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Advanced Traffic Pole Upgrade Module (ATPUM)

A Comprehensive Study on Hardware Design and System Operation
Flowchart for Real-Time Hazard Detection and Warning

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ABSTRACT:

Pedestrian safety remains a significant challenge within Finnish urban infrastructure, exacerbated by harsh Nordic winters that frequently lead to hazardous road conditions. Addressing this critical issue, this thesis proposes an Advanced Traffic Pole Upgrade Module (ATPUM), designed as a retrofit solution for existing traffic poles, integrating smart sensors and proactive alert systems for real-time hazard detection. The research adopts a constructive approach, emphasizing the selection and integration of robust hardware components through rigorous Multi-Criteria Decision Analysis (MCDA), primarily the Weighted Scoring System and Analytic Hierarchy Process (AHP). A high emphasis (weighted at 0.99) was placed on temperature tolerance during component evaluation, ensuring the system's functionality and reliability in sub-zero Finnish conditions. The study presents two conceptual designs along with a detailed operational flowchart that delineates ATPUM's intelligent hazard detection and alert logic. Although constrained by theoretical scope and limited resources, this work contributes significantly to future practical implementations aimed at enhancing pedestrian safety. The author expresses sincere gratitude to Olli Rossi, Head of Unit for Traffic Lights and Automated Speed Enforcement at Fintraffic, and Passi Ikonen, Electronics B2B & Embedded System Design Manager at InnoTrafik Oy, for their valuable industry insights during the initial phases of the project, as well as to thesis supervisor Professor Tauno Kekäle for his continuous support and expert guidance throughout the research process.

KEYWORDS: Pedestrian Safety, Preventive Road Safety Systems, Smart Traffic Poles, Real-Time Hazard Detection, Advanced Traffic Infrastructure.

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1 Introduction

Road safety remains a critical concern globally, with Finland experiencing particular challenges due to its harsh weather conditions, including icy roads, poor visibility, and prolonged winter seasons. According to Statistics Finland (2024), approximately 3,500 individuals are injured annually in traffic-related incidents, highlighting a significant public safety concern. Furthermore, data from the Finnish Crash Data Institute (OTI, 2024) indicates that pedestrians and cyclists constitute over half of urban traffic fatalities, while Liikenneturva (2024) reports that one in every ten road traffic fatalities involves pedestrians.

Given these alarming statistics, there is an urgent need for innovative, proactive measures to safeguard pedestrians and vulnerable road users. Traditional traffic safety systems predominantly rely on reactive measures, addressing issues post-incident rather than preemptively mitigating hazards. To address this limitation, there is a substantial opportunity to integrate advanced technological solutions within existing infrastructure to enhance real-time hazard detection and prevention capabilities.

This thesis proposes the design and integration of an Advanced Traffic Pole Upgrade Module (ATPUM), which retrofits existing traffic poles with smart sensor technologies to actively detect hazards and provide immediate warnings. The core aim of ATPUM is to shift traffic management from reactive to preventive safety practices, significantly reducing accident risks before incidents occur. By implementing sensor-enabled hardware and developing an optimized system operation flowchart, ATPUM targets real-time hazard detection, enabling instant communication of risks to pedestrians through innovative alert mechanisms.

The motivation behind this research is twofold. Firstly, it addresses an evident societal need for improved pedestrian safety measures, particularly in Finnish urban environments frequently challenged by adverse weather conditions. Secondly, it aligns

with Finland's broader vision of enhancing road safety through the integration of smart infrastructure solutions.

The primary research question guiding this thesis is: How can hardware design and system operation flowcharts for retrofitting existing traffic poles with advanced sensors and technologies be developed to ensure real-time hazard detection and maximize pedestrian safety within Finland's road infrastructure?

To systematically approach this overarching question, the thesis will pursue the following specific objectives:

- a. Identify key hardware components essential for retrofitting existing traffic poles to enable real-time hazard detection.
- b. Investigate the integration process of advanced sensors into existing traffic pole structures to optimize pedestrian safety.
- c. Determine relevant design constraints and standards, such as durability, energy efficiency, and scalability, critical to developing the ATPUM.
- d. Develop a comprehensive operational flowchart outlining the system's hazard detection, warning processes, and communication protocols.
- e. Analyze potential implementation challenges within Finland's existing traffic infrastructure, with a particular emphasis on applicability in the city of Vaasa.

Through addressing these objectives, this thesis aims to contribute a scalable and forward-looking solution to Finland's urban traffic safety landscape, ultimately protecting pedestrians and fostering safer communities.

2 Theoretical Framework and Literature Review

2.1 Introduction to the Literature Review

This chapter presents an overview of existing academic, technical, and regulatory literature relevant to the development of the Advanced Traffic Pole Upgrade Module (ATPUM). It critically analyzes current pedestrian safety challenges, explores technological innovations such as smart sensors and AI-driven systems, and evaluates regulatory frameworks in Finland to determine practical constraints. The purpose is to identify gaps in the existing body of knowledge and justify the need for ATPUM as a scalable and preventive solution in urban traffic safety infrastructure.

2.2 Road Safety and Pedestrian Vulnerability

Road safety is a global concern, particularly for vulnerable road users like pedestrians and cyclists. In the Finnish context, this concern is underscored by alarming statistics. According to Statistics Finland (2024), approximately 3,500 individuals are injured in traffic accidents annually. Moreover, more than 50% of urban traffic fatalities involve pedestrians or cyclists (Finnish Crash Data Institute [OTI], 2024), and one in every ten road traffic fatalities is a pedestrian (Liikenneturva, 2024). These figures highlight the inadequacy of current reactive safety strategies and underline the urgent need for preventive, real-time hazard detection systems tailored to urban environments.

2.3 Technological Approaches to Road Safety

The integration of smart technologies into transportation infrastructure is transforming traditional safety practices. Artificial intelligence (AI), machine learning, and computer vision are increasingly used to detect pedestrian movement, predict hazardous interactions, and provide timely alerts (Hasan, (2020); Pourhomayoun & Shaked, 2021). For instance, AI-powered systems can utilize real-time camera data to identify near-miss

incidents or risky pedestrian behaviors, allowing preemptive alerts before accidents occur.

Furthermore, research has emphasized the role of context-aware systems in enhancing pedestrian safety. Zhang, Qian, and Liu (2021) proposed a deep learning framework that accurately predicts pedestrian hazards in real time by analyzing traffic patterns and visual cues. Such studies demonstrate the practical feasibility of using AI to prevent accidents and support the transition from reactive to preventive traffic safety systems.

2.4 Advanced Sensor Technologies

Sensor technologies, particularly thermal imaging, are pivotal in ATPUM's design due to their ability to function under diverse environmental conditions and protect user privacy. Thermal sensors detect infrared radiation rather than visible light, enabling accurate detection of human presence and posture even in low-light scenarios (Guo et al., 2023). Compared to RGB cameras, thermal sensors are less intrusive and are compliant with European privacy regulations such as the General Data Protection Regulation (GDPR).

Guo et al. (2023) introduced a benchmark for posture detection using thermal images and validated its efficacy for public safety applications. Their results indicated that deep learning models like YOLOX and TOOD could effectively classify postures in real time, even with reduced resolution and visual cues. These findings validate ATPUM's sensor selection strategy and support its goal of providing continuous and privacy-preserving hazard monitoring.

2.5 Current Traffic Management Regulations and Policies in Finland

Smart traffic solutions must comply with local infrastructure standards and legal regulations. The Finnish Transport Infrastructure Agency (FTIA) has issued guidelines such as SFS-EN 50556 (road traffic signal systems) and SFS-EN 40 series (structural standards for lighting poles), which define critical design requirements (FTIA, 2022).

These include material specifications, environmental tolerance, mounting methods, and safety certifications.

Additionally, the Infra 2015 Measurement Instructions and FTIA (2022b) documents on temporary traffic arrangements emphasize strict adherence to structured maintenance procedures. Such standards are critical for ensuring compatibility between ATPUM components and existing urban infrastructure. They also reinforce the need for modular and regulation-compliant designs that avoid costly full-system replacements.

2.6 Implementation Challenges and Considerations

Despite technological readiness, several challenges hinder the widespread adoption of smart traffic systems. Environmental robustness is a major concern, especially in Nordic regions where snowfall, low temperatures, and limited daylight hours affect sensor accuracy and system durability. Furthermore, system integration, energy efficiency, public acceptance, and cost remain significant barriers (Neirotti et al., 2014).

The deployment of new technologies also requires substantial cross-sector collaboration between municipalities, transport authorities, and technology providers. As highlighted by Anthopoulos (2017), retrofitting smart systems into existing cities demands flexibility, interoperability, and user-centered design approaches. Therefore, ATPUM must be designed not only for technical performance but also for ease of integration, sustainability, and long-term maintenance.

While this thesis makes every effort to align the ATPUM design with relevant Finnish and European standards, it is important to note a key limitation in accessing complete versions of certain technical specifications. Standards such as SFS-EN 50556 (general requirements for road traffic signal systems) and the SFS-EN 40 series (covering structural safety for lighting columns) are not publicly available in full and typically require institutional or paid access. As a result, this study has relied on publicly accessible summaries, government guidelines, and secondary interpretations (e.g., FTIA technical

documents) to inform the design framework. This limitation is acknowledged, and it is recommended that future development phases, particularly any engineering implementation involve a detailed review of these standards through authorized institutional channels.

2.7 Gap in Literature and Research Contribution

While existing literature has thoroughly explored individual aspects of pedestrian safety, smart traffic technologies, and AI-based hazard detection, limited research addresses the practical integration of preventive technologies into existing urban infrastructure. Most smart pole projects are designed for new infrastructure developments, ignoring the vast number of existing traffic poles that could be retrofitted for a fraction of the cost (Anthopoulos, 2017; European Commission, 2023).

Additionally, few studies combine hardware engineering, regulatory compliance, and system flow design into a comprehensive framework for preventive safety applications. This thesis addresses that gap by proposing ATPUM — a retrofitting module for traffic poles that integrates thermal imaging, AI-driven posture analysis, and smart projection and alert systems. The proposed design is not only aligned with Finnish infrastructure policies but also addresses the national priority of enhancing pedestrian safety under Vision Zero goals (European Commission, 2023).

Through a unique combination of literature-backed sensor selection, system architecture development, and policy-oriented design thinking, ATPUM contributes to both theoretical advancement and practical implementation of smart urban safety infrastructure.

3 Research Methodology

3.1 Research Design and Approach

This thesis adopts the constructive research approach, a methodology focused on solving practical problems by constructing and conceptually testing new solutions (Kasanen, Lukka, & Siitonen, 1993). The study is rooted in the real-world need for proactive pedestrian safety measures and seeks to design a modular system that can be retrofitted into existing infrastructure. This study is aimed at developing and evaluating a theoretical framework for the Advanced Traffic Pole Upgrade Module (ATPUM). The research does not include the construction or deployment of a physical prototype, primarily due to resource constraints. While physical implementation is beyond the scope, the study constructs design alternatives, evaluates them using analytical tools, and simulates their operation via system logic models. It focuses on a comprehensive review of relevant literature, regulatory frameworks, and technical specifications to propose a feasible and scalable design model for ATPUM.

The methodology is structured around functional requirement development, comparative technology analysis, and conceptual hardware system design. Through functional decomposition, Multi-Criteria Decision Analysis (MCDA), and SWOT analysis, the thesis explores potential sensor technologies, integration strategies, and flowchart logic required for effective real-time hazard detection. This method ensures that each decision, from hardware selection to functional mapping, is logically aligned with practical needs, regulatory constraints, and the Finnish environmental context.

3.2 Functional Requirements Identification

Functional requirements for ATPUM were derived from multiple sources, including national traffic safety statistics, stakeholder insights (such as discussions with representatives from FinTraffic and InnoTrafik Oy), and the technical standards provided by the Finnish Transport Infrastructure Agency (Väylävirasto) and Traficom. These

requirements reflect societal safety demands, environmental challenges, and infrastructure constraints prevalent in Finnish urban areas, particularly in winter climates.

A structured functional diagram was created to map these needs into core requirements. Five primary Functional Requirements (FRs) were identified:

- I. FR1: Ensure Safety
- II. FR2: Ensure Durability & Maintenance Ease
- III. FR3: Optimize Cost & Scalability
- IV. FR4: Ensure Data Privacy & Cybersecurity
- V. FR5: Ensure Standard Compliance & Modularity

Each FR is linked with clearly defined Design Parameters (DPs), guiding the selection and evaluation of technical components such as thermal sensors, housing structures, alert systems, and regulatory adaptations. The functional diagram forms the backbone of the conceptual design process. Figure 1 illustrates the developed functional diagram for ATPUM, mapping the main functional requirements to their corresponding design parameters.

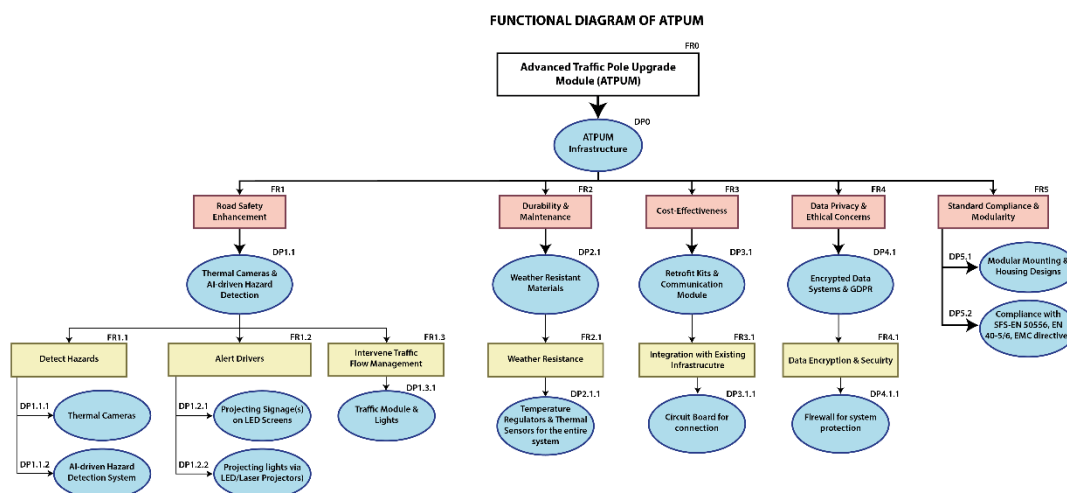


Figure 3.1: Functional Diagram of ATPUM: Mapping Functional Requirements to Design Parameters.

3.3 Design Parameter Development

Each Design Parameter (DP) was developed to align with a specific Functional Requirement, focusing on technical feasibility, integration potential, and compliance with known regulatory standards. For instance, DP1.1 involves using thermal imaging sensors combined with AI-driven algorithms to achieve real-time pedestrian hazard detection, directly supporting FR1: Ensure Safety. Similarly, DP3.1 emphasizes cost-efficient scalability, ensuring that ATPUM remains viable for widespread adoption across multiple Finnish cities.

A key component of the methodology was the inclusion of DP5.1 (Modular Mounting & Housing Design) and DP5.2 (Compliance with Finnish and European standards) under FR5. These parameters ensure the system can be adapted to various existing traffic pole types without requiring full structural replacement. Specific reference is made to:

- I. SFS-EN 50556 – General requirements for road traffic signal systems
- II. SFS-EN 40-5/6/7 – Structural and safety standards for steel, aluminum, and composite lighting columns

However, the full technical content of these standards is not freely available to the public, and access was limited during this study. Therefore, while every effort was made to interpret these requirements using summaries, government documents, and secondary sources (e.g., Väylävirasto technical guides), detailed specifications such as tolerances or certified procedures may not be fully reflected in the proposed design. This limitation is acknowledged in the methodology, with the understanding that future engineering implementation should revisit these documents in full through authorized institutional access or procurement.

Recent research demonstrates that AI-based real-time hazard detection systems have already been developed and deployed successfully. For example, Pourhomayoun (2024) presented a fully functional end-to-end system that detects and reports near-miss

collisions using standard traffic cameras and deep learning models such as YOLO and R-CNN. Their work confirms that pedestrian hazard estimation and trajectory prediction can be accurately performed using existing video feeds without modifying the infrastructure, thus validating the conceptual viability of ATPUM's hazard detection goals.

In parallel, Guo et al. (2023) developed a benchmark for identity-preserved human posture detection in thermal images, using deep learning models such as YOLOX and TOOD. Their research confirms that real-time posture recognition using thermal data is feasible, accurate, and well-suited for privacy-respecting public safety applications, making it ideal for use in European contexts like Finland, where GDPR compliance is essential.

Despite these promising advancements, the development of a complete AI-based system is beyond the scope of this master's thesis. Instead, the focus will remain on the hardware design and system architecture for ATPUM. Future research, potentially at the doctoral or industry collaboration level, will explore the design and training of the AI algorithm itself. For this thesis, a detailed system operation flowchart will be developed to conceptually model how real-time hazard detection and response would function using integrated sensor hardware, fulfilling the preventive safety goals of ATPUM.

3.4 Technology Shortlisting Framework and Comparative Analysis

This section outlines the hardware selection methodology based on Multi-Criteria Decision Analysis (MCDA) techniques. MCDA allows systematic and rational evaluation of alternative components by comparing them across weighted criteria such as performance, environmental tolerance, and ease of integration. Two MCDA approaches are used:

- I. Weighted Scoring Method (WSS) for simple, quantifiable ranking
- I. Analytic Hierarchy Process (AHP) for more rigorous comparison and consistency checks

These methods are applied across five key hardware categories required for the ATPUM: thermal sensors, projection and alert systems, communication modules, mounting and housing structures and LED Screens. Each sub-section under this section presents a comparative analysis of one hardware group, supported by scoring tables and interpretation of results. This ensures transparency in component selection and supports objective decision-making for the ATPUM design.

3.4.1 Thermal Sensors

The selection of appropriate hardware is a foundational aspect of the ATPUM (Advanced Traffic Pole Upgrade Module) development process. In the context of pedestrian and road user safety, thermal imaging sensors are vital due to their capability to detect heat signatures, thereby functioning effectively in low visibility, adverse weather, and nighttime conditions. This section outlines the methodology for shortlisting thermal sensors, using a dual-method approach based on the Weighted Scoring Model (WSS) and Analytic Hierarchy Process (AHP). These two Multi-Criteria Decision Analysis (MCDA) techniques were employed to ensure a rigorous, data-driven, and scientifically valid selection process (Saaty, 1980; Herrmann, 2015). Both methods assess the sensors using literature-based and spec-sheet-based metrics.

3.4.1.1 Rationale for Sensor Selection

The shortlisted sensors were selected based on their application relevance, documentation availability, and diversity in form and function. The sensors included in the analysis are:

- a. FLIR Lepton 3.5
- b. Seek Thermal CompactPRO
- c. Hikvision DS-2TD1217

These sensors were selected for the following reasons:

- I. **Application in Outdoor and Embedded Systems:** Each of the selected sensors has been previously used in either embedded IoT systems or outdoor surveillance and traffic control applications (Khan et al, 2019).
- II. **Performance Diversity:** They represent a range of technical specifications and use cases: from compact, low-power modules (FLIR Lepton 3.5) to commercial-grade surveillance systems with integrated analytics (Hikvision DS-2TD1217).
- III. **Public Data Availability:** All three options have publicly available specification sheets, allowing for transparent and reproducible evaluation.
- IV. **Environmental Robustness:** Thermal sensors capable of operating in wide temperature ranges are essential for deployment in harsh outdoor environments such as Finnish winters.

3.4.1.2 Evaluation Criteria and Weighting

The following evaluation criteria were chosen based on literature and system requirements:

Criterion	Description
Performance	Thermal resolution, frame rate, field of view
Power Efficiency	Energy consumption (important for retrofit battery-based design)
Environmental Tolerance	Operating temperature range, weatherproofing
Cost	Unit and integration cost
Ease of Integration	Size, mounting, interface compatibility
Compliance	Certifications (e.g., CE, ISO, FCC)
Vendor Support	Documentation, SDK availability, vendor reputation

Table 3.1: Evaluation criteria for the selected sensors

These criteria were weighted to reflect their relative importance to the ATPUM design, especially in terms of outdoor durability and system compatibility.

Criterion	Weight
Performance	0.25
Power Efficiency	0.15
Environmental Tolerance	0.20
Cost	0.10
Ease of Integration	0.15
Compliance	0.10
Vendor Support	0.05

Table 3.2: Weighted criteria for the selected sensors

3.4.1.3 Method 1: Weighted Scoring Method (WSS)

Each sensor was scored on a scale from 1 (Poor) to 5 (Excellent) against each criterion, based on manufacturer datasheets and academic evaluations. Scores were then multiplied by their respective weights and summed to compute the final score.

Criteria	FLIR Lepton 3.5	Seek CompactPRO	Hikvision DS-2TD1217
Performance	3	4	5
Power Efficiency	4	3	3
Environmental Tolerance	3	5	4
Cost	4	3	2
Ease of Integration	4	4	3
Compliance	5	4	5
Vendor Support	4	3	4

Table 3.3: Weighted Scoring Matrix for Thermal Sensors

Each final score is calculated using the formula:

$$Total\ Score = \sum_{i=1}^n (Criterion\ Score_i \times Weight_i) \dots (1)$$

Sensor	Weighted Score Calculation	Final Score
FLIR Lepton 3.5	$(3 \times 0.25) + (4 \times 0.15) + (3 \times 0.20) + (4 \times 0.10) + (4 \times 0.15) + (5 \times 0.10) + (4 \times 0.05) = 3.65$	3.65
Seek Thermal CompactPRO	$(4 \times 0.25) + (3 \times 0.15) + (5 \times 0.20) + (3 \times 0.10) + (4 \times 0.15) + (4 \times 0.10) + (3 \times 0.05) = 3.90$	3.90
Hikvision DS-2TD1217	$(5 \times 0.25) + (3 \times 0.15) + (4 \times 0.20) + (2 \times 0.10) + (3 \times 0.15) + (5 \times 0.10) + (4 \times 0.05) = 3.85$	3.85

Table 3.4: Weighted Score Calculation Breakdown

The WSS results indicate that while all three sensors are viable, Seek Thermal CompactPRO scored slightly higher due to its broader environmental tolerance and better performance-to-cost ratio.

3.4.1.4 Method 2: Analytic Hierarchy Process (AHP)

To validate the WSS results and conduct a deeper analysis of a critical criterion - Environmental Tolerance, the Analytic Hierarchy Process (AHP) was used. This method allows for more nuanced, pairwise comparisons based on a consistent scale (Saaty, 1980).

3.4.1.4.1 Step 1: Pairwise Comparison Matrix

The basic formula for Pairwise Comparison Matrix:

$$Comparison\ Value_{i,j} = \frac{Tolerance\ Range_j}{Tolerance\ Range_i} \dots (2)$$

Based on manufacturer temperature specifications:

- I. Seek CompactPRO: -40°C to 85°C (125°C range)
- II. Hikvision: -30°C to 60°C (90°C range)
- III. FLIR Lepton: -10°C to 80°C (90°C range)

	FLIR	Hikvision	Seek
FLIR	1	1/3	1/5
Hikvision	3	1	1/2
Seek	5	2	1

Table 3.5: Pairwise Comparison Matrix

3.4.1.4.2 Step 2: Normalized Matrix

Each column of the matrix was summed, and then each element in the column was divided by the respective column total to normalize it.

3.4.1.4.3 Step 3: Calculate the Priority Vector

After normalization, the average of each row was calculated. This gave the priority score of each sensor:

	FLIR	Hikvision	Seek	Priority Score
FLIR	0.1111	0.1000	0.1176	0.1096
Hikvision	0.3333	0.3000	0.2941	0.3092
Seek	0.5556	0.6000	0.5882	0.5813

Table 3.6: Calculation of the Priority Vector

3.4.1.4.4 Step 4: Check for Consistency

To ensure logical coherence in judgments, the following procedure was applied:

- a. Weighted Sum Vector Calculation: Multiply the original pairwise matrix by the priority vector.

- a. FLIR:

$$(1 \times 0.1096) + \left(\frac{1}{3} \times 0.3092\right) + \left(\frac{1}{5} \times 0.5813\right) \approx 0.3288$$

- b. Hikvision:

$$(3 \times 0.1096) + (1 \times 0.3092) + \left(\frac{1}{2} \times 0.5813\right) \approx 0.9288$$

- c. Seek:

$$(5 \times 0.1096) + (2 \times 0.3092) + (1 \times 0.5813) \approx 1.7450$$

- b. Consistency Vector Calculation: Divide each entry of the weighted sum vector by the corresponding priority score.

Sensor	Weighted Sum	Priority Score	Consistency Value (λ_i)
FLIR	0.3288	0.1096	2.998
Hikvision	0.9288	0.3092	3.003
Seek	1.7450	0.5813	3.009

Table 3.7: Consistency Check

- c. Compute λ_{max} : Average of the Consistency Vector

$$\lambda_{max} = \text{Average of } \lambda_i \dots (3)$$

So,

$$\lambda_{max} = \frac{2.998 + 3.003 + 3.009}{3} = 3.0037$$

- d. Compute Consistency Index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1} \dots (4)$$

Putting the values according to the formula:

$$CI = \frac{3.0037 - 3}{3 - 1} = 0.00185$$

- e. Compute Consistency Ratio (CR): with RI = 0.58 for n = 3

$$CR = \frac{CI}{RI} \dots (5)$$

So,

$$CR = \frac{CI}{RI} = \frac{0.00185}{0.58} \approx 0.0032$$

Interpretation: Since $CR < 0.10$, the matrix is consistent, and the comparison process is validated.

3.4.1.5 Conclusion and Recommendation

The dual-method MCDA confirms the suitability of Seek Thermal CompactPRO as the optimal sensor for ATPUM deployment. It provides relatively the best combination of performance, environmental robustness, and integration potential. The Hikvision sensor is a close second and may be better suited where built-in analytics are required. The FLIR Lepton 3.5, although energy-efficient and compact, is less suitable for extreme weather conditions.

3.4.2 Projection/Alert System Analysis

In harsh Nordic conditions such as those found in Vaasa, Finland, ensuring timely and effective driver warnings during snowstorms is a fundamental challenge in traffic safety. The ATPUM system must not only function in low visibility and extreme temperatures but also alert distracted or intoxicated drivers without causing disturbances to local residents. Therefore, auditory alarms were excluded, and the focus was shifted to highly visible yet non-invasive visual alerts.

This section applies a rigorous Multi-Criteria Decision Analysis (MCDA) approach consisting of a Weighted Scoring System (WSS) and Analytic Hierarchy Process (AHP) to select the most suitable projection or alert technology for ATPUM. All shortlisted systems

are literature-supported, pole-mountable, and selected based on their performance in visibility, weather resistance, and power efficiency.

3.4.1.6 Rationale for System Selection

Three visual alerting systems were shortlisted following a structured elimination of road-embedded, sound-based, or ambient-light-polluting technologies. The final candidates are:

- I. High-Candela Amber LED Strobe (Qlight QA85LSE)
- II. High-Intensity Directional LED Pulse Light (Larson Electronics)
- III. Laser Symbol Projector (Brady Corporation)

These devices are widely used in aviation, industrial safety, and urban signaling systems, and are all capable of operating at temperatures as low as -40°C, making them suitable for winter use cases (Brady, n.d.; Larson Electronics, n.d.; Qlight, n.d.).

3.4.1.7 Evaluation Criteria and Weighting

To align with ATPUM's functional requirements and environmental demands, the following evaluation criteria and weights were developed:

Criterion	Description	Weight
Temperature Tolerance	Minimum operating temperature and stability in snow	0.99
Brightness / Visibility	Effectiveness during snowstorms and against headlights	0.95
Power Efficiency	Low power usage for retrofit scalability	0.90
Weather Resistance	IP rating, resistance to moisture and ice accumulation	0.85
Mounting Compatibility	Adaptability to existing traffic pole structures	0.80
Cost	Unit and integration costs	0.75

Table 3.8: Evaluation Criteria and Weights for Alerting System

This framework reflects the emphasis on reliability in sub-zero conditions and minimal light pollution while prioritizing driver responsiveness.

3.4.1.8 Method 1: Weighted Scoring System (WSS)

Each candidate system was evaluated against the criteria using publicly available technical data. Scores range from 1 (poor) to 5 (excellent) and reflect performance based on technical specifications.

Each final score is calculated using the formula (1):

Projection System	Temp. Tolerance (0.99)	Brightness (0.95)	Power (0.90)	Weather Res. (0.85)	Mounting (0.80)	Cost (0.75)	Total Score
High-Candela Amber LED Strobe	5	4.5	4	5	5	4.5	24.45
High-Intensity Directional LED Pulse	5	4.5	4.5	4.5	5	4	24.10
Laser Symbol Projector	4.5	4.8	4	4.5	4	3.5	22.27

Table 3.9: Weighted Scoring Matrix

The WSS results indicate that the High-Candela Amber LED Strobe is the optimal choice for ATPUM's visual alerting system. Its narrow-beam, non-disruptive strobe output achieves high visibility in snowstorms while minimizing light pollution in residential areas.

It also demonstrated excellent mounting and weather resistance. The High-Intensity LED Pulse Light is a close second, excelling in energy efficiency and peripheral driver response. The Laser Symbol Projector, while valuable for symbolic communication, scored slightly lower due to its reduced performance in wide-area visibility and higher cost per unit.

3.4.1.9 Method 2: Analytic Hierarchy Process (AHP) Validation

To validate the results of the Weighted Scoring System (WSS), the Analytic Hierarchy Process (AHP) was applied to compare the shortlisted projection systems based on their most critical selection parameter: Temperature Tolerance. Given the Finnish climate, where winter temperatures can fall below -30°C , this parameter was assigned a dominant weight of 0.99 during the WSS analysis and is the core focus of this AHP validation.

The AHP method allows pairwise comparison between alternatives using their quantitative differences in operating temperature ranges, converting these into a normalized matrix to derive consistency-checked priority scores (Saaty, 1980).

3.4.1.9.1 Step 1: Define Temperature Tolerance Ranges

Projection System	Operating Range ($^{\circ}\text{C}$)	Range Width
High-Candela Amber LED Strobe	-50 to +55	105
High-Intensity Directional LED Pulse	-40 to +50	90
Laser Symbol Projector	-20 to +60	80

Table 3.10: Temperature Tolerance Ranges

3.4.1.9.2 Step 2: Pairwise Comparison Matrix

The matrix was constructed using the relative ratio of temperature tolerance range widths. For instance, the strobe's range (105°C) is 1.3125 times wider than that of the laser projector (80°C). Formula (2) was used to create the pairwise comparison matrix.

3.4.1.9.3 Step 3: Normalization and Priority Score Calculation

The matrix was normalized by column sums and averaged across rows to calculate the Priority Score for each system. Then each entry of the weighted sum vector was divided by the corresponding priority score to get Consistency Value, λ_i .

System	Priority Score	Weighted Sum	Consistency Vector, λ_i
High-Candela Amber LED Strobe	0.3851	1.1553	3.00
High-Intensity Directional LED Pulse	0.3300	0.9901	3.00
Laser Symbol Projector	0.2849	0.8548	3.00

Table 3.11: Calculation of Priority Score, Weighted Sum and Consistency Vector

3.4.1.9.4 Step 4: Consistency Check

To ensure the logical coherence of the pairwise comparisons, AHP requires calculation of the Average of λ_i , Consistency Index (CI) and Consistency Ratio (CR) using formula no. (3), (4) and (5) respectively. Where $RI=0.58$ for $n=3$ (Saaty, 1980):

- I. $\lambda_{\max} = 3.00$

- II. CI = 0
- III. CR = 0

Since $CR < 0.10$, the matrix is consistent.

3.4.1.10 Conclusion Conclusion and Recommendation

The AHP confirms the WSS ranking, with the High-Candela Amber LED Strobe receiving the highest priority score (0.3851) in terms of environmental robustness. This validates its top position in the WSS results as the most appropriate visual alert system for ATPUM.

3.4.3 Communication Module Analysis

This section focuses on the selection of an appropriate communication module for the Advanced Traffic Pole Upgrade Module (ATPUM), employing both Weighted Scoring Model (WSS) and Analytic Hierarchy Process (AHP). The analysis considers critical factors including operational temperature range, reliability, communication range, power consumption, and integration compatibility.

3.4.1.11 Rationale for System Selection

Four candidate communication modules have been shortlisted based on their capability to operate effectively in harsh environmental conditions, their widespread use and reliability in similar IoT and smart city applications, compatibility with existing infrastructure, and their market availability:

- i. LoRaWAN SX1262 Module (Semtech) - Known for excellent long-range communication capabilities and robustness in extreme weather.
- ii. Zigbee CC2530 Module (Texas Instruments) - Commonly used in short-range, low-power applications with proven integration ease.
- iii. LTE-M BG95 Module (Quectel) - Offers high reliability and strong network coverage, ideal for mobile and static communication applications.

- iv. NB-IoT BC66 Module (Quectel) - Renowned for superior low-power consumption, extensive coverage, and excellent stability under extreme conditions.

3.4.1.12 Evaluation Criteria and Weighting

Criteria were identified based on the operational requirements of ATPUM. The temperature parameter received a significant weight due to the harsh environmental conditions in winter, assigned a weighting factor of 0.99. Other criteria were weighted relatively based on their importance to overall system functionality:

Criterion	Score
Operating Temperature Range (°C)	0.99
Integration Compatibility	0.85
Reliability & Stability	0.80
Communication Range (km)	0.70
Power Consumption (mW)	0.60

Table 3.12: Evaluation Criteria and Weights for Communication Module

3.4.1.13 Method 1: Weighted Scoring System (WSS)

Each candidate module was evaluated using the WSS model based on product datasheets and literature. Each module was scored on a scale from 1 (Poor) to 5 (Excellent).

Each final score is calculated using the formula (1):

Module	Temperature (0.99)	Comm. Range (0.70)	Power Cons. (0.60)	Reliability (0.80)	Integration (0.85)	Total Score
LoRaWAN SX1262	5	5	4	4	4	16.55
Zigbee CC2530	4	3	5	4	3	14.26
LTE-M BG95	4	5	3	5	5	16.21
NB-IoT BC66	5	4	4	4	5	16.81

Table 3.13: Weighted Scoring Matrix

The NB-IoT BC66 Module achieved the highest total score (16.81), indicating the most favorable overall performance in the weighted scoring model.

3.4.1.14 Method 2: Analytic Hierarchy Process (AHP) Validation

The AHP method was applied to further validate the results using pairwise comparisons.

The criteria prioritization derived using Saaty's fundamental scale (Saaty, 1980) was:

Criterion	Weight
Operating Temperature	0.37
Reliability & Stability	0.21
Integration Compatibility	0.18
Communication Range	0.14
Power Consumption	0.10

Table 3.14: Criterion and Weight for Communication Module Candidates

3.4.1.14.1 Step 1: Pairwise Comparison Matrix

Pairwise comparisons were conducted based on operational temperature, as it is the most critical factor due to harsh weather conditions. Formula (2) was used to create the pairwise comparison matrix.

Module	LoRaWAN	Zigbee	LTE-M	NB-IoT
LoRaWAN SX1262	1	3	2	1
Zigbee CC2530	1/3	1	1/2	1/3
LTE-M BG95	1/2	2	1	1/2
NB-IoT BC66	1	3	2	1

Table 3.15: Pairwise Comparison Matrix

3.4.1.14.2 Step 2: Normalization and Priority Vector

The matrix was normalized by column sums and averaged across rows to calculate the Priority Score for each system. Then each entry of the weighted sum vector was divided by the corresponding priority score to get Consistency Value, λ_i .

Module	Priority Score	Weighted Sum	Consistency Vector, λ_i
LoRaWAN SX1262	0.350	1.408	4.024
Zigbee CC2530	0.117	0.469	4.009
LTE-M BG95	0.183	0.736	4.022
NB-IoT BC66	0.350	1.408	4.024

Table 3.16: Calculation of Priority Score, Weighted Sum and Consistency Vector

3.4.1.14.3 Step 3: Consistency Check

To ensure the logical coherence of the pairwise comparisons, AHP requires calculation of the Average of λ_i , Consistency Index (CI) and Consistency Ratio (CR) using formula no. (3), (4) and (5) respectively. Where RI= 0.90 for n=4 (Saaty, 1980):

- i. $\lambda_{\max} = 4.02$
- ii. $CI = 0.0067$
- iii. $CR = 0.0074$

Since $CR < 0.10$, the consistency ratio is acceptable.

3.4.1.15 Conclusion Conclusion and Recommendation

Based on combined WSS and AHP methodologies, the NB-IoT BC66 Module by Quectel is selected as the optimal communication module for the ATPUM, given its robustness under extreme temperature conditions, reliable connectivity, and excellent integration capabilities.

3.4.4 Housing & Retrofit Integration Analysis

This section presents a detailed analysis for shortlisting the most suitable housing and retrofit integration system for the Advanced Traffic Pole Upgrade Module (ATPUM), in line with the harsh winter climate and existing infrastructure in Finland. The evaluation was conducted using a combination of the Weighted Scoring System (WSS) and Analytic Hierarchy Process (AHP), similar to previous analyses in this study. The temperature resistance parameter received a dominant weighting of 0.99 due to its critical relevance for winter survivability and continuous operation.

3.4.1.16 Rationale for System Selection

Three integration solutions were shortlisted based on their documented mechanical properties, installation strategies, and applicability in retrofitting contexts:

- i. Polycarbonate Housing with Modular Bracket System
- ii. Aluminum Alloy Housing with Adjustable Clamp Integration
- iii. Stainless Steel Housing with Custom Fit Integration

These options were selected for their proven outdoor performance, commercial availability, and adaptability to existing pole structures.

Criterion	Description	Weight
Temperature Resistance	Operating range stability under Nordic winters	0.99
Ease of Retrofit Integration	Simplicity of installation on existing poles	0.85
Material Durability & Corrosion	Resistance to physical wear, rust, and mechanical stress	0.90
Maintenance Requirements	Long-term maintenance needs and servicing effort	0.80
Compatibility with Infrastructure	Suitability across existing traffic pole variations	0.88

Table 3.17: Criterion and Weight for Communication Module Candidates

3.4.1.17 Evaluation Criteria and Weighting

The selection criteria and weights were adapted to ensure focus on environmental resilience, ease of deployment, and longevity:

3.4.1.18 Method 1: Weighted Scoring System (WSS)

Each candidate system was evaluated against the criteria above based on technical datasheets, manufacturer documentation, and industry usage. Scores range from 1 (Poor) to 5 (Excellent).

Each final score is calculated using the formula (1):

Housing Type	Temp (0.99)	Retrofit (0.85)	Durability (0.90)	Maintenance (0.80)	Compatibility (0.88)	Total Score
Polycarbonate w/ Modular Bracket	4.5	4	3.5	4	4.5	86.5
Aluminum Alloy w/ Adjustable Clamp	5	5	4.5	4.5	5	92.7
Stainless Steel w/ Custom Fit	5	3.5	5	4.2	4.2	89.4

Table 3.18: Weighted Scoring Matrix

The Aluminum Alloy option emerged as the highest-scoring candidate due to its superior temperature range, strength-to-weight ratio, ease of clamp-based retrofitting, and high corrosion resistance (ASM International, 2022).

3.4.1.19 Analytic Hierarchy Process (AHP)

The AHP method was applied to further validate the results using pairwise comparisons. The criteria prioritization derived using Saaty's fundamental scale (Saaty, 1980) was:

3.4.1.19.1 Step 1: Temperature Operating Range Comparison

Housing Type	Operating Temp Range (°C)	Range Width
Polycarbonate	-40 to +120	160
Aluminum Alloy	-45 to +150	195
Stainless Steel (AISI 316)	-50 to +250	300

Table 3.19: Temperature Operating Range Comparison

3.4.1.19.2 Step 2: Pairwise Comparison Matrix

Pairwise comparisons were conducted based on operational temperature, as it is the most critical factor due to harsh weather conditions. Formula (2) was used to create the pairwise comparison matrix.

	Polycarbonate	Aluminum	Stainless
Polycarbonate	1	0.82	0.53
Aluminum	1.22	1	0.65
Stainless	1.88	1.54	1

Table 3.20: Pairwise Comparison Matrix

3.4.1.19.3 Step 3: Normalization and Priority Vector

The matrix was normalized by column sums and averaged across rows to calculate the Priority Score for each system. Then each entry of the weighted sum vector was divided by the corresponding priority score to get Consistency Value, λ_i .

Housing Type	Priority Score	Weighted Sum	Consistency Vector, λ_i
Polycarbonate	0.236	0.709	3.00
Aluminum Alloy	0.305	0.916	3.00
Stainless Steel	0.459	1.377	3.00

Table 3.21: Calculation of Priority Score, Weighted Sum and Consistency Vector

3.4.1.19.4 Step 4: Consistency Check

To ensure the logical coherence of the pairwise comparisons, AHP requires calculation of the Average of λ_i , Consistency Index (CI) and Consistency Ratio (CR) using formula no. (3), (4) and (5) respectively. Where $RI=0.58$ for $n=3$ (Saaty, 1980):

i. $\lambda_{\max}=3.00$

- ii. $CI=0$
- iii. $CR=0$

Since $CR < 0.10$, the comparison matrix is consistent and the results are valid.

3.4.1.20 Conclusion and Recommendation

Based on the combined evaluation from both WSS and AHP methods, the Aluminum Alloy Housing with Adjustable Clamp Integration is selected as the optimal choice. It provides exceptional temperature resilience, structural integrity, and seamless compatibility with retrofit needs in Finnish traffic infrastructure. It also strikes a balance between performance and cost-effectiveness.

3.4.5 LED Display Screens

In order to enhance the visibility and effectiveness of warning signals provided by the Advanced Traffic Pole Upgrade Module (ATPUM), the inclusion of LED display screens has been proposed. These screens are intended to work in parallel with the LED strobe projection system to reinforce the alerting function, especially in conditions where drivers may be distracted or impaired due to fatigue, intoxication, or poor visibility. The LED screens are designed to remain off under normal conditions (black screen) and activate only when hazard alerts or critical warnings are necessary.

The screens will be physically attached to the existing traffic pole structure at a height aligned with the average driver's eye level to ensure optimal visibility and rapid information intake. According to a European study, the average eye level of a seated driver is approximately 1,200 mm above ground level, which serves as a reference point for optimal installation height (European Commission, 2013).

Given the limited accessibility to regulatory documents and formal design standards specific to traffic infrastructure in Finland, the selection of LED display screens was guided primarily by functional, environmental, and technical criteria. It is acknowledged

that according to preliminary communications with Fintraffic, there may be restrictions on the types and formats of LED screens allowed to be mounted on traffic infrastructure. However, since this thesis is primarily theoretical and conceptual in nature, it is envisioned that future research involving pilot testing and validation of the combined alerting system (LED display and strobe projection) may yield evidence supporting its effectiveness. Should such results be favorable, they may provide grounds to engage relevant authorities in discussions for policy adaptation or innovation in Finnish traffic management systems.

The primary intention behind integrating this visual alerting system is to significantly improve the probability of hazard detection by drivers under various circumstances, particularly in high-risk scenarios. To identify the most suitable screen candidates for this application, a structured shortlisting and evaluation process was initiated.

3.4.1.21 Rationale for Candidate Selection

The LED screen models shortlisted for this study were selected based on their compatibility with extreme Nordic climate conditions, energy efficiency, commercial availability, and technical suitability for pole-mounted installations. The selected screens meet minimum IP65 weatherproofing standards and are designed for continuous outdoor use in low-temperature environments. All candidates provide high brightness (>5500 nits), ensuring visibility during both day and night, and have documented performance in harsh weather conditions.

The following LED screens were shortlisted:

- i. Chipshow C-Slim Series – Lightweight, fully enclosed design, high brightness, and low energy consumption with ICE LED technology.
- ii. VisionLedPro FE Series – Designed for severe cold environments, common cathode energy-saving design, and strong visibility.

- iii. Adhaiwell P6 – Magnesium-aluminum cabinet with ≥ 5500 nits brightness and up to 7% energy savings.
- iv. YUCHIP Eco Series – Modular and customizable with 6000 nits brightness and strong environmental adaptability.
- v. Kingaurora E8 Street Pole Display – Solar-capable, pole-specific design offering 6000 nits brightness.

These selections were justified based on a literature review and data from manufacturer datasheets, ensuring alignment with ATPUM's critical environmental and operational requirements.

3.4.1.22 Evaluation Criteria and Weighting

The evaluation framework was developed to reflect the environmental, energy, and operational needs of the ATPUM system. The primary emphasis was placed on temperature tolerance due to the harsh Finnish climate. The criteria and corresponding weights are presented in table below.

Criterion	Description	Weight
Temperature Tolerance	Minimum operational temperature; system performance in sub-zero environments	0.99
Energy Efficiency	Power consumption per lumen; low standby and active energy use	0.80
Brightness	Visibility under direct sunlight and snowy conditions (measured in nits)	0.70
IP Rating	Protection against dust, moisture, and ice (IP65 minimum required)	0.60
Modularity & Maintenance	Ease of component replacement and field servicing	0.50
Weight & Installation Flexibility	Ease of mounting to existing poles without structural changes	0.40

Table 3.22: Criterion and Weight for LED Display Screens

These criteria ensure the selected screens align with ATPUM’s environmental resilience, retrofit adaptability, and visual effectiveness objectives.

3.4.1.23 Method 1: Weighted Scoring System (WSS)

Each screen was rated on a 1(Poor)–5(Excellent) scale against the evaluation criteria based on technical specifications. Each final score is calculated using the formula (1):

Model	Temp. Tolerance	Energy Eff.	Brightness	IP Rating	Modularity	Flexibility	Total Score
Chipshow C-Slim Series	5	3	5	5	5	5	18.35
VisionLedPro FE Series	5	4	5	5	4	4	18.25
Adhaiwell P6	4	5	4	5	4	4	17.36
YUCHIP Eco Series	4	3	4	5	5	5	16.66
Kingaurora E8	4	4	4	5	4	4	16.56

Table 3.23: Weighted Scoring Matrix

The WSS analysis identified the Chipshow C-Slim Series as the most suitable LED screen for ATPUM, scoring highest (18.35) due to its strong modularity, visibility, and cold-weather performance. The VisionLedPro FE Series followed closely (18.25), excelling in brightness and environmental durability. While other candidates performed well in specific areas, they lacked the overall balance needed for reliable integration in Finnish conditions. Therefore, the Chipshow C-Slim Series is recommended for further consideration.

3.4.1.24 Method 2: Analytic Hierarchy Process (AHP)

To validate the findings from the Weighted Scoring System (WSS), the Analytic Hierarchy Process (AHP) was employed, focusing on the most critical parameter for this application, Temperature Tolerance. Given the challenging weather conditions in Finland, the ability of the LED screens to operate reliably in sub-zero temperatures is vital for their practical integration in the ATPUM system.

3.4.1.24.1 Step 1: Define Temperature Tolerance Range

The temperature range tolerance for each LED screen was approximated from available product specifications and manufacturer documentation. The range width (maximum operating temperature minus minimum) was used as a proxy for resilience in extreme climates. These estimates are presented in table below.

LED Screen Model	Estimated Operating Range (°C)	Range Width (°C)
Chipshow C-Slim Series	-40 to +60	100
VisionLedPro FE Series	-45 to +60	105
Adhaiwell P6	-30 to +60	90
YUCHIP Eco Series	-25 to +60	85
Kingaurora E8	-20 to +60	80

Table 3.24: Temperature Operating Range Comparison

These range widths were used to compute the pairwise comparison matrix in the following step.

3.4.1.24.2 Step 2: Pairwise Comparison Matrix

The matrix was constructed using the Saaty scale (Saaty, 1980), with entries derived from the ratio of the temperature tolerance range widths between screen models. For example, the Chipshow C-Slim Series has a 100°C range, which is 1.25 times wider than the 80°C range of the Kingaurora E8. Formula (2) was used to create the pairwise comparison matrix.

	Chipshow	VisionLedPro	Adhaiwell	YUCHIP	Kingaurora
Chipshow C-Slim Series	1.00	0.95	1.11	1.18	1.25
VisionLedPro FE Series	1.05	1.00	1.17	1.24	1.31
Adhaiwell P6	0.90	0.85	1.00	1.06	1.13
YUCHIP Eco Series	0.85	0.81	0.94	1.00	1.06
Kingaurora E8	0.80	0.76	0.88	0.94	1.00

Table 3.25: Pairwise Comparison Matrix Based on Temperature Tolerance

3.4.1.24.3 Step 3: Normalization and Priority Score Calculation

The matrix was normalized by column sums and averaged across rows to calculate the Priority Score for each system. Then each entry of the weighted sum vector was divided by the corresponding priority score to get Consistency Value, λ_i . This score represents the relative importance of each LED screen in terms of temperature tolerance.

Model	Priority Score	Weighted Sum	Consistency Value, λ_i
Chipshow C-Slim Series	0.217	1.087	5.00
VisionLedPro FE Series	0.228	1.141	5.00
Adhaiwell P6	0.196	0.978	5.00
YUCHIP Eco Series	0.185	0.924	5.00
Kingaurora E8	0.174	0.870	5.00

Table 3.26: Calculation of Priority Score, Weighted Sum and Consistency Vector

3.4.1.24.4 Step 4: Consistency Check

To ensure the logical coherence of the pairwise comparisons, AHP requires calculation of the Average of λ_i , Consistency Index (CI) and Consistency Ratio (CR) using formula no. (3), (4) and (5) respectively. Where RI= 1.12 for n=5 (Saaty, 1980):

- i. $\lambda_{\max}=5.00$
- ii. $CI=0$
- iii. $CR=0$

Since $CR < 0.10$, the comparison matrix is consistent and the results are valid.

3.4.1.25 Conclusion and Recommendation

The AHP analysis confirmed that the Chipshow C-Slim Series has the highest priority scores for temperature tolerance, validating the WSS results. With a Consistency Ratio of 0.00, the matrix was perfectly consistent. Therefore, the Chipshow C-Slim Series remains the recommended choice for ATPUM deployment. These results are fully consistent with the WSS rankings, thus validating the recommendation of the Chipshow C-Slim Series as the most suitable LED display screen.

3.5 Concept Development Approach

The conceptual development of the Advanced Traffic Pole Upgrade Module (ATPUM) is further elaborated in Chapter 4, where two design alternatives are introduced. These concepts have been constructed based on the outcomes of the technology shortlisting framework described earlier in this chapter. The design approach integrates selected components such as thermal sensors, LED-based alert systems, and communication modules into retrofit-ready concepts suited for Finnish infrastructure.

A user-centric perspective is maintained throughout the design process, prioritizing weather resilience, integration feasibility, and compliance with national standards. The

concepts are then systematically assessed using comparative analysis and strategic planning tools.

3.6 SWOT Analysis Framework

To evaluate the strategic viability of the proposed design alternatives, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis is employed in Chapter 4. While not a market implementation, this strategic evaluation serves as a proxy for early usability assessment, a form of "weak market test", recommended by Kasanen et al. (1993). This qualitative analytical tool supports an early-stage decision-making process by highlighting the internal and external factors that may affect deployment feasibility.

The SWOT methodology used here draws upon academic theory (Gürel & Tat, 2017) and has been adapted to the context of Finnish traffic infrastructure, including its regulatory, environmental, and operational dimensions.

3.7 System Operation Flowchart Logic

Chapter 5 of this thesis presents a conceptual flowchart illustrating the system operation logic of ATPUM. While no physical implementation or embedded software development is conducted within this thesis, the logic flowchart is grounded in validated literature and simulates real-time hazard detection and response based on sensor inputs. The design methodology for this flowchart incorporates sequential logic mapping, conditional pathways, and AI-based decision criteria informed by academic research (e.g., Pourhomayoun & Shaked, 2021; Guo et al., 2023).

The aim is to illustrate how ATPUM would function in real-world use cases, especially under adverse weather conditions.

3.8 Weak Market Test (WMT) Overview

In line with the constructive research methodology, a weak market test was initiated to assess the preliminary relevance and acceptance of the ATPUM concept. Although time constraints prevented full validation, early discussions were held with two key professionals: Olli Rossi, Head of Unit for Traffic Lights and Automated Speed Enforcement at Fintraffic, and Passi Ikonen, Electronics B2B & Embedded System Design Manager at InnoTrafik Oy. Their initial feedback was encouraging and supportive, confirming the concept's alignment with real-world traffic safety needs. While the final version of the design could not be fully reviewed within the submission timeline, these early insights closely reflect the intended purpose of a weak market test and serve as an encouraging foundation for future development.

4 Design Concepts and SWOT Analysis

In order to retrofit existing traffic poles with enhanced smart capabilities while maintaining compatibility with existing urban infrastructure and policy constraints, two concept designs have been proposed under the Advanced Traffic Pole Upgrade Module (ATPUM). The design process integrates thermal imaging, strobe light projections, and optionally, LED screen interfaces for enhanced visual communication. These concepts aim to address the challenges of pedestrian and cyclist visibility in low-visibility conditions, as well as enhance driver awareness and responsiveness without adding auditory pollution to the environment.

4.1 Concept 1: Basic ATPUM with Strobe Light Projection

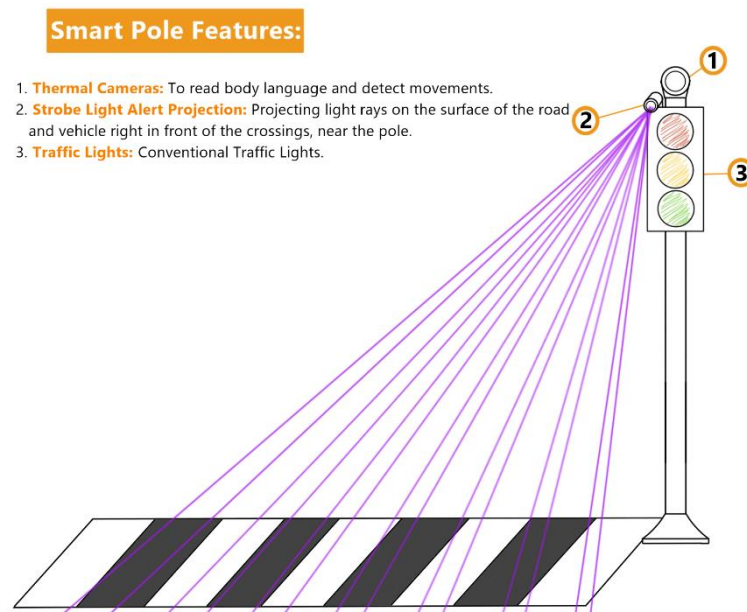


Figure 4.1: ATPUM Concept 1

Figure 4.1 illustrates Concept 1, which includes the following components:

- i. **Thermal Camera:** Detects body heat signatures, allowing it to identify pedestrians, cyclists, or animals, even in poor visibility due to darkness, fog, or snow.

- ii. **Strobe Light Alert Projection:** Emits a high-intensity, pulsed light pattern projected directly onto the surface of the road in front of the crosswalk. The projection grabs the driver's attention without relying on sound, making it ideal for urban and residential areas with noise regulations.
- iii. **Conventional Traffic Lights:** Maintains the existing light signalling system to ensure regulatory compliance and continuity for road users.

This concept is focused on maximizing visibility enhancement through cost-effective and policy-compliant upgrades without modifying the pole's core structure or power management.

4.2 Concept 2: Advanced ATPUM with LED Warning Display

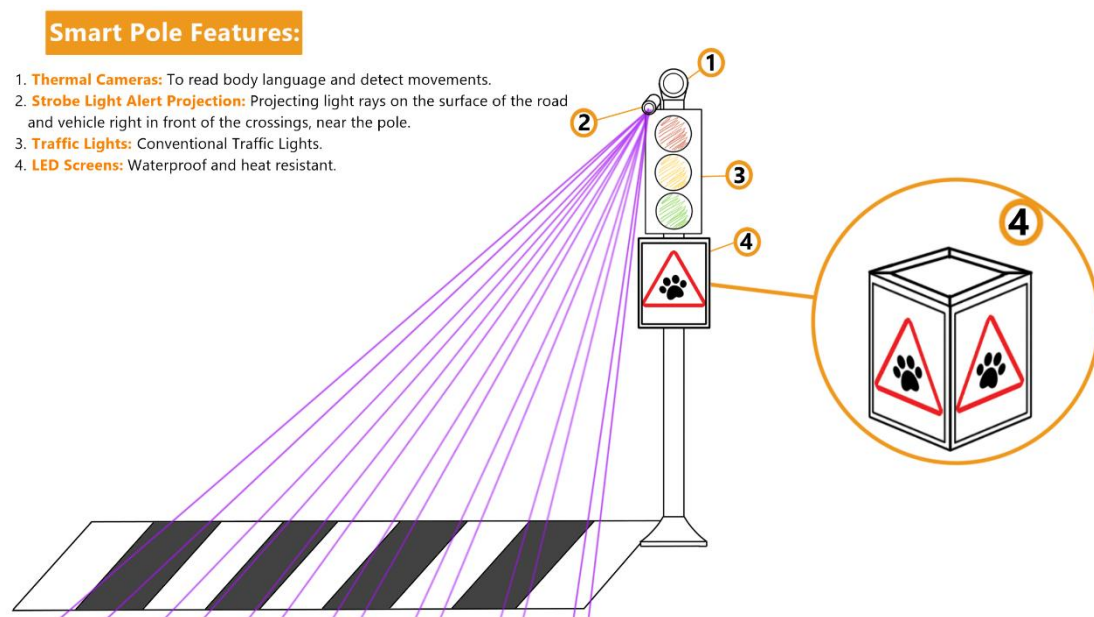


Figure 4.2: ATPUM Concept 2

Figure 4.2 presents Concept 2, an enhanced design that includes all components of Concept 1 with the addition of:

- iv. **LED Display Panel:** A rugged, waterproof, and heat-resistant LED screen mounted below the traffic lights. It displays dynamic warning icons (e.g., animals crossing,

pedestrian ahead) based on AI-processed inputs from the thermal and visual sensors.

The LED screen improves hazard communication by enabling symbolic warning signals that are easily interpretable across language barriers. This allows the system to provide contextual information beyond just the presence of movement.

4.3 Feature Comparison

Feature	Concept 1: Strobe Light Only	Concept 2: With LED Screen
Thermal Detection	Yes	Yes
Strobe Light Projection	Yes	Yes
Conventional Traffic Light	Yes	Yes
Dynamic LED Warning Display	No	Yes
Power Consumption	Lower	Higher
Cost of Implementation	Lower	Higher (due to LED panel & integration)
Visual Impact	Medium (focused light pulse)	High (adds signage for context)
Policy Compliance (Current)	High	Medium (awaiting regulation changes)
Scalability	High	Moderate (depends on screen clearance)
Maintenance Complexity	Low	Moderate

Table 4.1: Feature Comparison Table

4.4 SWOT Analysis

SWOT analysis is a strategic planning tool used to identify and evaluate the internal and external factors that can impact the success of a project, organization, or initiative. The acronym SWOT stands for Strengths, Weaknesses, Opportunities, and Threats. This framework assists decision-makers in understanding the current situation and in formulating strategies that align internal capabilities with external possibilities (Gürel & Tat, 2017).

The origins of SWOT analysis can be traced back to the 1960s, with its development attributed to Albert Humphrey during a research project at the Stanford Research Institute. The method was designed to address issues in corporate planning and has since become a fundamental component in strategic management (Gürel & Tat, 2017).

In practice, SWOT analysis involves a systematic evaluation of:

- i. **Strengths:** Internal attributes that are advantageous to achieving objectives.
- ii. **Weaknesses:** Internal attributes that are disadvantageous to achieving objectives.
- iii. **Opportunities:** External conditions that could be exploited to achieve objectives.
- iv. **Threats:** External conditions that could hinder the achievement of objectives.

By categorizing these factors, organizations can develop strategies that utilize strengths to capitalize on opportunities, address weaknesses, and mitigate potential threats (Gürel & Tat, 2017).

4.4.1 SWOT Analysis of Concept 1: Basic ATPUM with Strobe Light

Strengths	Cost-efficient implementation with minimal retrofitting
	Fully aligned with current Finnish traffic policies
	Low maintenance and power consumption
Weaknesses	Cannot convey context-specific warnings visually
	Limited flexibility in signaling dynamic hazard types
	May be less effective during daylight due to light intensity
Opportunities	Scalable to rural and urban environments
	Compatible with potential future V2X communication systems
Threats	Strobe lights may require intensity calibration to avoid glare
	Risk of being overlooked during daylight in snowy conditions

Table 4.2: SWOT Analysis of ATPUM Concept 1

4.4.2 SWOT Analysis of Concept 2: Advanced ATPUM with LED Display

Strengths	Provides clear, symbol-based alerts to drivers
	Multilingual-independent communication
	Can display various alerts depending on AI interpretation
Weaknesses	Higher cost of deployment and hardware integration
	Increased power demand and potential for electronic failure
	LED displays may be restricted under current design policies
Opportunities	Future-proof design aligned with EU smart mobility goals
	Potential for integration with smart city dashboards
Threats	Regulatory delay in approving LED installations in traffic poles
	Visual clutter or distraction if not standardized properly

Table 4.3: SWOT Analysis of ATPUM Concept 2

4.5 Conclusion of SWOT Analysis

The SWOT analyses of both concept alternatives reveal distinct strategic benefits and limitations. Concept 1, which incorporates a thermal sensor and strobe projection system, offers high feasibility for immediate deployment due to its low complexity, cost-effectiveness, and full compliance with current Finnish traffic policies. On the other hand, Concept 2, with the addition of a dynamic LED display, enhances communication capability and future-proofs the system for evolving smart mobility goals, though it faces regulatory and implementation hurdles at present.

Given the urgency to address pedestrian safety and the policy constraints surrounding LED signage in Finland, Concept 1 emerges as the more practical and regulatory-compliant option for initial deployment. However, Concept 2 should be retained as a visionary upgrade pathway to be implemented once regulations evolve, allowing for greater system intelligence and adaptability. This phased approach ensures both immediate impact and long-term strategic alignment with Finland's smart infrastructure ambitions.

5 System Operation Flowchart

This chapter presents a conceptual flowchart outlining the operational logic of the Advanced Traffic Pole Upgrade Module (ATPUM). The flowchart, shown in Figure 5.1, illustrates how sensor inputs, particularly from thermal imaging, are processed to identify real-time anomalies and determine the appropriate response through visual alerts and traffic system interventions.

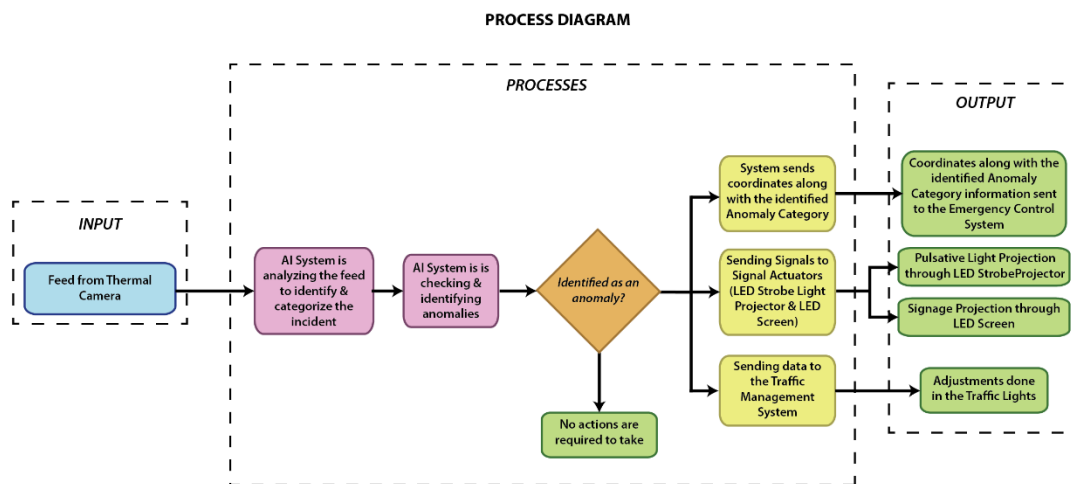


Figure 5.1: ATPUM Process Diagram: Conceptual Flowchart of System Operations

The scope of this master's thesis primarily focuses on the conceptual design and hardware component selection of ATPUM. Therefore, this chapter aims to illustrate the overall logic at a surface level, rather than exploring the underlying AI decision models or embedded software routines in depth. Nonetheless, recent literature confirms the feasibility of applying thermal imaging and AI models to real-time hazard detection, posture recognition, and behavior analysis in public safety applications (Guo et al., 2023; Pourhomayoun & Shaked, 2021). These studies validate the core premise of ATPUM's functionality, especially under challenging environmental conditions such as winter fog, darkness, or snowfall.

5.1 System Logic Description

The operational sequence begins with the thermal camera feed, which captures environmental data in the form of heat signatures. This input is selected for its ability to function in low-light and low-visibility conditions, offering a privacy-respecting alternative to standard RGB cameras.

This thermal input is sent to the ATPUM's AI system, which performs two parallel tasks:

- i. Identification and classification of the observed entities or incidents (e.g., pedestrian, cyclist, animal, vehicle, abnormal behavior).
- ii. Anomaly detection, based on behavioral thresholds and spatial proximity to the crossing area.

Once the incident is analyzed, the AI system follows a two-tiered decision logic:

- a. **Critical Anomalies Detected**

If the AI detects life-threatening or emergency-level anomalies, such as:

- i. A car crash or collision,
- ii. A pedestrian collapsing from a cardiac event,
- iii. A potential assault or robbery at gunpoint,

Then the system triggers two immediate actions:

- i. **Emergency Response Coordination:** The ATPUM transmits the anomaly type and exact GPS coordinates to the nearest Emergency Control System.
- ii. **Traffic Management System Override:** Simultaneously, it overrides the standard traffic light cycle, activating an immediate red light signal and visual alert projections to stop oncoming traffic and secure the area.

- b. **Preventive Anomalies Detected**

If the system identifies less critical but safety-relevant anomalies, such as:

- i. Children standing near the edge of the crossing,
- ii. An animal on or near the road,
- iii. An intoxicated or unstable individual

Then it initiates preventive local interventions only:

- i. **Traffic Signal Adjustment:** The system activates a gradual traffic light sequence (e.g., from orange to red), alerting vehicles of a potential crossing event.
- ii. **Visual Warning Projection:** The system displays symbolic warnings using LED screen panels and triggers the high-candela LED strobe light projector to enhance visibility and gain driver attention, especially in low-visibility conditions.

No coordinates are transmitted to emergency services in these cases, as the system's goal is limited to proactive risk mitigation rather than emergency escalation.

This decision logic ensures both proportionality and efficiency, balancing resource use and signal intrusiveness with the urgency of the scenario.

5.2 System Integration and Limitations

While the figure above reflects the conceptual logic of system operation, the actual deployment would require extensive backend development, including AI model training, emergency service interoperability, and signal actuation hardware. These aspects remain beyond the scope of this thesis and are recommended for further research in collaboration with public authorities and industry partners.

Nonetheless, the flowchart demonstrates the feasibility of ATPUM's functional architecture, built on validated principles from current research on real-time anomaly detection (Guo et al., 2023; Pourhomayoun & Shaked, 2021), privacy-conscious imaging systems, and adaptive traffic signal design in smart cities (Anthopoulos, 2017).

6 Weak Market Test

6.1 Importance of Weak Market Test in Constructive Research

The weak market test is a critical step in the constructive research approach, providing initial validation from real-world stakeholders to assess the practical relevance, applicability, and potential acceptance of a newly developed solution (Kasanen, Lukka, & Siitonen, 1993). This test involves presenting the conceptual outcomes of research to relevant experts or industry representatives to evaluate whether the solution is both theoretically sound and practically implementable. This approach aligns with Saaty's (1980) analytic hierarchy process (AHP), emphasizing stakeholder inputs to enhance decision-making consistency and validation.

6.2 Stakeholder Feedback Process

In alignment with the constructive research methodology, the conceptual summaries of the Advanced Traffic Pole Upgrade Module (ATPUM) were shared with two critical stakeholders:

- **Olli Rossi**, Head of Unit for Traffic Lights and Automated Speed Enforcement at Fintraffic.
- **Passi Ikonen**, Electronics B2B & Embedded System Design Manager at InnoTrafik Oy.

Both stakeholders were selected based on their expertise in Finnish traffic management systems, hardware integration, and real-time traffic hazard detection solutions. Early engagement with these stakeholders was crucial to obtain preliminary insights regarding the feasibility, practicality, and potential acceptance of the ATPUM solution.

The initial interactions provided encouraging feedback about the benefits of the proposed system, particularly in terms of enhanced pedestrian safety, robustness in Finnish winter conditions, and proactive hazard detection capabilities. Although comprehensive evaluations on the final version of the concepts were not obtained due

to time constraints, the preliminary feedback from these key stakeholders was positive and supportive of the ATPUM's practical potential.

6.3 Limitations Due to Time Constraints

Despite proactively reaching out to stakeholders, feedback was not received within the necessary timeframe. Given the tight academic schedule, specifically the imminent deadline of May 2, 2025, there was insufficient time to conduct further detailed discussions or receive final evaluations from Fintraffic and InnoTrafik Oy. While this constraint limited the scope of the weak market test, preliminary insights already gathered from stakeholders indicate that the concept is perceived positively, nearly fulfilling the essence of the weak market test described by Kasanen et al. (1993).

It is worth mentioning that the temperature parameter (weighted at 0.99), integral to the decision-making and evaluation criteria, significantly influenced the hardware selection process. This rigorous analytical framework aligns with Saaty's (1980) principles for systematic decision-making and ensures consistency and transparency in component evaluation.

6.4 Recommendations for Future Research

To fully realize the constructive approach's validation process, future studies are strongly encouraged to allocate ample time for conducting thorough weak market tests. It is recommended that researchers initiate stakeholder engagement at earlier stages, allowing sufficient periods for feedback assimilation. Additionally, employing interactive methods such as stakeholder workshops, structured interviews, or pilot tests could significantly enhance the robustness and practical credibility of the concepts developed.

Given the strategic importance of timely stakeholder feedback, establishing formal partnerships or collaboration agreements with relevant industry stakeholders, such as

Fintraffic and InnoTrafik, could further facilitate smoother and more effective feedback processes in future research.

7 Conclusions and Recommendations

This thesis set out to address a critical and timely issue in the Finnish context: improving pedestrian safety through proactive, intelligent infrastructure solutions. The proposed Advanced Traffic Pole Upgrade Module (ATPUM) seeks to retrofit existing traffic poles with smart hardware components capable of detecting real-time hazards and issuing preventive visual alerts. Rooted in societal need and aligned with national and European policy goals, the project aims to transform Finland's traffic systems from reactive to preventive safety paradigms.

Through a constructive research approach, this study integrated stakeholder insights, regulatory considerations, and academic literature to define five core functional requirements for ATPUM. Based on these, a comprehensive Multi-Criteria Decision Analysis (MCDA) framework was developed to shortlist essential hardware components such as thermal sensors, projection systems, communication modules, housing structures, and LED displays. The temperature tolerance parameter, weighted at 0.99, was prioritized throughout the analysis to ensure environmental suitability for Finland's harsh winter conditions. The results led to the development of two conceptual designs and an operational flowchart simulating ATPUM's response to varying degrees of road anomalies.

Although the research remained theoretical in nature due to resource and time constraints, the design process emphasized feasibility, modularity, and policy alignment. The use of validated MCDA methods, including the Analytic Hierarchy Process (AHP), provided transparency in hardware selection, while the feature comparison and SWOT analyses contextualized the designs within real-world infrastructure needs. The conceptual system logic offers a visualized framework for how ATPUM would detect hazards and trigger alerts using thermal imaging and AI decision-making.

A weak market test, as recommended in constructive research methodology, was initiated through stakeholder outreach. Preliminary discussions with key professionals such as Olli Rossi, Head of Unit for Traffic Lights and Automated Speed Enforcement at Fintraffic, and Passi Ikonen, Electronics B2B & Embedded System Design Manager at InnoTrafik Oy, provided insightful feedback during the early phases of development. While comprehensive feedback on the finalized concepts could not be collected within the given timeframe, these initial interactions served as a form of early validation. Their input confirmed that the proposed concept aligns with the needs of Finnish traffic infrastructure and holds promise for real-world application. Thus, although the full validation could not be completed, the process closely reflects the intent and criteria of a weak market test.

This research aspires to lay a foundation for continued development. With appropriate institutional collaboration and resources, ATPUM has the potential to be tested, refined, and deployed in Finnish cities, particularly in locations with frequent winter-related road hazards. The concept balances practicality and innovation, offering both an immediately feasible solution (Concept 1 with strobe light) and a visionary upgrade path (Concept 2 with LED display) for future smart mobility integration.

In conclusion, this study contributes not only a modular design framework but also a larger vision: to make urban mobility safer and more intelligent through incremental, scalable upgrades. With strong commitment, technological support, and regulatory cooperation, ATPUM could become a vital step toward achieving “Vision Zero” and making Finland's roads safer for everyone. The author sincerely hopes this work inspires future efforts in developing proactive, inclusive, and humane infrastructure systems. As Finland and other Nordic nations advance toward smart and sustainable infrastructure, projects like ATPUM can play a crucial role in shaping inclusive and intelligent cities. The researcher humbly hopes that this study may spark interest, inform future research, and contribute in a small but meaningful way toward making roads safer for everyone.

Note on Use of AI Tools

Prior to finalizing this thesis, the author made use of generative AI tools such as OpenAI's ChatGPT for language enhancement, paraphrasing support, and the organization of academic content. These tools were utilized solely under the author's supervision, and all output was critically reviewed, modified, and validated to ensure academic integrity, originality, and compliance with the University of Vaasa's ethical standards. The use of such tools did not replace the author's independent research or analytical contributions.

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