Evaluation of Comfort Levels and Prospects for Sensor Application in Elevators: Insights from China's Experience

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Abstract. As China's economy has flourished, there is an escalating pursuit for an enhanced quality of life. This has led to heightened expectations for superior elevator experiences, especially in upscale residential complexes. In this study, we delved into the evaluation of various factors influencing elevator comfort, such as operational noise, stability, interior conditions, and ventilation systems. Additionally, we analyzed the root causes of abnormal elevator noises and unsettling movements. From these investigations, we propose a tailored testing and evaluation strategy. We also foresee the integration of specific sensors dedicated to monitoring the indoor environment of passenger elevators, enhancing both safety and comfort levels. This research provides valuable insights for future comfort level evaluations in elevator operations, the formulation of inspection and testing standards, and the design and manufacturing of elevators focused on optimal user comfort.

Keywords. Elevator, Comfort level evaluation, Elevator maintenance, Elevator ride experience, Sensors

1. Introduction

The rapid urbanization across the globe has led to a marked rise in the number of high-rise structures, making elevators, especially traction-driven passenger elevators, a critical element of today's architectural landscape. Globally, the safety and efficiency of passenger elevators have always been paramount in manufacturing and maintenance. However, beyond these two core elements, the comfort of elevators has started to garner attention from both users and manufacturers. The comfort level of an elevator ride not only pertains to passenger experience but also influences the overall utility and value of the building.

Against this backdrop, countries worldwide have established relevant standards and regulations to ensure the quality and safety of passenger elevators. China, as one of the largest elevator markets globally, has particularly crucial standards for elevator regulation. Presently, inspections and tests for traction-driven passenger elevators in China are conducted in accordance with the "Elevator Supervision and Inspection and Regular Inspection Rules -

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Traction and Positive Drive Lift" guidelines [1]. These regulations comprehensively outline the procedures to ensure elevator quality and safety, aiming to protect the rights of users. However, they seem to lack in specifying parameters for evaluating comfort levels during everyday elevator operations and corresponding manufacturing standards [2].

In practice, the department overseeing special equipment safety only issues corrective recommendations based on established regulations and on-site inspection findings when passengers experience unsafe elevator conditions due to specific hazards. Often, subtler discomforts in elevator operations, such as excessive motor noise, pronounced shaking, dim cabin lighting, or piercing alarm bells, fail to garner the attention of administrative bodies [3, 4]. For regular users of these elevators, such factors can lead to negative experiences like disrupted sleep, anxiety, despondency, or even physical injuries, rivaling the effects of overt safety threats. Many of these discomforts arise from design shortcomings, manufacturing inconsistencies, installation errors, or notably, sporadic maintenance [5].

To address the growing expectations for superior elevator comfort and modern residential property management standards [6], it is imperative to develop comprehensive testing and evaluation protocols related to elevator operation comfort. This is similar to a hospital physical examination, in which the various testing items associated with comfort level should be set up for user choice. Followed by improving the comfort level of elevator ride via analysis of the testing results from various aspects.

In light of this, we've identified various test criteria to assess comfort levels during the operation of traction-driven passenger elevators, elucidating the crucial factors that contribute to comfort. Moreover, in response to the rising demands of elevator users for enhanced safety and comfort, we also explore the prospective applications of sensors monitoring temperature, humidity, and gas in the confined spaces of elevators.

2. Testing and evaluation of comfort level

2.1. Inspection standards, testing items and testing equipment

The testing items were selected and conducted according to the inspection standards as follows:"Regulation for Lift Supervisory Inspection and Periodical Inspection (TSG T7001-2023)","Regulation for Lift Examination by the Owner (TSG T7008-2023)", "Safety rules for the Construction and Instalation of Lifts (GB/T7588-2020)", "Technical Conditions for Elevators (GB/T 10058-2009)", "Elevator inspection method (GB/T 10059-2009)", "Measurement of Elevator Ride Quality (GB/T 24474-2009)", and "Standard for Lighting Design of Buildings (GB 50034-2013)". These tests evaluated various aspects such as acceleration and deceleration during elevator startup, operational noise, leveling precision and accuracy, in-cabin comfort levels, and vibration intensity during operation. The instruments for testing include: multimeter, comprehensive elevator tester, illuminometer, vernier caliper, steel ruler, standard sound level meter, stopwatch, tape measure, temperature and humidity meter, electrician tools, and portable lighting test lamp [7].

2.2. Acceleration and deceleration during elevator startup

The acceleration sensors were installed in the middle of the lift car floor, followed by the inspectors adopted an elevator comprehensive tester to respectively measure the acceleration and deceleration when the elevators go up and down under light load (up to 2 passengers) and rated load conditions.

1)The maximum starting acceleration and braking deceleration of the elevator should not exceed 1.5 m/s^2;

2)When the rated speed (v) of the elevator is $1.0 \text{ m/s} < v \leq 2.0 \text{ m/s}$, the acceleration and deceleration should be greater than 0.5 m/s^2; And when the rated speed of the elevator is $2.0 \text{ m/s} < v \leq 6.0 \text{ m/s}$, the acceleration and deceleration should be greater than 0.7 m/s^2.

Acceleration and deceleration significantly influence the comfort levels during elevator operation [8]. Excessive acceleration or deceleration can induce a feeling of weightlessness in passengers, making it challenging for them to maintain stability, and possibly leading to falls or injuries. Conversely, minimal changes in speed can prolong the time taken to reach the elevator's rated speed, compromising its operational efficiency. Therefore, fine-tuning the acceleration and deceleration ensures a balance between the elevator's efficiency and the comfort level for passengers.

2.3. Elevator running noise

Auxiliary equipment such as fans, air conditioners, alarms and broadcasts in the lift car should be turned off before noise testing.

2.3.1. Noise inside the lift car during operation

The acoustic sensors were installed at the circular region with a radius of 0.10 m in the center of the lift car floor, which are 1.50 ± 0.10 m from the floor and facing the lift car door in a horizontal direction. The elevators go up and down at maximum rated speed during the testing process.

2.3.2. Noise caused by opening and closing doors

The installed acoustic sensors are horizontally facing the lift car door and landing door, which are 0.24 m from the doors and 1.50 ± 0.10 m from the lift car floor. The lift car door is opened and closed to the maximum possible extent during the testing process.

2.3.3. Noise in elevator machine room

The acoustic sensors were successively installed at 1 m away from the front, back, left, right and top of the driving engine of the elevator. The elevator runs at rated speed during the testing process, in which the five measured values were averaged. Notably, the measurement points can be reduced because of the limitations of the building structure or equipment layout.

Similarly, the various noises generated during elevator operation also greatly affect its comfort level, and even affect the sleep quality of surrounding residents during nighttime operation. Fortunately, these noise can be reduced by optimizing the elevator car structure and shaft layout or installing sound-insulating materials. Table 1 present the noise requirements during elevator operation.

Table 1. Elevator Operation Noise Requirements

Rated speed (v, m/s)	Machine Room Noise	Cabin Interior Noise	Door Opening/Closing Noise	Noise at the Door Without a Machine Room
v≤2.5m/s	≤ 80 dB	≤ 55 dB	≤ 65 dB	≤ 65 dB
2.5m/s<v≤6.0m/s	≤ 80 dB	≤ 60 dB	≤ 65 dB	Not exceeding the allowable value set by the manufacturer. If not specified by the manufacturer, it is determined according to the limit value index of the elevator with a rated speed of 2.5m/s.
v>6.0m/s	Not exceeding the allowable value set by the manufacturer. If not specified by the manufacturer, it is determined according to the limit value index of the elevator with a rated speed of 6.0m/s.			

2.4. Leveling accuracy and precision

2.4.1. Leveling accuracy

After the elevators completes an ascending and descending process under light load and rated load conditions, the vertical height difference between the upper surface of the landing sill and the upper surface of the lift car sill was measured in the middle of the door.

2.4.2. Leveling precision

After the lift car stays on the bottom level position for 10 min under light load and rated load conditions, the vertical height difference between the upper surface of the landing sill and the upper surface of the lift car sill was measured in the middle of the door.

The leveling accuracy and precision of the lift car should be within the ranges of ± 10 mm and ± 20 mm, respectively. If they exceed these ranges, there will be a significant height difference between the lift car sill and the landing sill, which can cause users to trip, and even pose a safety hazard of persons or objects falling into the elevator hoistway when the height difference is too large.

2.5. Lighting, alarm and ventilation conditions in the lift car

2.5.1. Lighting system

The "Safety Code for Elevator Manufacturing and Installation (GB7588-2003 (2015))" dictates that lift cars must have permanent electrical lighting, ensuring illumination greater than 50 lx, including on the lift car floor. The national standard sets only a minimum illumination threshold. In practice, 50 lx might not adequately light the whole lift car, potentially making the experience feel more oppressive. Conversely, excessive brightness could be dazzling. However, achieving this balance in real-time requires more than just fixed standards. Building upon the earlier discussion, the integration of illumination sensors can play a pivotal role. Illumination sensors, paired with adaptive lighting systems in elevators, can dynamically monitor and adjust brightness based on ambient conditions, enhancing user comfort and promoting energy efficiency.

As per the "Standard for Architectural Lighting Design (GB 50034-2013)" [9], standard lighting parameters for residential buildings are shown in Table 2.

Table 2. Standard for Residential Building Lighting (Excerpt)

Places	Height	Illuminance level (lx)
Living room (general activities)	0.75 m from the ground	100
Elevator lobby	Ground	75
Living room for seniors (general activities)	0.75 m from the ground	200

2.5.2. Alarm system

According to the inspection standard of "Safety Code for Elevator Manufacturing and Installation (GB7588-2003 (2015))", an alarm device that is easy for passengers to recognize and touch should be installed inside the lift car for enabling them to seek assistance in time [10]. The standard does not specify the sound level of the alarm bell. In fact, the loud and piercing sound of the emergency alarm devices can exacerbate the anxiety and depression of the trapped persons. Therefore, it is suggested that the alarm devices with bell below 80 decibels are installed in the lift car.

2.5.3. Ventilation system

The aging of the ventilation system in elevator lift car is prone to resulting in the excessive noise mentioned above, and thus requires timely replacement and maintenance. Apart from that, the wind speed, temperature, and air quality are governed by the ventilation system, which affect the comfort level of elevator ride. To improve the comfort level, the ventilation system, air conditioning and air purification equipment should be periodically inspected and maintained.

2.6. Degree of elevator vibration during operation

The vibration sensors were installed in the middle of the lift car floor, followed by the inspectors adopted an elevator comprehensive tester to respectively measure the vibrational acceleration when the elevators go up and down under light load and rated load conditions.

1) The maximum peak value of the vibration in the vertical direction (Z-axis) should not exceed 0.30 m/s^2 when the elevator runs at a constant acceleration. The peak value of A95 should not exceed 0.20 m/s^2. (Note: Measuring according to T24474-2009 and recording the peak value of the vibration curve using the weighted time domain)

2) The maximum peak values of the vibration in the horizontal direction (X-axis and Y-axis) should not exceed 0.20 m/s^2 when the elevator runs at a constant acceleration. The peak values of A95 should not exceed 0.15 m/s^2.

There are many reasons for the vibration caused by elevator operation. It is recommended to periodically inspect and improve the running conditions concerned with the frequency converter, the straightness of the elevator guide rail, degree of wear of the elevator guide shoe, and elevator shaft.

3. Record of inspection results and evaluation of comfort level

Considering the aforementioned inspection results and analysis, we propose an evaluation method for elevator operational comfort based on a scoring mechanism. Table 3 presents the initial records from the comfort level testing of traction-driven passenger elevators. The maximum achievable score across all tests is 39 points. A score of 31 or higher signifies excellent comfort, allowing users to address specific lower-scoring aspects as needed. A score ranging between 15 and 30 indicates good comfort with certain areas warranting attention. However, a score of 14 or less reveals a subpar comfort level, necessitating immediate rectification. Undoubtedly, various factors influence elevator comfort. Comprehensive comfort assessments empower supervisory bodies to implement specific enhancements, addressing user feedback and promoting an improved elevator experience.

Table 3. SOriginal record of comfort testing of traction-driven passenger elevator

No.	Testing items	Testing contents		Evaluation standards	Sensor
1	Acceleration and Deceleration (m/s2)	Passenger elevator starting acceleration is ≤ 1.5 m/s2		When the rated speed of the elevator is 1.0 m/s <v ≤ 2.0 m/s, the acceleration and deceleration < 0.5 m/s2 is 2 points, ≥ 0.5 m/s2 and ≤ 1.5 m/s2 is 3 points, >1.5 m/s2 is 1 point;	Accelerometer
		Passenger elevator braking deceleration is ≤ 1.5 m/s2		When the rated speed of the passenger elevator is 2.0 m /s < v ≤ 6.0 m/s, the acceleration and deceleration < 0.7 m/s2 is 2 points, ≥ 0.7 m/s2 and ≤ 1.5 m/s2 is 3 points, > 1.5 m/s2 is 1 point.	
2	Noise level dB (A)	v ≤ 2.5m/s	The average noise in the equipment room is ≤ 80 when running at rated speed	Scoring 1 point when the noise level is > 80 dB, 3 points when the noise level is ≤ 80dB	Sound Level Meter
			The maximum noise value in the car during operation is ≤55	Scoring 1 point when the noise level is > 55 dB, 3 points when the noise level is ≤ 55 dB	
			The maximum noise value of the opening and closing process is ≤65	Scoring 1 point when the noise level is > 65 dB, 3 points when the noise level is ≤ 65 dB	
		2.5m/s < v ≤ 6.0m/s	Average noise in the equipment room when running at rated speed is ≤ 85	Scoring 1 point when the noise value is>85 dB, 3 points when the noise value is ≤ 85 dB	
			The maximum noise value in the car during operation is ≤ 60	Scoring 1 point when the noise level is > 60 dB, 3 points when the noise level is ≤ 60 dB	
			The maximum noise value of the opening and closing process is ≤ 65	Scoring 1 point when the noise level is > 65 dB, 3 points when the noise level is ≤ 65 dB	
3	Leveling accuracy and precision (mm)	Leveling accuracy of elevator lift car is ≤ ± 10		Scoring 3 points when the leveling accuracy is ≤ ±10, 1 point when the leveling accuracy is >±10	Leveling Accuracy Sensor
		Leveling precision of elevator lift car is ≤ ± 20		Scoring 3 points when the leveling precision is ≤ ± 20, Scoring 1 points	

					when the leveling precision is >±20	
4	Lighting, alarm and ventilation conditions in the lift car	Lighting of the elevator lift car (lx)		Ground illumination level is ≥ 75	Scoring 1 point when the illumination level is < 50 lx, Scoring 2 points when the illumination level is ≥ 50 lx and < 75 lx, Scoring 3 points when the illumination level is ≥ 75 lx	Illuminance Sensor
				Illumination level on 0.75 m from ground is ≥ 100	Scoring 1 point when the illumination level is < 75 lx, Scoring 2 points when the illumination level is ≥ 75 lx and <100 lx, scoring 3 point when the illumination level is ≥ 100 lx	
		Emergency alarm device (dB)		Noise value is < 120	Scoring 1 point when the noise level is >120 dB, Scoring 2 points when the noise level is > 80 dB and ≤ 120 dB, Scoring 3 points when the noise level is ≤ 80 dB	
		Ventilation system of the elevator lift car			Scoring 1 point when the noise level is > 80 dB or dust accumulation causes failure, Scoring 2 points when the ventilation system works fine and its noise level is ≤ 80 dB, Scoring 3 points when the ventilation system works fine, its noise level is ≤ 80 dB and there are air conditioners or air purifiers.	Sound Level Meter, Anemometer, Air Quality Sensor
5	Degree of elevator vibration during operation (m/s2)	The vibration in the vertical direction (Z-axis) at a constant acceleration		Maximum peak value of vertical vibration is ≤ 0.30 A95 peak of vertical vibration is ≤ 0.20	Scoring 1 point when neither of the two items meets the requirements, Scoring 2 points when only one of the two items meets the requirements, Scoring 3 points when both items meet the requirements	Operating Quality Sensor, Vibration Sensor
		The vibration in the horizontal direction (X and Y axis) during operation	X-axis	Maximum peak of horizontal vibration is ≤ 0.20 Horizontal vibration of the A95 peak is ≤ 0.15	Scoring 1 point when neither of the two items meets the requirements, Scoring 2 points when only one of the two items meets the requirements, Scoring 3 points when both items meet the requirements	
			Y-axis	Maximum peak of horizontal vibration is ≤ 0.20 Horizontal vibration of the A95 peak is ≤ 0.15	Scoring 1 point when neither of the two items meets the requirements, Scoring 2 points when only one of the two items meets the requirements, Scoring 3 points when both items meet the requirements	

4. Application of sensors for environmental monitoring in future elevators

In the wake of rapid advancements in science and technology, there exists an escalating demand for more intelligent living. This thrust towards high-quality, tech-driven lifestyles has spurred the development of numerous sophisticated devices, fundamentally anchored by a diverse range of sensors. Particularly, with atmospheric pollution becoming a pressing concern, the rise in specialized temperature, humidity, and gas sensors for both ambient and interior monitoring has been remarkable. This technological evolution doesn't merely cater to environmental challenges but is reshaping the very spaces we inhabit, making them more intuitive and attuned to our needs.

Amidst this tech revolution, elevators, once simply seen as mechanical means for vertical transportation, are also poised for a dynamic shift. Like our evolving homes and workspaces, elevators are transitioning into sentient spaces that amplify user comfort and experience. The envisaged future for these elevators sees them integrated with the mentioned state-of-the-art sensors. This not only allows for real-time adjustments of internal parameters like temperature, humidity, and air quality but also enables proactive responses to varying occupancies and external conditions. For instance, elevators of tomorrow could detect higher occupancies and enhance ventilation accordingly or preemptively cool interiors on sweltering days before users even step in. Further, the symbiotic relationship between modern elevators and building management systems hints at elevators that are in sync with broader building conditions. These systems, when equipped with AI capabilities, can even predict and signal maintenance needs, ensuring longevity and seamless operation. Another pivotal transformation steered by the Internet of Things (IoT) is the metamorphosis of elevators into communication nodes. Should sensors detect anomalies, like hazardous gas concentrations, they could rapidly relay this data to central systems, potentially initiating emergency responses. Moreover, to align with global hygiene concerns, future elevators might be characterized by touch-free controls. Think gesture-driven commands or voice-activated floor selections, minimizing contact and fostering a more hygienic environment.

In essence, the ongoing revolution driven by sensors for environmental monitoring is reshaping the fundamental role of elevators. No longer just a mode for moving between floors, it's being re-envisioned as a smart, adaptive segment of contemporary buildings, prioritizing safety, efficiency, and above all, user comfort.

5. Conclusions

The exploration of elevator comfort level assessment, particularly in the Chinese context, uncovers a critical gap in the existing theoretical framework and normative standards both domestically and on a global scale. This shortfall translates to a lack of uniformity in the evaluation processes across different regions within China, driven largely by individual customer preferences rather than established criteria. The transformation of elevators from a luxury to a fundamental amenity, owing to China's economic progression and improved living standards, underscores the necessity for advancing the comfort level evaluations to meet the rising expectations of urban dwellers.

The focus of the current study on traction-driven passenger elevators provides a thorough examination of comfort evaluation methodologies, elucidating a broad spectrum of testing parameters and assessment standards. This investigation serves an important purpose: it addresses a theoretical necessity concerning elevator comfort assessments in China. The intrinsic connection between the comfort level of elevator operations and its design, manufacture, installation, and maintenance is duly acknowledged, setting a solid foundation for future investigative efforts.

Going forward, it is imperative to broaden the scope of research to refine evaluation metrics, develop robust statistical models, and advocate for a standardized national framework for elevator comfort assessments. In line with this, the prospective trajectory of elevator technology and comfort assessment envisaged in this paper emphasizes the integration of sensor technologies to continuously monitor and optimize elevator internal conditions, thereby elevating the user's travel experience. These anticipated advancements resonate well with the broader objective of aligning elevator operational comfort with the evolving demands of urbanization.

Moreover, future research endeavors could draw inspiration from the fields of conversational emotion recognition and graph convolutional neural networks as explored in studies by [11] and [12][13]. For instance, employing advanced machine learning techniques, such as Masked Contrastive Graph Representation Learning, could pave the way for developing sophisticated comfort level assessment models that can perceive and adapt to user preferences and emotional states in real-time. Additionally, exploring cross-modal feature fusion methods as discussed in [13], could provide novel insights into integrating diverse sensory data for a more holistic evaluation of elevator comfort. Through a multidisciplinary approach, the fusion of these cutting-edge technologies holds the promise of significantly enhancing the precision and effectiveness of elevator comfort level assessments, thereby contributing to the improved quality of urban living standards in China and beyond.

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