Table of Contents

8. Conclusions

8.1 Achievements

The CONNECT and share project successfully demonstrated the feasibility of transforming a standard metro carriage into a participatory space, counteracting digital isolation through ambient light interaction and asynchronous text messaging. Evaluated against the core objectives defined in Section 1.4, the primary functional milestones were achieved within the scope of the development environment.

The technical core of the distributed network was validated. The implemented two-node benchtop prototype proved the viability of pressure detection via custom air-gap Velostat sensors, bidirectional CAN bus communication between standard ESP32 nodes, and real-time RGB LED feedback via a 1-meter Seeed WS2813 strip. The ADC infrastructure mapped the compression curves reliably, and the CAN network achieved a 100% packet delivery ratio under laboratory conditions. Although the physical calibration potentiometer was bypassed for a optimized fixed resistor in the final bench layout, the stateless, interrupt-driven firmware architecture was fully validated, demonstrating correct deep-sleep transitions and the capacity to scale to an 11-node network without firmware modifications.

Key performance and structural metrics were successfully satisfied. End-to-end latency from initial touch to LED response was verified below the 100 ms threshold. While high-voltage rails were omitted from the bench setup, the continuous 5V loop maintained an end-of-line voltage above 4.7V under full load, with the enclosure surface temperature remaining safely below 50 °C. Structural safety was verified through Finite Element Analysis (FEA) within SimScale, confirming that peak Von Mises stresses under a 100 N force vector remain securely below the elastic yield threshold of the polymer.

Software testing passed in full validation. CAD integration models confirmed zero mechanical interference between components while maintaining the target 5 mm clearance. In software simulations, the CAN arbitration logic correctly prioritized critical node IDs during forced frame collisions, and the animation algorithms ran continuously for 24 hours without memory leaks or buffer overflows. Additionally, the heartbeat timeout detection logic triggered within 500 ms of a simulated CAN failure, successfully switching the LED output to a static safety white state.

The web platform reached a fully deployable state. The Supabase database and Next.js backend demonstrated high scalability during load testing, sustaining 1000 concurrent requests with a zero error rate and a mean write latency of 195.77 ms. All five Jest unit test cases covering the API routes passed successfully in 0.277 seconds.

The System Usability Scale (SUS) evaluation yielded an “Excellent” mean score of 86.59 across 11 participants, proving the interface is highly intuitive. User acceptance testing (UAT) confirmed that non-technical participants successfully identified the interaction zones without instructions, reported no glare or eye strain under the diffuser profile, correctly associated the light animations with the system states, and successfully triggered the interaction across a wide range of tested heights and hand strengths.

The complete physical prototype was delivered within the 100 EUR budget constraint at a total cost of 97.92 EUR.

8.2 Limitations

As a deliberate functional reduction for laboratory validation, several gaps remain between the ideal designed solution and the implemented prototype:

- **Network Scale:** The prototype was restricted to a two-node configuration on a single handrail segment. While this validated the protocol loop, it did not fully exercise bus arbitration under simultaneous multi-node transmissions at a full 11-node carriage scale.
- **Signal Mismatch and Artifacts:** The visual feedback subsystem suffered from high-frequency flickering during idle states. This was isolated to a logic-level mismatch, as the ESP32 GPIO operates at 3.3V CMOS, while the Seeed WS2813 LED strip requires a minimum input high threshold (VIH) of 3.5V when powered at 5.0V.
- **Material and Fire Safety Compliance:** Due to budget restrictions, fire-rated Nanovia PA Rail enclosures, LSHF cabling, and specific railway testing (such as continuity tests, 5 kg impact tests, and cleaning mist exposure) could not be physically executed. The prototype relied on standard 3D-printed PLA, meaning compliance against the EN 45545-2 railway flammability matrix remains pending.
- **Power Architecture Simplification:** The dual-rail (12V + 5V) distribution network and its six decentralized step-down switching converters were replaced by a single 5V bench supply. The empirical behavior of the power network under worst-case current draws across all eleven nodes remains unverified.
- **Real-World Behavior Testing:** Phase 2 (the text platform) was evaluated via isolated load tests and usability surveys, but end-to-end passenger behaviors—such as QR code discovery at exit doors and the intentional interaction delays—were not observed within a realistic transit environment.

8.3 Future Development

Future iterations must focus on transitioning the validated benchtop architecture into a rail-compliant deployment:

- **Hardware Sizing and Signal Optimization:** Incorporating a dedicated hardware logic-level shifter (such as the 74HCT125) is required to step the ESP32 data lines up to 5.0V, permanently eliminating LED flickering. Additionally, physical 10 kΩ calibration potentiometers should be populated onto custom Sensor Node PCBs to enable manual threshold adjustments.
- **Full Network and Power Scaling:** Fabricating the full 11-node network is necessary to stress-test simultaneous CAN bus collisions. This must be paired with the implementation of the designed dual-rail power architecture to verify voltage drop stability along the full multi-strip framework under full white load.
- **Regulatory Manufacturing:** Future enclosures must be fabricated using Nanovia PA Rail or equivalent EN 45545-2 certified polymers. Physical testing for electrical continuity (below 0.1 Ohm), impact resistance, and ingress protection (IP) must be conducted using these production-grade materials.
- **Transit Pilot and Social Impact:** Deploying the prototype or the recycled cork “Social Hub” packaging modules within a controlled transit mockup or station concourse will allow for the validation of passenger flows, QR discovery mechanics, and content moderation pipelines under realistic conditions. Collecting a longitudinal dataset from these interactions will provide quantitative grounding for the project's long-term social impact claims.
- **Sensor Integration:** Future iterations should implement the biometric heart-rate sensing

arrays and auditory feedback channels outlined in the original scope to enrich the inclusive interaction model.