

## **CASE STUDY OF THE IMPLEMENTATION OF MODERN FIRE SAFETY AND EVACUATION TECHNOLOGIES AT SANT CUGAT STATION (BARCELONA): ACTIVE DYNAMIC SIGNAGE SYSTEM—ADSS/IADSS ACTIVE DYNAMIC EVACUATION SIGNAGE IN FULL-SCALE TRIALS**

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### **Abstract**

This study evaluates the effectiveness of evacuation guidance in large transport facilities based on full-scale trials conducted at Sant Cugat Station in Barcelona. The analysis is grounded in the assumption that, under dynamically worsening fire conditions involving smoke, elevated temperature, and toxic combustion products, occupants tend to rely primarily on the “nearest-exit” heuristic, while conventional static signage has limited operational influence on route-choice behavior. Three guidance configurations were compared: static signage (T.2.1), prototype dynamic signage supported by voice messaging (ADSS; T.2.2), and an integrated Intelligent Active Dynamic Signage System (IADSS; T.3) combining a decision-support module with synchronized visual–audible communication (ADSS + DSO/PA). The methodology included a structured analysis of controlled evacuation trials conducted on the same platform, video-recording analysis, questionnaire-based assessment, and performance evaluation using T50, T95, and total evacuation time. In the static configuration, nearly all participants selected the nearest exit, confirming the dominance of intuitive route choice. The ADSS configuration improved redirection toward the target exit, but its effectiveness depended strongly on signal visibility and was reduced by inconsistent public-address messages. The strongest overall performance was observed in the integrated IADSS configuration, where the simultaneous presentation of positive and negative cues within the user’s field of view, combined with consistent voice communication, improved rerouting effectiveness and shortened the final evacuation phase, as reflected in the temporal interpretation of the evacuation curves. The findings demonstrate that effective evacuation guidance requires full information at decision nodes, continuity of guidance along the route, and strict synchronization between visual and audible communication layers.

**Keywords:** evacuation guidance, dynamic evacuation signage, Active Dynamic Signage System (ADSS), Intelligent Active Dynamic Signage System (IADSS), Voice Alarm System (DSO), building EXODUS

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## 1. INTRODUCTION

In large transport facilities such as railway stations, metro systems, and passenger terminals, evacuation is complicated by complex spatial topology, multiple route branches, locally restricted visibility, and incomplete information available to occupants. Under such conditions, evacuees often rely on simple heuristics—most notably selecting the nearest visible exit or retracing the path by which they entered—rather than following the intended evacuation strategy [1,2,3]. This behavioral tendency becomes especially problematic under dynamically deteriorating conditions involving smoke, heat, and toxic gases, where the available safe egress time can rapidly decrease.

Previous research has shown that conventional static evacuation signage, although compliant with formal code requirements, may have limited operational effectiveness in real emergencies [4,5,6]. Earlier experimental studies also showed that conspicuousness, flashing-light cues, and directional visual stimuli can significantly influence exit recognition and exit choice during evacuation [6,7,8]. In the Sant Cugat-related ADSS/IADSS research stream, Galea et al. demonstrated that many occupants either fail to notice conventional signage or do not treat it as the decisive factor in route choice, particularly when intuitive “nearest-exit” decisions dominate behavior [2,3]. This problem is consistent with broader contemporary research on emergency wayfinding. Lin et al., in a systematic review and meta-analysis, showed that individual wayfinding decisions in emergencies are shaped by stress, perception, attention, and conflicting information, while enhanced signage can substantially increase the likelihood of selecting the indicated exit [9]. In metro environments specifically, recent studies further confirm that signage effectiveness depends not only on the presence of signs, but also on their visibility, placement, perceptual salience, and consistency with other information channels [10,11,12].

Against this background, dynamic evacuation signage has become an increasingly important research direction. A recent NFPA / Fire Protection Research Foundation review emphasizes that dynamic directional exit signage offers clear potential advantages over static systems in complex and evolving emergencies, especially where routes may become unavailable or suboptimal during the incident [13]. At the same time, the review identifies persistent regulatory, technological, and knowledge gaps, particularly concerning real-time sensing, control logic, human interpretation, and integration with emergency communication systems. Similar conclusions emerge from recent studies in urban rail transit and subway environments, where dynamic signage has been shown to improve evacuation efficiency, reduce wrong-route choices, and better support decision-making in complex layouts [10,11].

From this perspective, the ADSS/IADSS concept is not merely a technological modification of conventional wayfinding, but part of a broader shift from passive, code-compliant signage toward adaptive, information-rich evacuation guidance. The present study therefore examines the Sant Cugat Station trials not only as an isolated case, but as an important full-scale demonstration of how dynamic signage, when integrated with decision support and voice communication, can influence occupant behavior and improve evacuation performance under realistic transport-facility conditions.

Despite the growing body of research on dynamic evacuation signage, several important gaps remain. First, much of the existing literature is based on simulation, virtual reality environments, or laboratory experiments, with relatively limited evidence from full-scale field trials conducted in operational transport facilities. Second, while previous studies have demonstrated the potential of dynamic signage to influence evacuation behavior, less attention has been paid to the comparative effectiveness of different levels of system integration—from static signage, through partially active systems, to fully adaptive, multimodal guidance solutions.

This study addresses these gaps by providing a detailed analysis of full-scale evacuation trials conducted at Sant Cugat Station, comparing three distinct guidance configurations: static signage, ADSS-based dynamic signage, and an integrated IADSS solution combining real-time decision support

with synchronized visual–audible communication. In particular, the study contributes empirical evidence on the role of “full information” at decision points, the importance of perceptual visibility and message continuity, and the critical impact of consistency between visual signage and voice announcements on evacuation performance [2,3,10–13].

To structure the analysis, the study addresses the following research questions:

**RQ1:** To what extent does dynamic evacuation signage (ADSS) influence route-choice behavior compared with static signage?

**RQ2:** How does the effectiveness of dynamic signage depend on perceptual conditions such as visibility, sign placement, and information completeness?

**RQ3:** What is the impact of integrating visual and audible guidance (IADSS) on evacuation performance and user compliance?

The original contribution of this study lies in a structured case-study synthesis of the Sant Cugat full-scale evacuation trials and their interpretation in the light of more recent research on dynamic evacuation signage, multimodal emergency communication, and adaptive evacuation-control systems. While the primary empirical trials were originally reported by Galea et al. [2,3], the present manuscript does not merely reproduce those findings. Instead, it re-examines the trials through a broader contemporary framework, focusing on the transition from static signage to ADSS and IADSS, the role of full information at decision nodes, the interaction between visual and audible communication, and the practical implications for risk-informed evacuation design in large transport facilities.

## 2. RESEARCH OBJECTIVE

### 2.1. IADSS - Intelligent Active Dynamic Signage System

In response to the limitations of conventional static signage, the Intelligent Active Dynamic Signage System (IADSS) was proposed as an adaptive evacuation-guidance solution built around active dynamic signage (ADSS) [3,13]. From an engineering perspective, IADSS combines an executive interface layer—implemented as illuminated dynamic signage distributed in the built environment—with a supervisory decision layer capable of selecting and updating evacuation strategies in response to changing conditions [3,13,14]. This general logic is consistent with more recent research on adaptive guidance systems, which increasingly combines environmental monitoring, crowd-state estimation, simulation, and algorithmic route optimization to support real-time evacuation control [15].

The rationale for such systems is grounded in both behavioral and perceptual evidence. Emergency wayfinding studies indicate that occupants under stress are highly sensitive to the salience, clarity, and consistency of cues provided at decision points [9]. In metro settings, recent eye-tracking and VR-based studies further show that sign placement, message visibility, and the spatial relationship between guidance and route-choice nodes significantly affect how quickly and correctly users interpret evacuation information [10–12]. These findings help explain why static signs often remain secondary to intuitive route-choice heuristics, and why dynamic systems that present clearer and more salient information can achieve better compliance.

The study compared three evacuation-guidance configurations in the same station environment: static signage (T.2.1), a baseline ADSS solution with dynamic visual cues and a general voice message (T.2.2), and the integrated IADSS solution (T.3), in which the recommended route, the negation of

unavailable routes, and the PA/DSO message were coordinated. In contemporary terms, this corresponds to a progression from passive guidance, through partially active signage, to a fully integrated multimodal decision-support system. Recent work in urban rail transit and BIM/VR-supported subway evacuation similarly indicates that dynamic signage performs best when it reduces ambiguity, limits wrong-route choices, and remains coherent with users' cognitive needs under emergency conditions [10,11].

## **2.2. Architecture of the system under study**

### **2.2.1 Starting point and scope**

IADSS operates continuously and, in real time, collects two primary data types: signals from the fire detection system and video streams from CCTV. It then integrates this information into a single, coherent operational picture. On this basis, the decision module performs rapid short-term forecasts describing expected changes in environmental conditions (visibility, smoke conditions, toxicity, temperature) and, in parallel, compares several variants of evacuation flow guidance toward available and safe exits.

Once a strategy is selected, control is immediately passed to the executive layer. ADSS boards display unambiguous commands: green directional arrows guide occupants along recommended routes, while red crosses actively “close” routes deemed unavailable or hazardous. Critical here is the coupling with the public address (PA) system—the audio message is synchronized with the algorithm's decisions so that no contradictions arise between what the user hears and what is displayed on the signage.

The decision cycle is repeated at short intervals. Each new data packet triggers another assessment update and, if necessary, a change of strategy, ensuring that guidance remains adaptive and tracks the incident evolution. The system also provides for emergency modes, and the operator (human supervision over the AI module) remains “in the loop”—they can approve the selected strategy or introduce a correction if required by operational needs. As a result, IADSS is intended to function not only as a tool for reducing evacuation times, but also as a mechanism for mitigating the risk of secondary congestion and limiting occupants' exposure to deteriorating environmental conditions [3,13,14].

### **2.2.2 Information acquisition**

At the input stage, the system builds a current operational picture by integrating the “fire signature” from the detection system (smoke, temperature, toxicity) with CCTV image analysis. In the vision component, a people-counting algorithm (Vision Semantics) estimates both the number of occupants and their spatial distribution within the facility. Both data streams are updated in real time and, in this form, forwarded to the decision module—i.e., they constitute its “input,” on which subsequent inference and the selection of the guidance strategy are based. In other words, this does not refer to entry into the building, but to the entry of data into the control algorithm: on the one hand, the system receives information on how the hazard evolves (smoke/temperature/toxicity), and on the other, where people are located, how many there are, and where congestion may develop. Only after combining these data can the decision module generate up-to-date indications for the signage and public address messages [3,14].

### **2.2.3 CFD library (SMARTFIRE) as the basis for environmental forecasting**

A key element that “drives” the decision-making process is the CFD library (SMARTFIRE)—i.e., a pre-prepared set of fire development simulations for a specific facility. This is not a single simulation executed during an incident, but a database of ready-made scenarios computed in advance.

Each scenario in this library contains time histories of key environmental parameters in individual zones: temperature fields, visibility, smoke-layer height, and toxin concentrations. The simulations are parameterized to reflect typical uncertainties: different fire source locations, varying fire power (HRR), door configurations, and the operation of ventilation and/or smoke-extraction systems. As a result, the library covers realistic “families” of trajectories that may occur in a given spatial layout.

The essence of the solution is that the scenarios exhibit characteristic “signatures” that can be rapidly matched to sensor data and to information derived from CCTV analytics. In practice, the decision module does not run CFD from scratch; instead, it compares current measurements against the library templates and, within a very short time, selects the most probable fire development variant. The matched scenario is then treated as a short-term forecast of environmental conditions and is used to select the evacuation guidance strategy [3,13,14].

#### **2.2.4 Movement model (buildingEXODUS)**

In this arrangement, buildingEXODUS operates in parallel—an agent-based evacuation model that simulates pedestrian movement within the actual geometry of the facility. It accounts for capacity constraints of passages, stairs, and circulation nodes, as well as how people respond to smoke, thermal load, and toxicity. The model also reproduces the influence of informational stimuli: visual indications from ADSS and voice messages from the DSO (voice alarm system).

BuildingEXODUS is supplied with hazard fields provided by the matched CFD scenario from the SMARTFIRE library. As a result, walking speeds, directional decisions, and the ability to continue movement are derived directly from the current environmental conditions in individual zones, rather than from an assumption of constant parameters. The same model then makes it possible to rapidly compute multiple evacuation-control variants. These may differ, for example, in the set of available exits, guidance priorities in selected corridors, the sequence of directional signals and prohibition signals at nodes, and the way the inflow of people from platforms is metered to limit the formation of bottlenecks [3,14].

#### **2.2.5 SERM ranking function**

The SERM ranking is used to order the results for all tested evacuation-control variants. Its purpose is practical: instead of considering evacuation time, congestion, and health risk separately, SERM consolidates these elements into a single, comparable assessment of each strategy. This makes it possible to identify not only which option is the fastest, but which is simultaneously efficient and safe.

Within SERM, the logistical component is evaluated, i.e., how efficiently the crowd leaves the facility. This includes, among others, the total evacuation time and the time by which 95% of people have left the platform. It is complemented by parameters describing the “cost” and flow of movement: the cumulative distances walked by occupants, the number of level changes (e.g., stairs), as well as loads and bottlenecks at circulation nodes, indicating where and to what extent capacity is exceeded.

The second part is the health-risk component, i.e., an assessment of occupants’ exposure to a deteriorating environment. It accounts for visibility, doses of toxic substances, and thermal loads, as well as the resulting forecast of health consequences, including the potential occurrence of injuries among affected individuals. Under this approach, a strategy cannot be considered good merely because it is fast. If it routes people through zones with unacceptable environmental parameters, it is rejected.

Crucially, this set of measures acts as limit criteria for acceptable safety conditions. If a given variant exceeds hard safety thresholds—for example, permissible limits of toxin exposure or thermal

load—it is eliminated regardless of its evacuation times. Only strategies that satisfy these thresholds are then compared further: the indicators are normalized and weighted, and a ranking is produced from the safest and most effective variant to the weakest.

In brief, SERM is a multi-criteria evaluation mechanism that first enforces boundary safety conditions and only then orders the admissible strategies according to overall operational efficiency and risk to occupants [3].

### **2.2.6 Integrated evacuation information system: visual + audible (ADSS + DSO)**

On the user-communication side, ADSS is coupled with the DSO (Voice Alarm System). In practice, this means full synchronization of the visual and audible messages: light indications are issued in parallel with DSO announcements, and there is no situation in which the audio suggests something different from the signs. If ADSS guides occupants with a green direction or closes a route with a red prohibition signal, the DSO simultaneously specifies the recommended direction, informs about local closures, and explains the reason for rerouting—especially when it is non-intuitive (e.g., please proceed to the right toward stairwell D; exit A is temporarily unavailable).

Such coupling reduces information ambiguity and shortens users' response time. Importantly, DSO message scenarios are generated based on the same decision of the decision module, ensuring that the integrated visual–audible interface remains consistent throughout the entire guidance update cycle [3,15].

### **2.2.7 Faster-than-real-time (FTRT) computational–decision cycle**

The entire operational chain can be described as a sequence of repeated control cycles. An incident is triggered by a signal from the fire alarm system (SSP) or by a manual notification, after which the system aggregates the current data from environmental sensors and CCTV. The decision module compares the current readings with the scenario signatures stored in the CFD library (SMARTFIRE) in order to match the closest variant—potentially a combination of variants—and thereby obtain a short-term forecast of hazard fields in the facility's zones.

On the basis of this forecast, buildingEXODUS is executed to perform rapid evacuation simulations in the facility geometry for a set of feasible movement-guidance strategies. The computations are carried out in a faster-than-real-time mode, which makes it possible to anticipate incident evolution and evaluate the consequences of different decisions before they manifest in the physical space. The results are passed to the SERM ranking, which identifies the preferred strategy while simultaneously reporting the implications of the choice: evacuation time, exposure level, and critical locations such as nodes with limited capacity and a risk of congestion.

The recommendation is then submitted for approval within the decision loop, where the AI operator remains under operational supervision: the operator accepts the indicated variant or selects an alternative variant if required by operational constraints. After the strategy is chosen, the system proceeds to execution. ADSS activates sequences of green directional signals and red prohibition signals at nodes and along corridors, while the DSO broadcasts voice messages synchronized with the current guidance so that the visual and audible information remains consistent.

The update loop operates cyclically. Each new data batch triggers re-matching of the scenario in SMARTFIRE, rapid recomputation of variants in buildingEXODUS, an update of the SERM ranking, and—if necessary—an immediate switch of the guidance strategy together with the next package of synchronized visual–audible notifications delivered by ADSS/DSO [3,13–15].

### **2.2.8 Three-tier comparison architecture: T.2.1 (static) → T.2.2 (ADSS + PA) → T.3 (IADSS)**

Introducing IADSS into the control loop meant that the selection of the guidance strategy was no longer based solely on predefined, static rules, but on current observations and short-term forecasts of environmental conditions. In practical trials, this translated into a higher share of successful reroutings to the target exit, a faster transition into the high-intensity flow phase, a shortening of the final evacuation phase, and a reduction in the risk of secondary overloads at circulation nodes compared with configuration T.2.2 [3].

## **3. METHODOLOGY (PROCEDURES AND SCENARIOS)**

The present study is based on a structured analysis of previously reported full-scale evacuation trials conducted at Sant Cugat Station. These trials provide rare empirical field evidence for dynamic evacuation guidance, while the present manuscript develops a comparative synthesis and interpretation of their implications in relation to more recent research on ADSS/IADSS, multimodal emergency communication, and adaptive evacuation-control systems.

The trials involved recruited volunteer participants rather than a statistically random sample. Most participants were unfamiliar with the station layout or used it only occasionally, which made it possible to examine route-choice behavior driven primarily by current informational stimuli rather than by well-established spatial habits [2,3].

The trials were conducted on Platform 2, approximately 38 m in length. Along the platform edge, four exits were located and designated A, B, C, and D. Exits A and D provided direct egress to the outside. Exit B was a passenger elevator, which was taken out of service for the duration of evacuation. Exit C consisted of stairs leading to an underground passage. For clarity, the notation TS2.1, TS2.2, TS3.1, TS3.2, and TS3.3 is used to denote the original trial identifiers reported in the source studies, whereas T.2.1, T.2.2, and T.3 are used in this manuscript as analytical configuration labels corresponding respectively to static signage, baseline ADSS, and the integrated or improved ADSS/IADSS configuration.

Participants were distributed across seven holding areas arranged along the platform, maintaining a density of approximately 2 persons/m<sup>2</sup> in order to reproduce conditions close to peak-hour crowding as faithfully as possible. In trial TS2.1, 139 people participated and only static signage was used. In trial TS2.2, 152 people participated, and guidance was provided by the Active Dynamic Signage System (ADSS) [2,3].

### **3.1. Trial TS2.1**

In TS2.1, only static signs compliant with Directive 92/58/EEC were used, arranged in a manner typical for guiding occupants to the nearest exits. A total of 139 people participated in the trial. An additional informational stimulus was a PA-VA (Public Address & Voice Alarm) message—an integrated public address and voice alarm system—stating: “leave via the nearest exit”.

The results indicate that participants were dominated by an instinctive preference for the shortest route. As many as 99% of individuals headed toward the nearest exit, and video analysis showed that only approximately 5% of participants consciously looked at the signage. The platform was cleared in about 45 s, measured as the time until the last person passed through. The pedestrian flow was distributed almost evenly between exits A and D, whereas markedly fewer people used exit C, which led down

stairs to the underground passage—i.e., in a direction opposite to the intuitive movement toward the outside and daylight. This outcome confirms that, under platform conditions, decisions are made largely reflexively, and static signs have a limited influence on route choice as a decision factor [2,3].

### **3.2. Trial TS2.2**

Trial TS2.2 was a full-scale evacuation test conducted on the same Sant Cugat Station platform as TS2.1, while maintaining comparable initial conditions. Before the procedure was initiated, participants were distributed across seven marked holding areas along the platform, approximately 38 m in length, maintaining a similar occupant density. The start of evacuation was initiated by a voice alarm played in a loop to provide an unambiguous start signal.

In TS2.2, ADSS was activated in a configuration intended to force a redirection of the flow. Above the three nearest exits (A, B, C), a prohibition signal in the form of a red cross was displayed, whereas above the target exit D a flashing directional arrow was shown. The objective was to verify whether active signage can override the dominant habit of choosing the nearest exit and deliberately redirect occupants toward exit D.

The overall result demonstrated a clear behavioral shift: 63% of participants (95 of 152) used exit D, even though for most it was not the closest exit. A box-by-box analysis revealed an important perceptual mechanism. The highest compliance was achieved where participants could simultaneously see two messages: the prohibition signal above their own nearest exit and the positive signal indicating the alternative direction toward D. Prohibition alone, without a concurrent indication of where to move, proved insufficient. The authors also report “saw and ignored” cases, i.e., situations in which a participant looked at the prohibitive sign but still chose the nearest exit. In the authors’ interpretation, this did not result from misunderstanding the red cross, but from a failure to perceive the positive sign above the distant exit D. This led to a design conclusion: to achieve high compliance, direction negation and the indication of an alternative should appear within the user’s field of view at the same time [3]. Measurements in TS2.2, analogously to TS2.1, were based on video analysis and questionnaires. From the recordings, the authors determined how many participants used each exit, the time at which flows to each exit were terminated, and the time required to clear the entire platform. In parallel, the questionnaire was used to assess signage perception and the factors that actually influenced route-choice decisions. The authors indicate that ADSS had a more direct and unambiguous effect on route selection than static signs. The most effective configuration was one in which the participant simultaneously received negative information—do not use this exit—and positive information directing them toward exit D. In groups that had access to both messages at the same time, the proportion of participants following the indication increased to 71%. At the scale of the entire trial, 63% of participants completed the intended procedure and used the target exit D without staff intervention [2,3].

### **3.3. Trial T.3**

In trial T.2.2, a standard ADSS configuration was applied, in which the information displayed on the signs was insufficient to consistently enforce the intended rerouting. In parallel, the voice message was general in nature and could be interpreted as encouraging occupants to choose the nearest exit, which in practice weakened the movement-guidance logic and introduced message inconsistency. As a consequence, after the alarm-recognition phase the movement flow increased more slowly, and the evacuation profile exhibited an extended, almost linear character. The final phase was also visibly prolonged, i.e., the closure of evacuation when only a small number of people remain in the space, yet their removal takes disproportionately long.

After analysing these limitations, a correction was introduced and trial T.3 was designed, applying the IADSS variant. The key change was full information on each signboard: simultaneous indication of the recommended direction and an unambiguous negation of non-recommended exits. In addition, the voice message was modified to be neutral and not conflict with the system’s decisions. The signage operated as a synchronized chain of indications at successive route-choice points, so that after a short initial delay a dynamic start of flow and rapid evacuation closure were achieved.

In the TS3 series, three full-scale trials were conducted at the same station: TS3.1 with 171 participants, TS3.2 with 139 participants, and TS3.3 with 64 participants [3]. The same general platform geometry and the same operational assumption regarding the unavailability of exits A, B, and C were maintained. The objective was to direct participants toward exit D, which was treated as the target exit. TS3.1 used the modified signage configuration but retained the original voice message instructing users to use the nearest exit, whereas TS3.2 and TS3.3 introduced a modified, non-contradictory voice message. TS3.1 and TS3.2 used a broader distribution of participants along the platform, while TS3.3 concentrated participants near the end of the platform opposite the target exit, creating a more demanding rerouting condition. This arrangement made it possible to evaluate the system under both distributed and more challenging route-choice conditions, where the pressure to choose the nearest exit was stronger [3].

As a result, with a comparable number of participants, configuration T.3 provided a shorter median evacuation time and a markedly lower T95%, as well as a smaller proportion of individuals remaining in the final phase of the process. This indicates more effective rerouting of the flow to the target exit and a reduction of critical capacity overloads compared with T.2.2 [3].

#### 4. RESULTS

The results are presented comparatively across the three configurations to highlight the behavioral and operational differences between static, partially dynamic, and fully integrated guidance systems.

Table 1. Comparative summary of evacuation-performance indicators for the analysed configurations

Trial	Guidance system	Voice message		Main routing outcome	Actual rerouting effect	Temporal / operational interpretation
TS2.1 / T.2.1	Conventional static signage	“Use nearest exit”	139	99% selected the nearest exit	Not applicable	Platform cleared in approximately 45 s; movement was governed primarily by exit proximity rather than by signage.
TS2.2 / T.2.2	ADSS with separated positive and negative information	“Use nearest exit”	152	63% used target exit D	43% after excluding participants for whom D was the nearest exit	ADSS influenced route choice, but effectiveness was reduced by limited visibility of the positive cue and conflicting PA information.

<b>TS3.1 / T.3</b>	Modified ADSS / IADSS-related configuration	Original “use nearest exit” message	<b>171</b> / <b>168</b>	66.7% used target exit D	48.6% after excluding participants for whom D was the nearest exit	More complete signage improved rerouting, but the original voice message still conflicted with the signage logic.
<b>TS3.2 / T.3</b>	Modified ADSS / IADSS-related configuration	Modified non-contradictory voice message	<b>139</b>	66.9% used target exit D	57.8% after excluding participants for whom D was the nearest exit	Non-contradictory voice information strengthened the effect of dynamic signage.
<b>TS3.3 / T.3</b>	Modified ADSS / IADSS-related configuration	Modified non-contradictory voice message	<b>64</b>	65.6% used target exit D	65.6%; all participants started closer to other exits	Most demanding rerouting condition; participants had to pass nearer exits to reach the target exit.

*Note: T50 and T95 are discussed in the manuscript based on the available evacuation curves and documented temporal interpretation; the table reports only consistently available comparative indicators. For TS3.1, 171 denotes the number of participants in the trial, whereas 168 denotes the number of participants included in the video-based behavioural analysis.*

#### **4.1 Characteristics of the evacuation process—T.2.1**

In the baseline trial TS2.1, which served as the reference condition for guidance based on static signage, the choice of the nearest exit was dominant. It was recorded that 99% of participants evacuated according to a simple distance-minimization rule [2,3]. The questionnaires confirmed this mechanism: proximity of the exit was the most frequently indicated reason for the decision (51% of responses), whereas the influence of the static signs themselves was rated markedly lower, at approximately 27% [2,3].

The authors also note that video recordings showed only a small number of individuals exhibiting behavior associated with consciously searching for and reading the signage. This reinforces the conclusion that passive evacuation signs in platform conditions have limited decision-making agency when proximity to an exit remains the primary route-selection criterion [2,3].

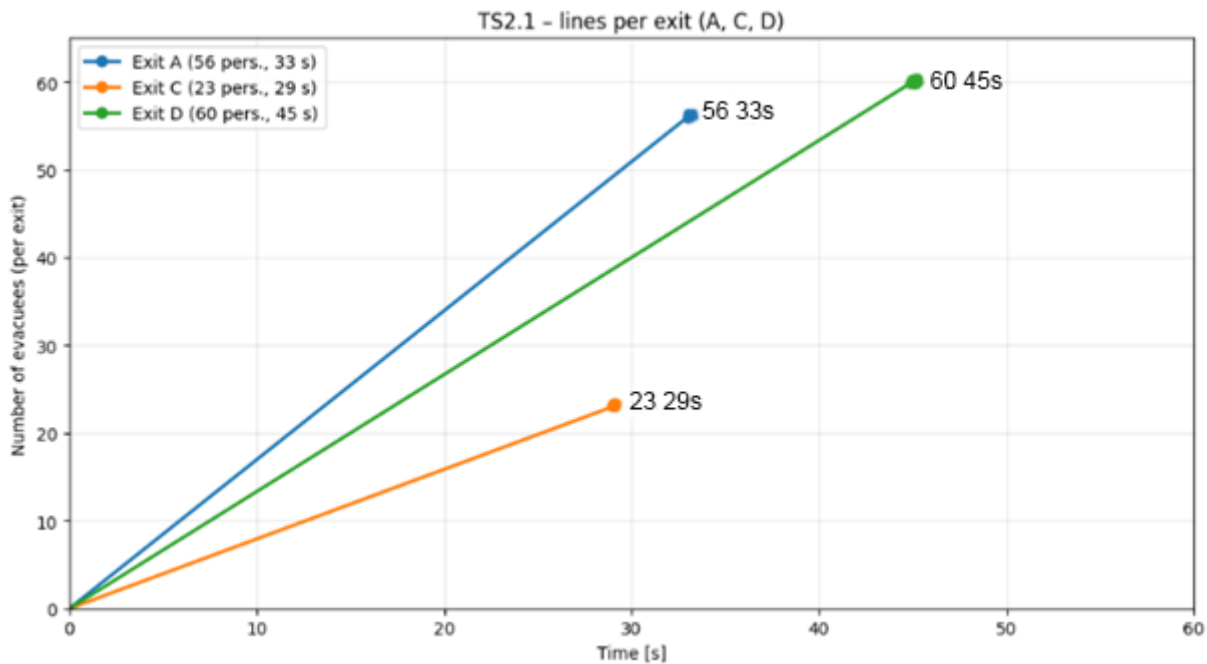


Fig. 1. Number of occupants evacuating through exits A, C, and D over time

The chart presents the evacuation progression in trial TS2.1, i.e., the variant based on static signage. The data are shown separately for three exits: A, C, and D. Each curve represents the cumulative number of occupants who left the platform via a given exit as a function of time. The end points indicate the moment the flow ceased and the total number evacuated: for exit A, 56 occupants in 33 s; for exit C, 23 occupants in 29 s; and for exit D, 60 occupants in 45 s. From the slope of the curves, the flow intensity can be inferred: approximately 1.7 persons/s for A, 0.8 persons/s for C, and 1.3 persons/s for D.

The chart shows a typical nearest-exit choice pattern. The highest loads occur at exits A and D because these exits are closest to the main initial clusters. Exit C, which leads down stairs to the underground passage, is used markedly less frequently and reaches the lowest flow intensity. Operationally, this indicates that in configuration TS2.1 the distribution of movement is shaped primarily by geometry and the reflex to minimize travel distance rather than by information conveyed by the signage: the flow self-distributes toward the most intuitive directions (A and D), while the route requiring a level change and descent via stairs (C) remains underutilized.

#### 4.2 Characteristics of the evacuation process -T.2.2

In trial TS2.2, a prototype ADSS system was applied. Above exits A, B, and C, a red prohibition signal (cross) was activated, while above exit D a pulsating green directional arrow was displayed. At the global level, 63% of participants reached the target exit D [2,3]. After excluding those for whom D was the nearest exit, the actual rerouting effect was **43%** [2,3].

The effectiveness of ADSS strongly depended on the initial position. Participants located in the C area had, simultaneously within their field of view, the negating signals at A, B, and C and the positive

signal above D; consequently, as many as 71% of them chose exit D [2,3]. In the A–B zones, the green arrow was less visible, and decision-making more often reverted to the distance-minimization mechanism, i.e., selecting the nearest available exit.

The questionnaires confirmed that the ADSS visual message was legible to users and influenced their decisions. Among participants who noticed at least one ADSS sign, 65.6% declared that the flashing arrows helped them choose the direction, 61.5% indicated that they accelerated decision-making, and 51.0% regarded the red cross as unambiguous information about which exit should not be used [2,3].

The authors, however, identified two significant weaknesses of the TS2.2 configuration. First, the positive signal appeared only above exit D, and along the route there were no additional green indications to sustain guidance at intermediate decision points. Second, the concurrently broadcast voice message suggested using the nearest exit, which weakened the intended ADSS control logic and introduced informational inconsistency [3].

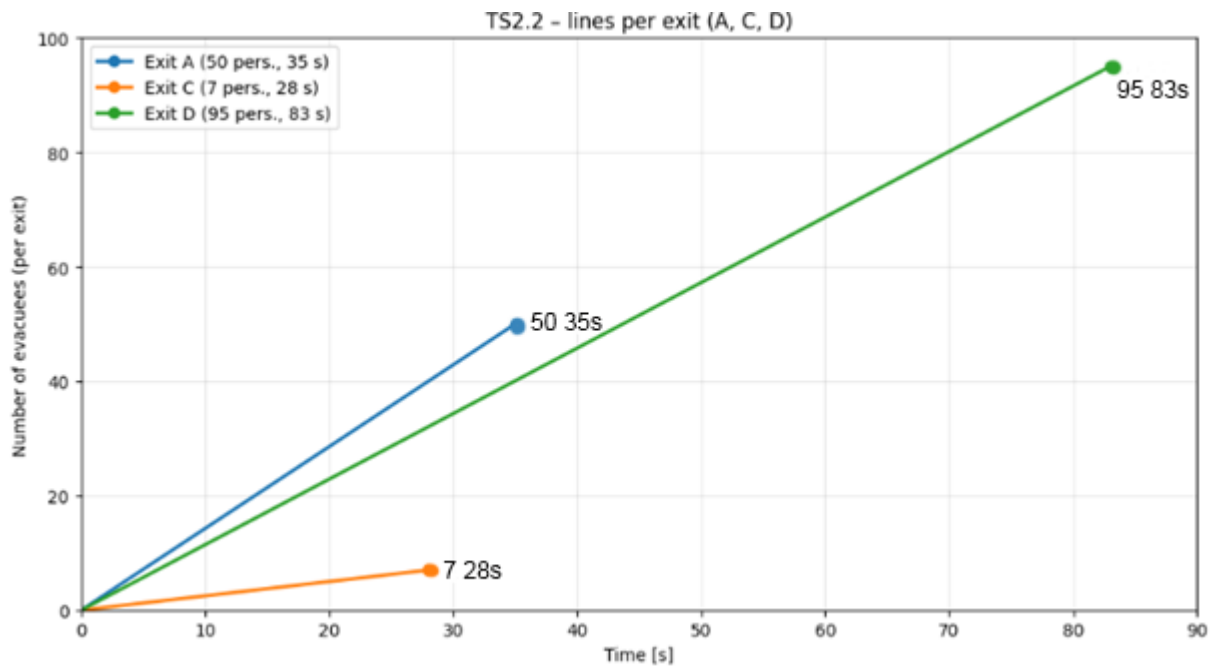


Fig. 2. Number of occupants evacuating through exits A, C, and D over time

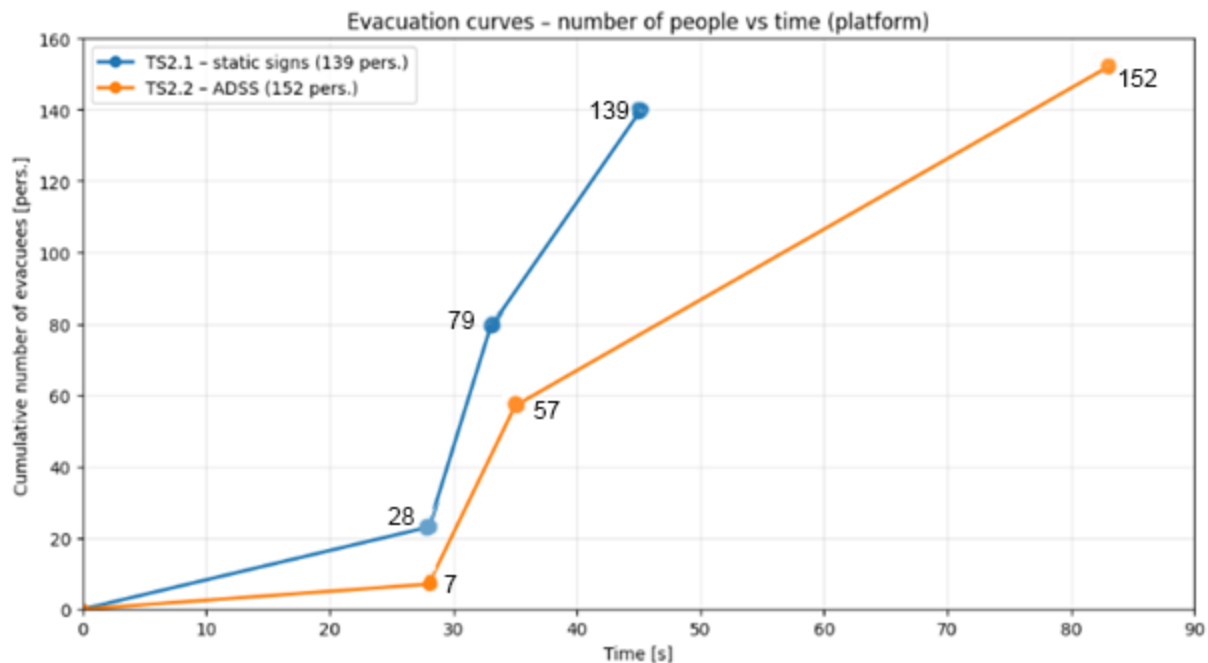


Fig. 3. Evacuation curves showing the number of people leaving the platform over time

After completing T.2.2, two key weaknesses of the applied configuration were identified. The first was the lack of continuous guidance along the route: the positive signal in the form of a green arrow appeared only above the target exit, while intermediate decision points lacked additional indications that would reinforce the user's choice. The second was informational inconsistency resulting from the voice message "use nearest exit," which could direct participants toward the closest exit and thus act against the intended rerouting.

After implementing corrections, T.3 was initiated as a series of trials with a fully integrated IADSS. In this configuration, full information was provided on the signboards: the recommended direction was displayed simultaneously with an unambiguous negation of non-recommended directions. In parallel, the content of the voice messages was modified so that it remained consistent with the guidance logic and did not conflict with the system's decisions [3].

### 4.3 Characteristics of the evacuation process - T.3

The T.3 results confirmed a clear increase in the effectiveness of guidance toward the target exit D. The actual rerouting effect was higher than in T.2.2 and varied across the TS3 trials, reaching 48.6% in TS3.1, 57.8% in TS3.2, and 65.6% in TS3.3, depending on the voice-message condition and initial participant distribution [2,3]. In configurations where participants simultaneously had good visibility of both the positive signal (recommended direction) and the negative signal (closed directions), the compliance level increased to about two thirds of the population [3].

In parallel, the questionnaires indicated improved message legibility. Flashing green arrows facilitated direction selection and reduced decision time, while red crosses acted as an unambiguous indication that a non-recommended route was closed. Time-curve analysis showed that T.3 achieved a

shorter median evacuation time and a clearly shortened final phase compared with T.2.2. This translated into a lower T95 and faster closure of the operation, i.e., more efficient removal of the last occupants from the test area [3].

Overall, the third series of trials demonstrated that combining the adaptive IADSS decision module with a complete and non-contradictory visual–audible interface tangibly increases the share of successful reroutings while simultaneously reducing the risk of secondary congestion at circulation nodes [3].

#### **4.4 Limitations and quality evidence**

The limitations identified in the Sant Cugat trials remain important and should be interpreted carefully. The lower-than-planned crowd density reduced the pressure on circulation nodes and may therefore have led to a conservative estimate of the benefits of dynamic guidance. At higher occupant densities, the effectiveness of dynamic guidance may differ because congestion, reduced inter-personal visibility, slower reaction propagation, and stronger pressure toward the nearest visible exit could alter both route-choice behavior and flow dynamics. The sample was also dominated by occasional or unfamiliar users of the station, which supports the ecological validity of the study for casual passengers but may not fully represent the behavior of regular users with established spatial habits [2,3]. Regular users may rely more strongly on habitual routes or pre-existing spatial knowledge, which could either weaken the influence of dynamic signage or modify the way in which guidance information is interpreted during evacuation. In addition, CCTV-based reconstruction suffered from blind spots, limiting direct observation of when participants actually perceived the signs. These blind spots primarily limited the reconstruction of perceptual behavior, i.e., whether and when individual participants visually detected specific signs. However, they had a smaller effect on the core outcome measures, such as exit choice, platform-clearance time, and evacuation-flow distribution, which could still be derived from the available recordings and trial documentation. Therefore, the CCTV limitation mainly affects the interpretation of signage perception rather than the overall comparison of evacuation outcomes.

An additional limitation concerns the combined nature of the T.3 intervention. In this configuration, several elements were modified simultaneously: the visual signage logic was improved, the voice-message content was made consistent with the guidance strategy, and the integrated IADSS control concept was introduced. Consequently, the observed improvement in evacuation performance should be interpreted as the effect of an integrated system configuration rather than as the isolated effect of a single component. The available trial design does not allow the separate quantitative attribution of the improvement to the signage layer, the voice-communication layer, or the decision-support module. This should be considered when interpreting the results and when transferring the findings to other facilities.

At the same time, the strength of the evidence should not be understated. These were full-scale trials conducted in an operational rail environment, with controlled comparison between several signage configurations and with measured evacuation outcomes such as route distribution, T50, T95, and total platform-clearance time. This gives the Sant Cugat case particular value within the wider literature, which is still dominated by simulation, VR, and laboratory-based studies [10–12]. Recent metro-related research using BIM, VR, eye tracking, and controlled experiments strongly supports the importance of visibility, cue consistency, and dynamic guidance logic, but such studies usually do not offer the same level of ecological realism as full-scale field trials. Therefore, the Sant Cugat trials remain especially important as empirical support for dynamic-signage concepts in transport environments.

The transferability of the results is also limited by the relatively simple spatial configuration of the tested platform. In more complex facilities, such as multi-level stations, long corridors, spaces with

turns, obstructed sightlines, or areas with locally reduced visibility due to smoke, the distance between a prohibitive signal and the indication of an alternative route may be greater. Under such conditions, the effectiveness of ADSS/IADSS may depend more strongly on the continuity of the guidance chain, sign repetition, local voice clarification, and the positioning of signs within the user's field of view. Further research is therefore needed to validate these findings under higher-density conditions and in facilities with different spatial configurations.

## 5. DISCUSSION

From a research perspective, the Sant Cugat trials provide rare full-scale empirical evidence from a real transport environment, helping to bridge the gap between simulation-based evacuation studies and observed user behavior under operational conditions [2,3,10–12].

The Sant Cugat case demonstrates that the effectiveness of evacuation guidance depends not only on whether information is present, but on how it is structured, perceived, and synchronized. In practice, the findings show that guidance is most effective when the user receives “full information” at a decision point: the preferred direction is indicated clearly, locally unsafe or unavailable directions are explicitly negated, and the information remains consistent across visual and audible channels. This interpretation is strongly aligned with recent research on emergency wayfinding, which shows that conflicting or incomplete cues can impair decision-making, while enhanced and unambiguous cues significantly increase the probability of compliance [3,9].

The case also highlights the importance of perceptual design [11,12]. Recent metro-focused studies confirm that signage effectiveness is highly sensitive to placement, visibility, and field-of-view conditions. Eye-tracking results suggest that low and medium sign positions may offer specific perceptual advantages in emergency conditions, while other VR studies show that signage layout and sign position directly affect wayfinding efficiency in subway stations [11,12]. These findings strengthen the interpretation of Sant Cugat: the success of dynamic signage is not merely a matter of adding flashing arrows, but of ensuring that users can simultaneously detect the negation of one option and the indication of the preferred alternative at the precise moment of route choice [3,11,12].

Another critical issue concerns multimodal consistency. In T.2.2, the ADSS logic was weakened by a voice message that could be interpreted as favoring the nearest exit, thereby introducing semantic conflict between the visual and audible layers. This is consistent with broader evacuation research showing that voice alarms can influence both recognition and movement phases, and that more directive, better-structured voice communication can improve evacuee response and exit-finding behavior [14,15]. The improved performance of T.3 therefore supports the conclusion that dynamic signage should not be treated as a stand-alone technology, but as part of an integrated visual–audible information system [3,15].

Finally, the Sant Cugat case can also be read in relation to the wider development of adaptive evacuation systems. Recent reviews and modelling studies indicate that the field is moving toward real-time or near-real-time systems combining detection data, environmental forecasting, crowd modelling, and coordinated dynamic guidance [13,14]. In that broader context, IADSS can be seen as an early but important full-scale implementation of the same general paradigm: guidance that is no longer fixed, but updated according to incident evolution, environmental conditions, and crowd distribution. Importantly, the findings also reveal limitations of partially implemented dynamic systems. The TS2.2 configuration demonstrates that dynamic signage alone does not guarantee effective rerouting if

perceptual visibility is insufficient or if contradictory information is provided through other communication channels.

## 6. RECOMMENDATIONS

The recommendations derived from the Sant Cugat case can be translated into practical and regulatory implications for large transport facilities and other public-use buildings. First, current design and regulatory approaches should move beyond the formal compliance of static signage alone and explicitly recognize operational effectiveness as a design objective [2,13]. In complex facilities, the ability of the system to influence actual route choice under changing hazard conditions should be treated as a performance criterion alongside conventional code compliance [2,13].

Second, regulations and design guidance should incorporate the principle of “full information” at decision nodes. Users should not only be told where to go, but also which route should not be used. The Sant Cugat trials suggest that dynamic rerouting is much more effective when the positive and negative messages are available in the same field of view [3]. Recent metro studies support this interpretation by showing that sign position, layout, and perceptual accessibility strongly influence users’ understanding and compliance. Accordingly, dynamic signage should be designed as a continuous chain of decision support rather than isolated sign points [10–12].

Third, the relationship between visual and audible communication should be normatively clarified. The Sant Cugat results indicate that even technically promising dynamic signage can be undermined by contradictory voice messages [3]. This is reinforced by more recent experimental evidence showing that voice alarm characteristics influence evacuee recognition time, response, and exit-finding performance [15]. Therefore, DSO/PA content should remain semantically and temporally synchronized with the visual guidance strategy, especially where the safest route is not the nearest one [3,15]. As a practical implication, emergency-communication procedures should therefore be developed and tested as integrated visual–audible scenarios rather than as separate signage and voice-alarm components. In particular, predefined PA/DSO message templates should be checked against the dynamic signage logic to avoid contradictory instructions at route-choice points.

Fourth, adaptive evacuation systems should be framed as part of a broader decision loop integrating hazard detection, facility monitoring, and evacuation control. The NFPA/FPRF review on dynamic directional exit signage emphasizes the need for further development in sensing, control logic, interoperability, and code guidance for such systems [13]. Recent research in urban rail transit and dynamic guidance optimization also confirms that integrated, data-informed control can improve both safety and efficiency [10,11,14]. In regulatory terms, this supports establishing minimum requirements for power redundancy, telemetry, communication reliability, and safe degradation procedures when adaptive components fail or input quality is reduced.

Finally, for high-occupancy transport nodes such as metro stations, interchange hubs, and terminals, periodic functional validation should be encouraged or required. This may include full-scale drills where feasible, but also simulation- or VR-supported testing focused on measurable KPIs such as rerouting rate, T50, T95, total evacuation time, final-phase duration, bottleneck formation, and correct message interpretation. Such an evidence-based approach would better connect design requirements with real operational performance [10–12]. More broadly, evacuation guidance should also be considered within a risk-informed design and planning framework. Safety in complex facilities depends not only on the operational evacuation phase, but also on earlier planning-stage decisions, including the identification of site-specific hazards and environmental constraints. Recent research on geoenvironmental hazards in development planning shows that systematic assessment of environmental constraints can support safer spatial development and reduce exposure to risk [16]. Therefore, adaptive

evacuation systems such as ADSS/IADSS should be understood as one component of a wider risk-management continuum linking planning, design, operation, and emergency response.

## 7. CONCLUSIONS

The Sant Cugat trials show that under dynamically evolving hazard conditions, static evacuation signage has limited operational effectiveness. In the reference configuration, route choice was dominated by the nearest-exit heuristic, while the sign itself rarely became the decisive factor in user decision-making [1,2,3]. This conclusion is consistent with broader emergency-wayfinding research, which indicates that stress, perception, attention, and conflicting information strongly shape occupant choices, and that enhanced signage can significantly increase compliance with intended routes [9].

The baseline ADSS configuration improved performance compared with static signage, but its effect remained spatially uneven and dependent on perceptual conditions [2,3,11,12]. Where the positive signal was less visible or where intermediate guidance was missing, route-choice behavior reverted more strongly to intuitive distance-based decisions. Recent metro studies provide additional support for this interpretation, showing that evacuation-sign effectiveness depends heavily on sign placement, visibility, and message salience. Dynamic signage, therefore, should not be treated as inherently effective by default; its success depends on how the information is perceived at the point of decision [11,12].

A more substantial improvement emerged only in the integrated IADSS configuration. The simultaneous presentation of positive and negative information, together with non-conflicting voice communication, increased successful rerouting and shortened the later phase of evacuation, reflected in lower T50 and T95 values. This is also consistent with newer work showing that dynamic evacuation information, multimodal communication, and data-driven evacuation modelling can improve evacuation efficiency, reduce confusion, and better support passengers in complex rail-transit scenarios [10,11,14,15]. However, this conclusion should be interpreted with caution because the T.3 configuration introduced several changes simultaneously. The available evidence supports the effectiveness of the integrated configuration as a whole, but it does not allow the individual contribution of the signage content, voice-message consistency, guidance-chain continuity, and decision-support logic to be quantified separately.

Although the results are based on a single case study, the identified mechanisms—particularly the importance of perceptual visibility, full information at decision nodes, and multimodal consistency—are likely to be relevant to other complex transport environments with similar spatial and behavioral characteristics [3,10–12].

Taken together, the findings suggest that evacuation guidance in complex transport environments may benefit from a gradual transition from passive signage toward adaptive, integrated, multimodal systems, provided that such systems are validated for the specific geometry, occupant profile, and operational conditions of the facility [3,10,11,15]. In this respect, the Sant Cugat case remains important not only as a historical experiment, but as a practically relevant demonstration of principles now reinforced by more recent literature: perceptual salience, full information at decision nodes, consistency across communication channels, and dynamic updating based on changing conditions [3,10,13–15].

## Abbreviations

**ADSS** — Active Dynamic Signage System

**IADSS** — Intelligent Active Dynamic Signage System

**PA** - Public Address

**DSO** - Voice Alarm System

**PA-VA** - Public Address & Voice Alarm

**FTRT** - Faster-Than-Real-Time (decision loop)

**CFD** - Computational Fluid Dynamics

**SMARTFIRE** - CFD scenario-library tool used for environmental fire modelling

**buildingEXODUS** - agent-based evacuation-modelling tool

**SERM** - multi-criteria ranking function for evacuation-control strategies

**CCTV** - Closed-Circuit Television

**BMS** - Building Management System

**SCADA** - Supervisory Control and Data Acquisition

**SSP** - fire alarm system

**AI** - Artificial Intelligence

**HRR** - Heat Release Rate

**KPI** - Key Performance Indicator

**VR** - Virtual Reality

**EEC** - European Economic Community

**T50** - time by which 50% of occupants have evacuated

**T95** - time by which 95% of occupants have evacuated

**TS2.1 / TS2.2 / TS3.1 / TS3.2 / TS3.3** — trial identifiers

**T.2.1 / T.2.2 / T.3** - configuration identifiers: static signage → ADSS + PA → IADSS

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### Conflicts of Interest

The author(s) declare no conflict of interest.

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