SMART ELEVATOR: REAL-TIME CAR ARRIVAL ESTIMATION

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ABSTRACT:

This paper presents a comprehensive review of elevator car arrival time prediction methodologies, beginning with traditional approaches such as queuing theory, deterministic models, and discrete event simulations. These foundational techniques shall be evaluated in terms of their applicability to real-world scenarios and their limitations in dynamic environments.

Advances in intelligent control systems, including Destination Control Systems (DCS) and AI-driven dispatching algorithms, are explored for their potential to enhance system responsiveness and reduce passenger waiting times. Key performance indicators (KPIs) such as Average Waiting Time (AWT), Round-Trip Time (RTT), and Handling Capacity (HC) are discussed as essential metrics for evaluating elevator performance.

The paper further investigates the many influences on arrival time calculations, encompassing building characteristics, passenger behaviour, elevator design parameters, and control system architecture. Challenges in real-world implementation such as data accuracy, dynamic traffic management, and integration with building management systems are addressed.

Finally, the study envisions the integration of elevator systems within smart building ecosystems, where elevators interact seamlessly with access control, and lighting to create responsive, efficient, and occupant-centric environments

1. INTRODUCTION

The efficiency of vertical transportation systems, particularly elevators, is paramount in modern multi-storey buildings. As urbanization intensifies and building heights soar, elevators are critical infrastructure components, impacting building functionality, energy consumption, and passenger satisfaction. The core challenge in elevator traffic management lies in minimizing passenger waiting and travel times while maximizing system throughput. This paper presents a comprehensive examination of methodologies used to calculate elevator car arrival time, ranging from foundational analytical models to cutting-edge intelligent approaches utilizing machine learning and artificial intelligence.

2. FUNDAMENTALS OF ELEVATOR TRAFFIC ANALYSIS

Understanding the fundamental components and operational characteristics of elevator systems is crucial for accurate arrival time prediction. An elevator system comprises a car, hoistway, control systems, and user interfaces. Traffic within buildings can vary significantly throughout the day, influencing elevator performance.

Elevator control systems are evolving, with innovative technological advances. Here are some widely known elevator control systems:

- Manual control
- Relay-based group control
- Microprocessor-based control
- Destination control system (DCS)
- AI driven predictive controls

2.1. Types of Access Control:

Refer to **Figure 1**[1] for types of access control

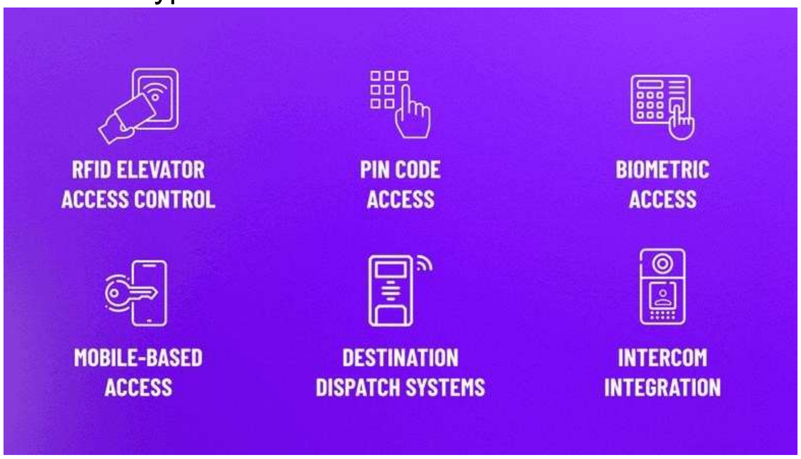

Figure 1

2.2. Key Traffic Patterns Include:

- **Incoming (Up-Peak) Traffic:** High demand for travel from the main terminal (ground floor) to upper floors, typically observed during morning peak hours.
- **Outgoing (Down-Peak) Traffic:** High demand for travel from upper floors to the main terminal, common during evening peak hours.
- **Interfloor Traffic:** Movement between floors, often less structured and occurring throughout the day.

The performance of an elevator system is evaluated using several key performance indicators (KPIs):

- **Average Waiting Time (AWT):** The average duration a passenger waits before an elevator arrives to pick them up.
- **Average Time to Destination (ATTD):** The total time elapsed from a passenger initiating a call to reaching their desired floor.

[1] Disclaimer: All AI-generated images used in this publication are for conceptual illustration only and were created using publicly available generative tools (Copilot). No real-world entities, individuals, or proprietary data are represented.

- **Handling Capacity (HC):** The maximum number of passengers an elevator system can transport within a specified timeframe, typically expressed as a percentage of the building's population moved in five minutes.
- **Interval (INT):** The average time between consecutive elevator departures from the main terminal, particularly relevant during up-peak traffic.
- **Passenger Load Factor:** The average occupancy rate of an elevator car, indicating how effectively car capacity is utilized.

A fundamental concept in elevator traffic analysis is the Round-Trip Time (RTT). This metric represents the time taken for an elevator to complete a full cycle of picking up passengers, delivering them, and returning to its starting point. It forms the basis for designing elevator traffic systems.

The standard formula for RTT is given by: **RTT**

$$= 2Htv + (S+1)(T-tv) + 2Ptp$$

Where:

H: Highest reversal floor.

S: Probable number of stops in a round trip.

tv: One-floor cycle time under rated speed.

T: Performance time (as defined in CIBSE Guide D).

P: Average number of in-car passengers.

tp: Average passenger transfer time.

Accurately estimating H and S, especially in dynamic, real-world scenarios, poses a significant challenge, driving the development of various analytical and simulation methods to improve RTT calculation.

3. TRADITIONAL ARRIVAL TIME CALCULATION METHODS

Historically, elevator arrival time estimation has relied on a combination of analytical and simulation-based approaches.

3.1. Analytical Models (Queuing Theory)

Queuing theory offers a mathematical framework for analyzing systems where requests (passengers) arrive and are processed (elevators), refer to Figure 2. It models passenger arrival rates (λ) and service rates (μ) to predict waiting times and queue lengths. These models are particularly effective under steady-state conditions, where arrival and service rates are relatively constant. Typically, passenger arrivals are modeled using a Poisson distribution, while service times might follow an exponential distribution. However, the

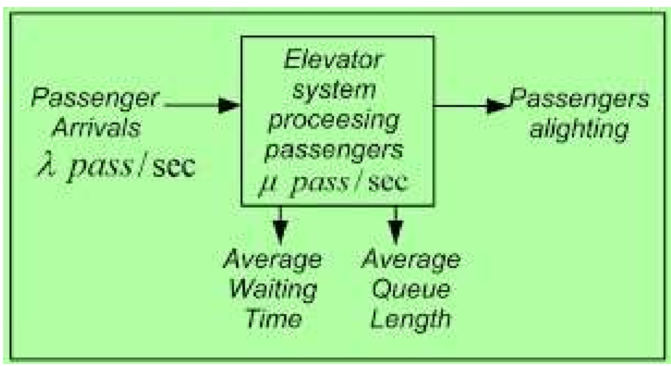

Figure 2

complexity and dynamic nature of real-world elevator traffic, with varying passenger demands and diverse control strategies, often limit the applicability of pure analytical models to simplified scenarios.

3.2. Simulation-Based Methods

Discrete event simulations provide a more robust approach to modeling elevator systems by mimicking the sequence of events (passenger arrivals, calls, car movements, stops) over time. This methodology allows for the analysis of complex interactions, such as multiple elevator cars, diverse traffic patterns, and sophisticated dispatching algorithms. Simulation software, such as specialized elevator traffic simulators or general-purpose tools like MATLAB/Simulink, enables designers to evaluate system performance under various conditions, test different control strategies, and optimize elevator configurations. The accuracy of simulations depends heavily on realistic input data, including travel times, door operation times, and passenger boarding/alighting times. Careful consideration of simulation time and initial transient periods is necessary to obtain reliable results.

3.3. Deterministic Models

Simpler, rule-based or deterministic models can be used for initial estimations or specific, well-defined scenarios. These models often rely on average travel times per floor and fixed stop durations. While providing a quick approximation, they often fail to capture the complexities of real-world traffic variations and dynamic system behaviour. These models might be suitable for preliminary design but should be augmented with more sophisticated analysis for detailed system planning.

4. ADVANCED METHODOLOGIES: INCORPORATING INTELLIGENCE

The advent of smart building technologies, interconnected systems, and advancements in artificial intelligence has revolutionized elevator control and arrival time prediction.

4.1. Destination Control Systems (DCS)

Image Source https://www.otis.com/en/us/products-services/products/compass-360

Destination control systems represent a significant leap in elevator efficiency. Instead of simply pressing "up" or "down," passengers input their destination floor at a terminal in the lobby. The system then assigns a specific elevator car, often grouping passengers with similar destinations. This approach significantly reduces the number of stops each car makes and minimizes overall travel time by optimizing car assignments and minimizing unnecessary travel, DCS enhances efficiency and improves the passenger experience by providing clearer instructions and reducing waiting times.

4.2. Machine Learning and AI In Elevator Control

Machine learning (ML) and artificial intelligence (AI) are transforming elevator dispatching by enabling predictive capabilities and adaptive control. ML models can analyze historical and real-time traffic data, including passenger arrival rates, destination patterns, and car occupancy, to forecast elevator demand and optimize car dispatching policies. Deep learning and reinforcement learning algorithms can create highly adaptive control systems that learn from changing traffic patterns and adjust dispatching strategies in real time, even managing complex scenarios with overlapping or mixed traffic patterns. These systems can also incorporate sensor data, including computer vision and weight sensors, to detect car occupancy and optimize passenger grouping, further enhancing real-time efficiency. AI-powered algorithms aim to minimize waiting times and maximize throughput under varying conditions.

5. FACTORS INFLUENCING ARRIVAL TIME CALCULATIONS

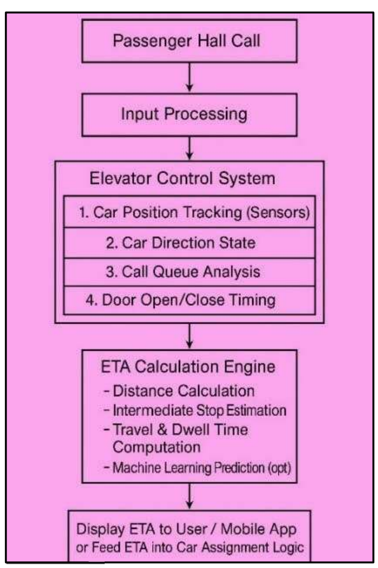

Figure 3

The accuracy of arrival time calculations is significantly influenced by a multitude of factors related to the building, passengers, elevator system design, and control mechanisms. Refer to Figure 3.

5.1. Building Characteristics

- **Building Type and Occupancy:** The purpose of a building (e.g., residential, office, hotel) dictates its typical traffic patterns and the associated demands on the elevator system.
- **Building Height and Layout:** Taller buildings necessitate higher elevator speeds and may benefit from zoning strategies to reduce travel time. The physical layout, including floor plate size and core design, also plays a role.
- **Number of Floors and Stops:** Each additional floor and stop directly contributes to increased Round-Trip Time (RTT) and overall journey duration.

5.2. Passenger Behaviour

Arrival Patterns: The distribution of passenger arrivals (e.g., concentrated peaks, dispersed random arrivals) impacts queuing dynamics and waiting times.

Destination Selection: The method by which passengers register their destination (e.g., destination keypads vs. simple up/down buttons) influences how dispatching algorithms can group and assign cars.

Passenger Transfer Times: The time taken for passengers to board and alight an elevator car, affected by factors like car capacity and passenger flow, contributes to the overall cycle time. Door opening and closing times are critical components of this transfer time.

5.3. Elevator System Design Parameters

- **Car Speed and Acceleration/Deceleration:** Higher speeds and faster acceleration/deceleration rates reduce travel time but are constrained by shaft dimensions and passenger comfort limits.

- **Number and Capacity of Cars:** The number of elevators and their capacity directly affect the system's handling capacity and the average waiting time for passengers.
- **Door Operations:** The time required for doors to open and close contributes significantly to the overall cycle time and, consequently, to arrival time estimation

.5.4. Control System Architecture

- **Control Algorithms:** Different algorithms, such as collective control, group control, and destination control, manage car assignments and influence arrival times.
- **Optimization Strategies:** Techniques like zoning (dividing floors into segments served by specific cars), load balancing, and priority control (giving precedence to certain calls) further refine system performance.

6. CHALLENGES AND FUTURE DIRECTIONS

While significant progress has been made, challenges remain in achieving fully optimized and predictive elevator systems.

6.1. Challenges In Real-World Implementation

Data Accuracy and Completeness: Obtaining precise, real-time data for all variables influencing arrival times can be challenging.

Managing Dynamic Traffic: Accurately predicting and managing highly dynamic and unpredictable traffic patterns remains a complex task.

Integration with Building Systems: Seamless integration of elevator systems with other building management systems (BMS) is essential for holistic smart building operation.

6.2. Emerging Technologies

Future elevator systems will likely incorporate:

- **Multi-car Elevator Systems:** Innovations like cars that operate independently in the same shaft promise enhanced capacity and reduced waiting times.

- **Cable-Free technology:** Maglev technology could enable horizontal and vertical movement, revolutionizing building design and passenger flow.
- **Advanced AI and Machine Learning:** Further research in these areas will lead to more sophisticated predictive maintenance according to MDPI and opportunity for ML-based dispatching improvements, like predictive parking to anticipate demand, etc.
- **Sensing Technologies :** LiDAR, video analytics, mmWave, etc. There is potential to use this to sense demand and car capacity to make intelligent adjustments to dispatching.

6.3. The Vision of Smart Buildings

Elevator systems are becoming integral components of broader smart building ecosystems. Future intelligent buildings will seamlessly integrate elevators with floor access control, lighting, HVAC, and security systems, creating a fully interconnected and responsive environment that optimizes resource allocation and enhances occupant comfort.

7. CONCLUSION

This paper summarized the complexities of elevator car arrival time calculation and its importance in modern buildings. The fundamental principles of elevator traffic analysis, including key performance indicators, were established. The foundational RTT formula and the challenges in accurately estimating its components were discussed.

Traditional methodologies, such as analytical models based on queuing theory and discrete event simulation, were presented. While queuing theory offers a mathematical framework, simulation-based methods are more versatile in real-world scenarios.

The paper highlighted the impact of advanced methodologies, particularly Destination Control Systems (DCS), on reducing stops and optimizing car assignments. Machine Learning (ML) and Artificial Intelligence (AI) were identified as key drivers for predictive arrival time estimation and adaptive control. The role of IoT integration and predictive maintenance in enhancing system reliability was also emphasized.

Factors influencing arrival time calculations were explored. These include building characteristics, passenger behaviour, elevator system design parameters, and control system architecture. The challenges in real-world implementation and future directions, such as multi-car systems and further integration of AI, were also discussed.

Key Learning and Takeaways

The main takeaway is that elevator car arrival time calculation is evolving from basic theoretical models to sophisticated, data-driven, and adaptive systems. The key takeaways are:

Understanding the fundamentals is essential: A solid grasp of KPIs, such as AWT and RTT, along with their influencing factors, is essential for effective elevator system design and management.

Simulation is a critical tool: Simulation provides a robust platform for evaluating performance under diverse, real-world conditions.

Intelligence enhances efficiency: Advanced technologies like Destination Control Systems and AI-powered dispatching demonstrably improve efficiency.

Data is key: The use of real-time data, enabled by IoT integration and analysed by ML/AI, is key for predictive maintenance, adaptive control, and continuous performance optimization.

Holistic design is key: Optimizing elevator arrival times requires a holistic approach, considering not just the elevator system itself but also building characteristics and passenger behaviour.

Continuous improvement: Staying abreast of emerging technologies and adopting a proactive approach to system upgrades is vital for maintaining optimal performance.

By adopting these learnings and leveraging the advancements discussed, vertical transportation systems can be optimized to meet the demands of modern urban environments and contribute to the vision of smart buildings.

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BIOGRAPHICAL DETAILS

Vinoth Rajendran is a seasoned engineering professional with extensive experience in elevator design and mechanical systems. He currently serves as Assistant Manager at Otis India, where he plays a pivotal role in harmonizing engineering modules across global regions, driving innovative design strategies, and leveraging the product portfolio to enhance operational efficiency and market responsiveness.

S. Vignesh is an experienced Engineering executive currently working in Otis India at Bengaluru. With a strong background in elevator systems and technology integration, he plays a key role in driving innovation and operational excellence. His work focuses on leveraging emerging technologies such as enhance elevator design, installation, and predictive maintenance.

Mohamed Shameer is a distinguished engineering professional with extensive expertise in elevator design and mechanical systems. Currently serving as Assistant Manager at Otis India, he spearheads global engineering module harmonization initiatives, formulates innovative design strategies, and streamlines the product portfolio to enhance operational efficiency and responsiveness to market dynamics.