, and guardrail/sign retroreflectivity loss automatically into Digital Twin NSW.

2.2 Self-Healing Asphalt & Dynamic Inductive EV Charging Lanes (Electreon)

- **Self-Healing Pavements:**
- *Micro-encapsulated Bio-Rejuvenators:* Polymeric microcapsules mixed into bitumen rupture when micro-cracks form, releasing maltene oils that seal the crack via capillary action.
- *Induction-Heated Conductive Asphalt (TU Delft):* Embedding conductive steel wool fibers into porous asphalt allows a maintenance vehicle carrying an induction coil to heat the binder locally to $85–110^\circ ext{C}$, melting bitumen to close micro-cracks and extending road surface life by **30–50%**.
- **Dynamic Wireless Power Transfer (DWPT — Electreon):**
- Copper induction coils buried $8–10 ext{ cm}$ beneath asphalt (operating at $85 ext{ kHz}$ magnetic resonance per **SAE J2954**) energize only when an authenticated EV bus or heavy truck passes overhead (`https://www.electreon.com/`).
- Deployed in Sweden, Israel, USA (Detroit), Germany, and France's **A10 motorway ($200–300 ext{ kW}$ dynamic transfer)**, allowing heavy electric trucks and buses to downsize onboard batteries by **50–70%**.



Inductive Charging & Smart Pavement Architecture

2.3 Autonomous Roadworks Robotics & Bridge Structural Health Monitoring (SHM)

- **Autonomous Cone Laying Machines (ACLM) & Crack Robots:**
- Automated Cone Trucks (**BladeRunner / Kier / Highways England** and Australian trials) deploy and retrieve traffic cones at $15–20 ext{ km/h}$ via robotic arms, keeping human workers out of live $110 ext{ km/h}$ lanes.
- **Robotiz3d (ARU)** uses stereo vision and 3D LiDAR to autonomously detect, clean, and fill road cracks with bitumen sealant.
- **Structural Health Monitoring (SHM) for Iconic Bridges & Tunnels:**
- **Fiber Bragg Gratings (FBG) & Distributed Strain/Acoustic Sensing (DSS/DAS):** Optical fibers bonded to bridge girders and suspension cables measure wavelength shifts ($\Delta \lambda_B$) to monitor micro-strain ($\mu arepsilon$) and temperature immune to electromagnetic interference.

- **Acoustic Emission (AE) Wire-Break Sensors:** Piezoelectric sensors ($20 ext{ kHz}–1 ext{ MHz}$) detect the exact acoustic elastic wave of a single high-tensile steel wire snapping inside a bridge cable or post-tensioned concrete box girder years before visible structural sagging occurs.
- **UTS Robotics on Sydney Harbour Bridge:** Autonomous climbing grit-blasting robots (**CROC**) inspect and strip lead paint inside confined bridge arches safely.

05. Trains & Rail Systems: Autonomy, Signalling & Predictive Asset Tech Stack

Prepared for the Architect of Tech — Transport for NSW (TfNSW)



GoA4 Metro & Depot Inspection Portal

1. Next-Generation Signalling, Autonomy & 5G-R Communications

1.1 GoA4 Unattended Train Operation (UTO) — Sydney Metro Benchmark

- **IEC 62267 Grades of Automation (GoA):**
- *GoA1:* Manual driving with ATP (Automatic Train Protection).

- *GoA2:* Semi-automatic Train Operation (STO) — ATO drives between stations, driver sits in cab to close doors and handle emergencies (target of Sydney Trains ETCS L2 + ATO).
- *GoA3:* Driverless Train Operation (DTO) — no cab driver, but an onboard attendant operates doors/emergencies.
- *GoA4:* **Unattended Train Operation (UTO)** — 100% autonomous starting, stopping, Platform Screen Door (PSD) synchronization, depot wake-up/sleep, and automated disruption recovery with zero onboard staff.
- **Sydney Metro Architecture (`https://www.sydneymetro.info/`):**
- Powered by **Alstom Urbalis 400 CBTC (Communications-Based Train Control)** across the M1 Metro North West & Bankstown Line (including the twin under-harbour & CBD tunnels opened August 2024), Sydney Metro – Western Sydney Airport, and Sydney Metro West.
- **Capacity Advantage:** Achieves **115-second (sub-2-minute) theoretical headways**, moving **40,000 to 60,000 passengers per hour per direction (pphpd)**—equivalent to **25 to 30 highway lanes** of private car traffic in a single rail tube!



Shenzhen & Global GoA4 Autonomous Metro

1.2 ETCS Level 2, Level 3 (Moving Block) & Virtual Coupling

- **ETCS Level 2 (Sydney Trains Digital Systems Program):**
- Replaces legacy trackside colour-light signals and electromechanical relays across the Sydney suburban heavy rail network with in-cab **Driver Machine Interface (DMI)** screens, sleeper-mounted **Eurobalises** for exact odometry calibration, and continuous **Movement Authorities (MAs)** from a Radio Block Centre (RBC).
- Paired with **ATO over ETCS (GoA2)**, reduces minimum safe headways by **25–33%** (increasing line capacity from 20–24 trains per hour to **30+ trains per hour** on existing double-track corridors without digging new tunnels).
- **ETCS Level 3 (Full Moving Block):**

- Eliminates expensive trackside axle counters and track circuits altogether by placing **Train Integrity Monitoring Systems (TIMS)** onboard the train to verify continuously that the train is complete. Safe separation shrinks to the exact dynamic braking curve of each train.
- **Virtual Coupling (Train-to-Train V2X):**
- Moving block still assumes the leading train could stop instantaneously ("brick-wall assumption"). **Virtual Coupling** uses ultra-low-latency direct **Train-to-Train (T2T) 5G sidelink** so the trailing train tracks the leading train's real-time velocity and braking rate—allowing two trains to travel **meters apart at $130 ext{ km/h}$** on a trunk line and dynamically split at a junction switch without stopping, serving two different outer-suburban branches!

1.3 FRMCS (Future Railway Mobile Communication System — 5G-R)

- Standardized by **UIC** and **3GPP (Releases 16–19)** to replace sunsetting 2G **GSM-R** globally between 2026 and 2035 (`https://www.uic.org/rail-system/telecoms-signalling/frmcs`).
- Uses a dedicated **5G Standalone (SA) Core** with **Network Slicing** and **MCX (Mission-Critical Push-to-Talk, Video, and Data)** delivering **99.9999% Ultra-Reliable Low-Latency Communication (URLLC)**.
- Enables simultaneous SIL-4 ETCS signalling packets, live forward-facing 4K camera + LiDAR obstacle detection streaming from GoA4 trains, and gigabit wayside telemetry offloading at station stops.

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2. Predictive Rail Asset Maintenance & Autonomous Robotics



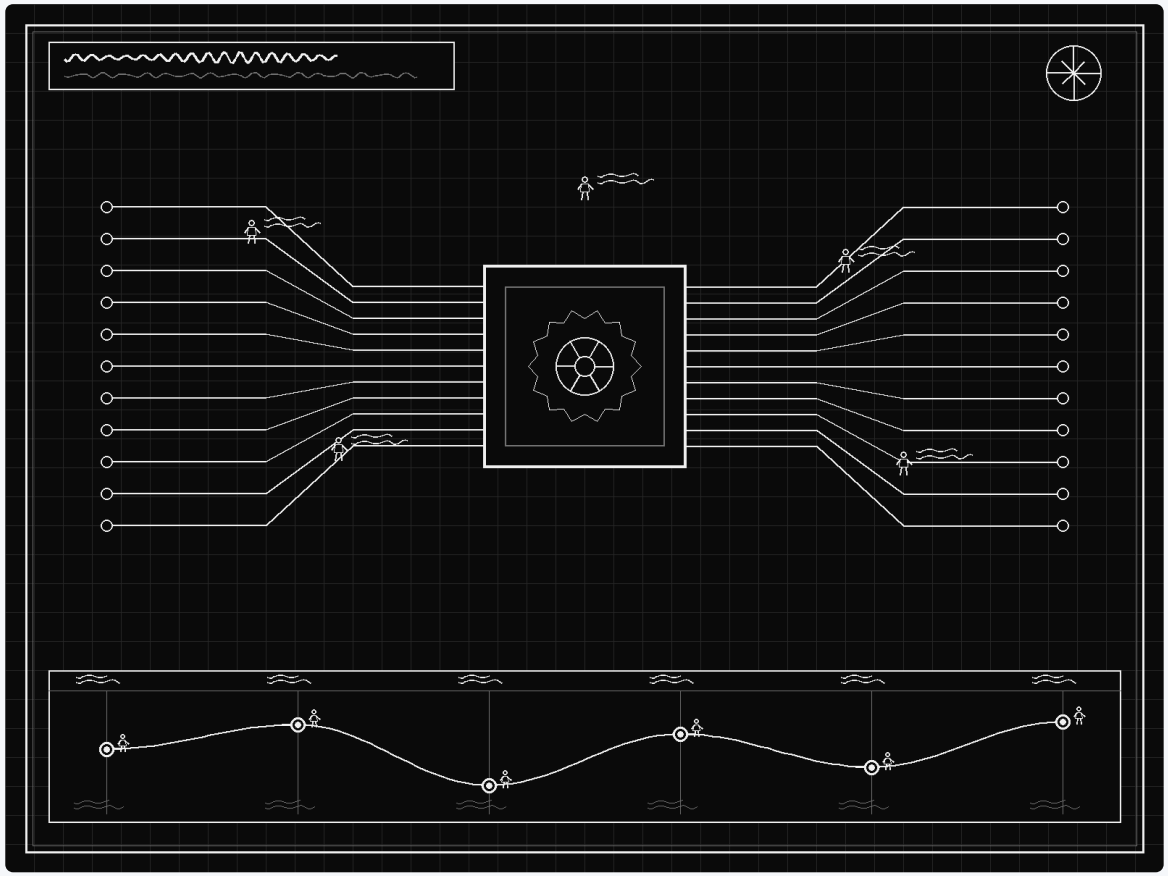
2,200-Sensor Bogie & Predictive Telemetry

2.1 Wayside Acoustic Bearing Detection — RailBAM (Australian Sovereign Innovation!)

- **The Physics & Advantage:** Developed in Australia by **Trackside Intelligence (Track IQ)** (now part of **Wabtec**), **RailBAM (Railway Bearing Acoustic Monitor)** uses wayside phased-array microphones positioned beside the rail to analyze the acoustic signature of every wheel bearing passing at revenue speed ($40–160+ ext{ km/h}$).
- **Why It Beats Hot-Box Detectors:** Legacy infrared Hot-Box Detectors (HBDs) only trigger when a bearing is already overheating near catastrophic seizure (leaving minutes before a derailment). RailBAM isolates subtle acoustic frequency harmonics—**Ball Pass Frequency Outer race (BPFO), Inner race (BPFI), and roller flats**—detecting bearing degradation **months or tens of thousands of kilometers before thermal failure**.

2.2 DAS Dark Fibre, Zero-Spark Rail Milling & High-Speed Inspection Cars

- **Distributed Acoustic Sensing (DAS) on Dark Fibre:** Connecting an optoelectronic interrogator to existing dark telecom fibre alongside Sydney Trains tracks turns $50 ext{ km}$ of fibre into $5,000+$ virtual microphones—detecting rail breaks, wheel flats, rockfalls on the South Coast/Blue Mountains lines, and copper cable thieves in real time.



DAS Dark Fibre & Zero-Spark Rail Milling

- **Automated Track & Overhead Wiring (OHW) Vision:** High-speed inspection cars (**Plasser & Theurer / MERMEC**) and in-service passenger trains fitted with roof-mounted 3D laser profilers, phased-array ultrasonics, Ground Penetrating Radar (GPR for ballast fouling), and UV/thermal pantograph cameras detect catenary wire wear and internal rail head cracks at $120+ ext{ km/h}$.
- **Laser Rail Cleaning & Zero-Spark Milling:** High-power laser trucks vaporize autumn leaf-film contamination on rail heads (eliminating wheel slip), while automated zero-spark milling trains reprofiling corrugated rails inside tunnels without bushfire or dust ignition risks.



Laser Rail Head Treatment & Track Robotics

2.3 Quadruped Depot Robots (Spot / ANYmal) & GPS-Denied Tunnel Drones (Elios 3)

- **Boston Dynamics Spot & ANYbotics ANYmal in Depots:** Autonomous four-legged robots patrol maintenance pits beneath stabled trains, using thermal cameras (spotting overheated brake calipers/bearings), acoustic cameras (**Fluke Sorama** localizing compressed-air leaks), and computer vision to verify cotter pins and oil levels.
- **Flyability Elios 3 LiDAR Drone (`https://www.flyability.com/elios-3`):** Collision-tolerant geodesic cage drone carrying an **Ouster OS0-128 LiDAR** and **FlyAware SLAM** engine. Flies inside pitch-black, GPS-denied rail tunnels, drainage culverts, and bridge box girders to build millimeter-accurate 3D crack maps without track possessions or scaffolding.



Tunnel LiDAR Drone & UVC Sanitation

3. Energy Recovery, Discontinuous Electrification & AI Disruption Solvers

- **Wayside Battery Energy Storage (WESS) & Inverting Substations (Alstom HESOP / ABB Enviline):** Captures **95–99% of regenerative braking energy** from decelerating trains in $1500 ext{ V DC}$ traction networks, either storing it in wayside Lithium-Titanate (LTO) batteries for the next accelerating train or inverting it back to the AC grid—cutting net traction electricity bills by **15–30%** and reducing tunnel heat.
- **Battery-Electric Multiple Units (BEMUs — Stadler FLIRT Akku / Alstom Coradia Stream):** Charge batteries while running under existing Sydney Trains $1500 ext{ V DC}$ catenary and run $80–150 ext{ km}$ on non-electrified regional branches (e.g., Hunter Valley, Southern Highlands, South Coast beyond Kiama)—avoiding the $\$3 ext{M}–\$6 ext{M per track-km}$ cost of stringing overhead wires under heritage bridges.

- **MILP + Graph Neural Network (GNN) Disruption Recovery:** Solves conflict-free train re-routing, platform assignment, and crew legalities across the Rail Operations Centre (ROC) in **$<15 ext{ seconds}$**, slashing knock-on passenger delays by **30–50%**.

06. Ferries & Maritime Tech Stack: Autonomy, Hydrofoils & Smart Wharves

Prepared for the Architect of Tech — Transport for NSW (TfNSW)



Candela Electric Hydrofoil Ferry

1. Zero-Wake Electric Hydrofoils & Next-Gen Propulsion

1.1 The Physics Problem of Conventional Ferries in Sydney Harbour & Parramatta River

Conventional displacement or planing catamaran ferries suffer from massive hydrodynamic wave-making and skin-friction drag that scales exponentially with speed ($P \propto v^3$). This creates two major operational barriers for **Sydney Ferries**:

- **Destructive Riverbank Wake:** Along the **Parramatta River** (F3 route), conventional ferries must slow down in upper river sections to prevent wake waves from eroding riverbanks and damaging pontoons, lengthening commuter journey times.
- **Massive Battery Weight Penalty:** Electrifying a conventional displacement ferry requires $1.5–4 ext{ MWh}$ of heavy lithium-ion batteries, demanding multi-megawatt shore substation upgrades.

1.2 Computer-Stabilized Electric Hydrofoils (Candela P-12 & Artemis EF-24)

By mounting submerged **carbon-fiber wings (hydrofoils)** beneath the hull controlled by an avionics-style **Digital Flight Controller updating foil ailerons at 100 Hz** using bow ultrasonic/laser ride-height sensors and Inertial Measurement Units (IMUs), the ferry lifts entirely above the water surface at $16–18 ext{ knots}$:

Vessel Platform	Capacity & Speed	Energy & Wake Performance	Relevance to Sydney Ferries	Reference URL
Candela P-12 Shuttle *(Sweden — deployed in Stockholm Public Transit)*	**30 passengers** (bicycles/wheelchairs step-free) **25–30 knots** ($46–55 ext{ km/h}$)	**-80% energy consumption** per pax-km vs. diesel ferries ($252 ext{ kWh}$ battery, $40–50 ext{ NM}$ range). **$<15 ext{ cm}$ wake height** (exempt from Stockholm speed limits!). Charges via standard $175–200 ext{ kW}$ CCS automotive fast charger.	Ideal for high-frequency **Parramatta River**, **Lane Cove River**, and cross-harbour on-demand shuttle routes—halving travel times with zero riverbank erosion.	https://candela.com/
Artemis EF-24 Passenger *(UK / Belfast — Condor / Orkney deployments)*	**150 passengers** $24 ext{ m}$ foiling catamaran **38 knots max / 25–32 knots cruise**	**85–90% energy/fuel savings**, $115 ext{ NM}$ range, powered by patented **Artemis eFoiler®** high-voltage electric propulsion pods. Actively dampens pitch and roll in rough seas.	Sized for high-volume exposed crossings such as **Manly–Circular Quay (F1)** (cutting crossing time to ~14 minutes with zero seasickness roll across Sydney Heads!).	https://www.artemistechnologies.co.uk/



Wind-Foil & Zero-Emission Sydney Ferry Concept

2. COLREGs-Compliant Maritime Autonomy & Auto-Docking

2.1 Multi-Sensor Fusion in Busy Mixed-Traffic Waterways

Operating autonomous or semi-autonomous vessels (IMO **MASS Degrees 1–4**) in **Sydney Harbour** requires navigating around cruise ships, sailing yachts, water taxis, unlit kayaks, and marine life while strictly obeying **IMO COLREGs (International Regulations for Preventing Collisions at Sea)**:

- **Perception Stack:**
- **Solid-State X-Band & 77 GHz W-Band Millimeter-Wave Marine Radar:** Long-range ($5 ext{ NM}$) and ultra-precise near-field ($1–300 ext{ m}$) velocity tracking.
- **3D Marine LiDAR + Stereo RGB Optical Arrays:** High-resolution point clouds of wharf pilings and vessel silhouettes.

- **Cooled/Uncooled LWIR Thermal Imaging:** Crucial for detecting **unlit kayakers, paddleboarders, swimmers, or floating timber** in night/fog/glare conditions where radar cross-section is near zero.
- **AIS, VHF & GNSS-RTK / Photonic INS (Advanced Navigation):** Centimeter-level heading and dead-reckoning even under the steel deck of the Sydney Harbour Bridge.

2.2 Global & Sovereign Australian Maritime Autonomy Leaders

- **Greenroom Robotics (Sydney, NSW & Fremantle, WA — `https://www.greenroomrobotics.com/`):**
- Sovereign Australian maritime AI pioneer. Develops **GAMA (Greenroom Advanced Maritime Autonomy)** and **Lookout+**, an edge-AI optical/thermal/radar collision-avoidance and situational-awareness co-pilot trialed on Royal Australian Navy vessels and commercial passenger ferries.
- **Immediate TfNSW Quick Win:** Retrofitting **Lookout+** onto existing Emerald-class, Freshwater-class, and River-class Sydney Ferries gives human masters 360° AI blind-spot alerts for kayaks and small craft around Circular Quay today.
- **Zeabuz (Norway/Sweden — `https://www.zeabuz.com/`):**
- Spin-off from NTNU (creators of *milliAmpere*). Powers the commercial **MF Estelle** autonomous electric passenger ferry in central **Stockholm** (operated by Torghatten), crossing Riddarfjärden autonomously with automated docking and remote shore supervision.
- **Kongsberg Maritime (*Yara Birkeland* & Norwegian Fjord Ferries — `https://www.kongsberg.com/maritime/`):**
- Deployed the world's first autonomous electric container ship (*Yara Birkeland*) and **Auto-Crossing / Auto-Docking** systems on Norwegian electric car/passenger ferries (*Bastø Fosen*).



Norwegian Zero-Emission Autonomous Ferry

3. Smart Wharves: Automated Vacuum Mooring, MCS Battery Buffering & Hull ROVs

3.1 Model Predictive Control (MPC) Auto-Docking & Vacuum Mooring

- Manual docking at Circular Quay or Manly in strong crosswinds and prop-wash accounts for up to **25–35% of a ferry's total trip fuel/energy burn** and causes the majority of fender/wharf wear.
- **MPC Auto-Docking** fuses RTK-GNSS and wharf LiDAR fiducials to command azimuth thrusters smoothly to centimeter precision.
- **Cavotec MoorMaster™ / Trelleborg AutoMoor:** Shore-mounted robotic vacuum pads or magnetic arms extend and lock onto the ferry hull in **$<10 ext{ seconds}$**, eliminating manual rope handling, cutting wharf turnaround time by **2–4 minutes per stop**, and automatically mating the shore charging plug.

3.2 Megawatt Charging Systems (MCS) with Pontoon Battery Buffering

- High-capacity electric ferries require **$1.5 ext{ MW to }4.5 ext{ MW}$** charging bursts via **CharIN MCS** or robotic pantographs (**Cavotec PowerAlign, ABB Shore Connection, Zinus**).
- To avoid overloading inner-Sydney distribution substations (Ausgrid) at Circular Quay, Balmain, or Parramatta, smart wharves house **1–3 MWh Stationary Lithium-Iron-Phosphate (LFP) Battery Buffers** inside the floating concrete pontoon—trickle-charging continuously at $250 ext{ kW}$ from the street grid and discharging at $2.5 ext{ MW}$ during 5-minute passenger boarding.

3.3 Underwater Inspection & Hull-Cleaning ROVs

- Marine biofouling (barnacles and slime on ferry hulls) increases hydrodynamic drag and energy consumption by **15–30%**.
- Micro-ROVs (**Reach Robotics** in Sydney, **Blueye**, **Deep Trekker**) and magnetic hull-crawling grooming robots (**HullWiper, Armach Robotics**) use **multibeam imaging sonar (Blueprint Subsea Oculus)** and cavitation waterjets to inspect wharf pilings and clean ferry hulls overnight at the shipyard without commercial diver hazards or dry-docking.