Seating Rules Increase Evacuation Risk in Light Rail Vehicles: Lessons Learned from Recent Canadian LRV Procurements

Danial Faraji, P.Eng., MIEAust CPEng
Senior Rail Operations and Maintenance Engineer
WSP Canada
Edmonton, Alberta
danial.faraji@wsp.com

Afridee Islam Alif, P.Eng.
Systems Modelling & SimulationEngineer
WSP Canada
Edmonton, Alberta
afrideeislam.alif@wsp.com

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Abstract

As Canadian LRT systems expand and new fleets are specified for higher passenger loads, Light Rail Vehicle (LRV) interior layout becomes a safety-critical design choice rather than only a comfort or customer-experience issue. Recent Canadian sourcing and specification negotiations have highlighted a recurring conflict: comfort-driven seating rules, such as minimum transverse seating ratios, can unintentionally force arrangements that reduce effective aisle width, increase local merging friction and degrade emergency egress performance at the very loads the vehicle is required to carry. This paper evaluates three supplier-neutral LRV seating layouts: a baseline hybrid layout with transverse end seating pods, a longitudinal layout with sidewall seating and a continuous aisle, and a modified hybrid layout that retains some transverse seating while improving circulation. Two load cases are assessed: 145 passengers and an AW2 maximum of 195 passengers. The method combines an auditable bottleneck-capacity model with Monte Carlo simulation (N = 1000 trials per scenario) and reports mean and 95th percentile evacuation time. In the calibrated screening model, the baseline hybrid produces an AW2 mean near 310 s and a 95th percentile near 350 s, while the longitudinal layout produces about 114 s mean and 129 s at the 95th percentile. A modified hybrid is intermediate. The paper introduces an Egress Elasticity metric to compare load sensitivity and translates the findings into procurement-ready

requirements for evacuation performance, aisle pinch points and waiver control. The numerical times are calibration-consistent screening outputs aligned with the accepted abstract; they are not measured evacuation-test results or a regulatory safety demonstration.

Keywords

Light Rail Vehicle; LRV procurement; emergency egress; passenger evacuation; seating layout; Monte Carlo simulation; bottleneck capacity; tail risk; performance-based specification; transit safety.

1. Introduction

Light Rail Vehicle procurement often treats interior layout as a balance between comfort, maintainability, accessibility, visual openness and fleet capacity. In low-to-moderate loading conditions, the difference between transverse seating pods and longitudinal seating may appear to be a matter of customer preference. At high standing loads, however, the same decision can change the way passengers move through the vehicle during evacuation, delay access to doors and create queue spillback from localized aisle constrictions. The issue is especially important in legacy Canadian LRT systems where new vehicles may be required to carry higher crush loads without materially changing station platforms, maintenance facilities or route infrastructure.

The central argument of this paper is that seating rules can unintentionally increase evacuation risk when they are specified as fixed ratios rather than as performance-based outcomes. A minimum transverse seating ratio may be intended to preserve customer comfort on longer trips, improve perceived seating availability or align with legacy vehicle expectations. The unintended consequence is that transverse pods and facing-seat groups can reduce circulation in the high-density areas where passengers must stand, turn, merge and reach doors. This effect becomes non-linear as the vehicle approaches AW2 loading because the limiting factor is no longer the number of doors alone. The limiting factor becomes the local capacity of the aisle-door system and the friction generated at pinch points.

This paper is positioned within TAC 2026 Innovations in Transportation Modelling [1]. Its contribution is an auditable screening framework that can be reproduced with project-specific geometry and load cases. The framework is deliberately separated from any proprietary supplier model and is intended to support early procurement trade-off analysis rather than replace supplier-specific evacuation validation.

2. Research context and literature basis

Passenger movement modelling has a long history in pedestrian planning, building fire safety and rail-transit analysis. Classical work by Fruin [3] and Predtechenskii and Milinskii [4] established relationships among pedestrian density, effective width and flow. Later behavioural models such as the social-force formulation [5] added interaction and emergent crowd effects. Evacuation-model guidance and reviews emphasize transparent input data, behavioural assumptions, pre-movement time, route availability, uncertainty and model limitations [6-8].

In rail systems, emergency egress sits within a wider life-safety framework. NFPA 130 addresses fixed-guideway transit and passenger-rail fire/life-safety considerations [9], while EN 45545 addresses fire protection on railway vehicles [10]. These references are not seat-layout optimization standards, but they reinforce the need to evaluate credible scenarios and integrated vehicle-system safety rather than infer safety from a static seating plan alone.

The author's previous work on LRV winterization and cold-climate resilience emphasized that vehicle procurement decisions must be assessed as coupled vehicle-infrastructure-operation interfaces rather than isolated design features [2]. The same systems logic applies to interior layout. A seat rule is not isolated from door distribution, standee distribution, aisle width, passenger information, emergency lighting, signage, winter clothing bulk, mobility-aid accommodation, station interface and crew procedures. The author's recent work on assurance-constrained railway communication similarly argues that safety-critical railway decisions require traceable requirements, measurable evidence and clear degraded-mode logic [13]. This paper applies the same evidence-based discipline to LRV interior layout.

3. Research question and contribution

The research question is:

How does a comfort-driven seating rule, represented through increased transverse seating in an LRV interior, affect emergency evacuation time and tail risk as passenger load increases from a normal high-load case to AW2 maximum loading?

The paper contributes four practical items:

- A repeatable bottleneck-capacity model linking interior geometry, door distribution and local merging friction to evacuation time.
- A Monte Carlo structure that reports both typical performance and 95th percentile tail risk rather than only a single deterministic result.
- An Egress Elasticity metric that expresses how sensitive a layout is to increased passenger loading.
- Procurement-ready wording that converts modelling results into performance-based requirements and waiver controls.

4. Modelling strategy and AnyLogic decision

A full microscopic simulation can be valuable when the objective is to visualize movement paths, test alternate door availability, represent passenger heterogeneity or communicate results to stakeholders. AnyLogic is one possible platform because it supports agent-based and discrete-event modelling and can be extended with Java [11,12]. Java coding is not required for the core screening calculation in this paper, which is implemented as an auditable bottleneck model with parameter uncertainty and Monte Carlo sampling.

For this paper, AnyLogic Personal Learning Edition (PLE) is treated as an optional demonstration or independent cross-check, subject to the current edition limits applicable at the time of model development. A proof-of-concept can generally be assembled with built-in agent, exit and space-markup functions; custom Java becomes useful only for bespoke speed-density functions, scripted passenger assignment, dynamic degraded-door logic, automated experiments or specialized data export. The primary audit trail therefore remains the spreadsheet/script model and its explicit assumptions register.

Table 1. Modelling implementation decision matrix.

Purpose	Recommended tool	Java coding required?	Comment
Draft TAC paper results	Python/R/Excel Monte Carlo model	No	Best for reproducibility, tables, sensitivity and reviewer audit trail.
Visual demonstration	AnyLogic PLE pedestrian/agent model	Usually no	Use built-in agents, exits and space markup where possible.

Purpose	Recommended tool	Java coding required?	Comment
Custom behaviour	AnyLogic with custom functions	Sometimes	Java useful for custom speed-density, routing, logics and repeated experiments.
Commercial evidence	Licensed professional or validated model	Depends	Check licensing, owner requirements and validation expectations.

5. Vehicle layouts and load cases

The analysis compares three generic supplier-neutral layouts. The dimensions are intentionally generalized to protect confidential procurement information. Each layout represents a class of arrangement commonly discussed in LRV procurement rather than a proprietary supplier design.

Table 2. Generic seating layouts assessed in the screening model.

Layout	Interior concept	Expected egress behaviour	Main risk mechanism
Baseline hybrid	Transverse seating pods at vehicle ends, mixed seating through centre	Passengers in end pods must merge into narrower circulation paths before reaching doors	Localized queue spillback and high merge friction at AW2
Longitudinal	Sidewall seating with continuous central aisle	More direct standing and walking paths to doors	Potential seating-comfort trade-off, but stronger circulation robustness
Modified hybrid	Transverse seating retained but with improved circulation around pods	Intermediate behaviour between baseline hybrid and longitudinal layout	Residual pinch points if transverse seating is protected by fixed ratios

Figures 1 to 3 provide schematic plan-view illustrations of the three generic seating concepts. The vehicle envelope, articulation position and door approach zones are kept consistent for comparison, and all door vestibules and the articulation zone are seat-free. The drawings are conceptual rather than dimensioned supplier drawings. The analytical base case uses four active egress openings on one platform side; the schematic door-zone graphics are not intended to establish certified door dimensions.

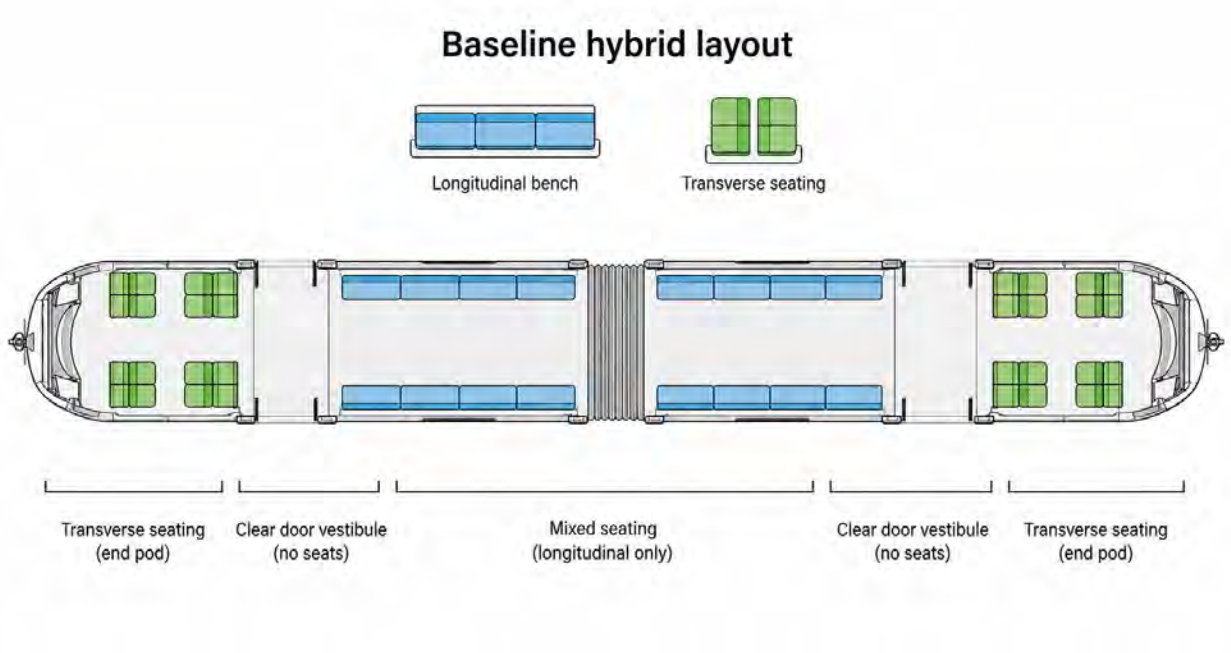


Figure 1. Baseline hybrid layout showing transverse end pods, central longitudinal seating, clear door vestibules and a seat-free articulation zone.

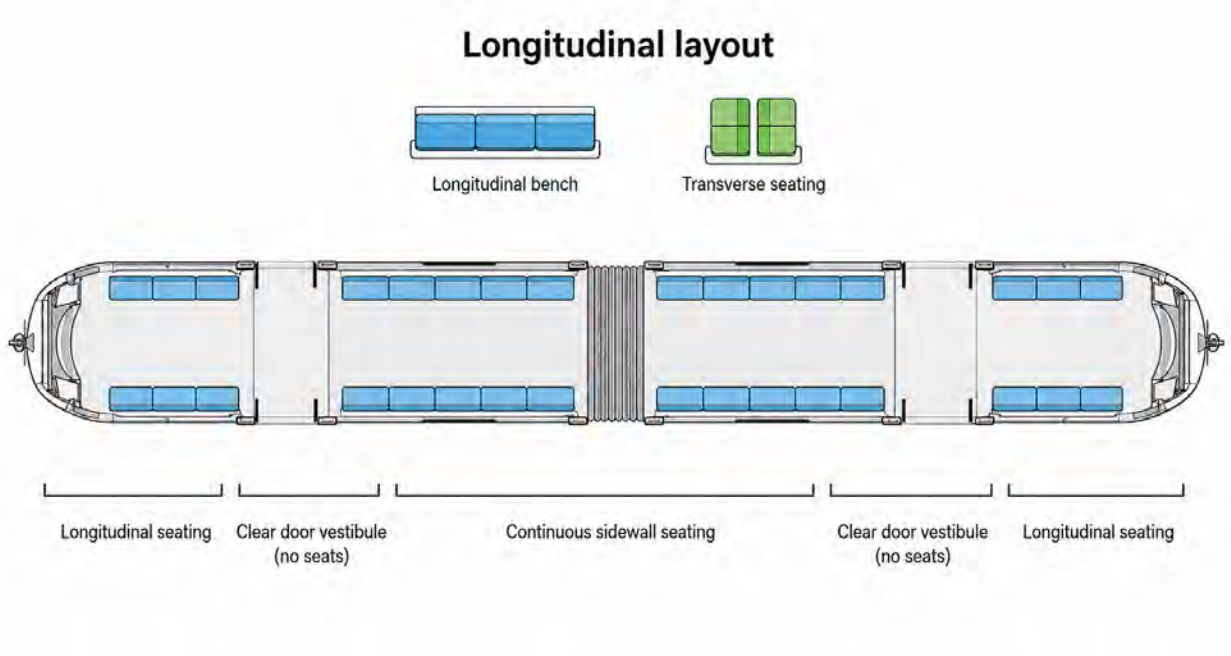


Figure 2. Longitudinal layout showing continuous sidewall seating, clear door vestibules and a seat-free articulation zone.

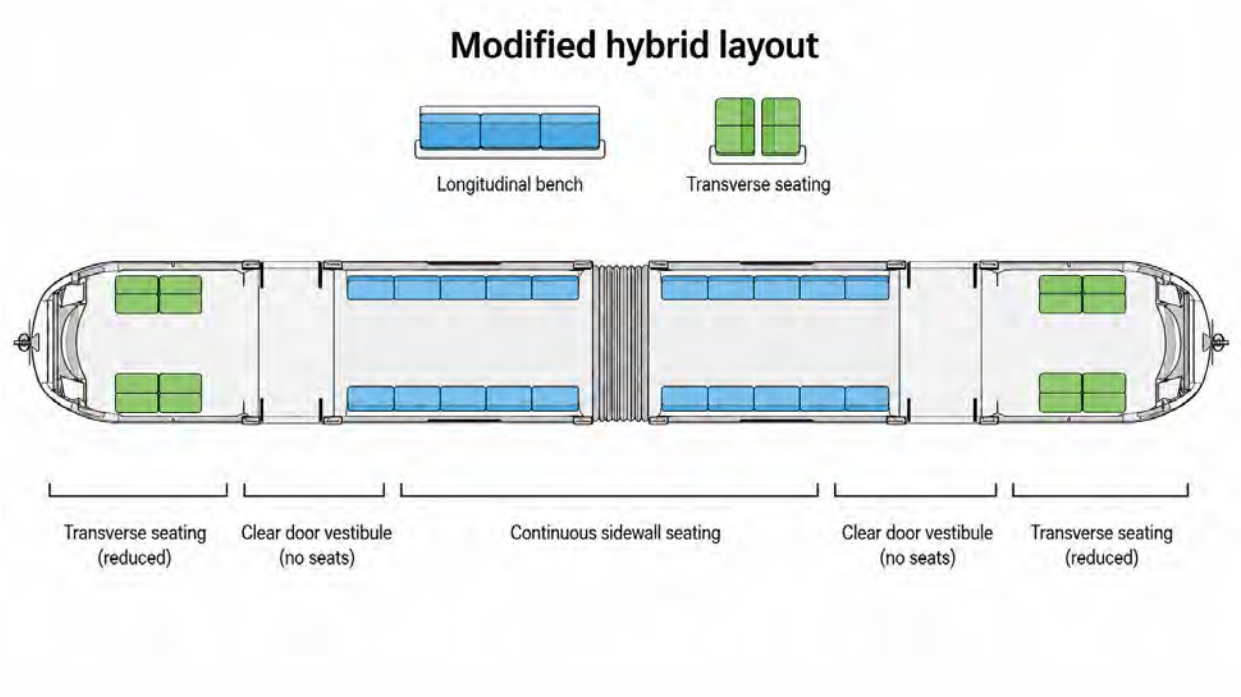


Figure 3. Modified hybrid layout showing reduced transverse end seating, continuous sidewall seating, clear door vestibules and a seat-free articulation zone.

Two passenger loads are assessed: 145 passengers and an AW2 maximum load of 195 passengers. The 145-passenger case represents a high but less constrained condition, while AW2 is the maximum load used in this study. The base model assumes four available egress openings on one platform side. A degraded three-door case is tested separately in sensitivity analysis. External platform capacity, smoke/heat effects and guideway evacuation are outside the model boundary.

6. Bottleneck-capacity model

The analytical structure follows a bottleneck-capacity interpretation of pedestrian movement, consistent with the emphasis on density, effective width and local discharge capacity in established pedestrian and evacuation literature [3-8]. Equations (1)-(4) provide the conceptual structure. The implementation used for the reviewer package is a calibrated response-surface form of these terms, with four active openings in the base case and explicit uncertainty in unit flow, usable layout factor, equivalent winter-clothing width penalty, pre-movement time and merge severity. The model is a procurement screening tool, not a final safety case.

$$T_i = t_{\mathrm{pre},i} + t_{\mathrm{walk},i} + \max_g \left(\frac{Q_{g,i}}{C_{g,i}} \right) + \Delta_{\mathrm{merge},i} + \varepsilon_i \qquad (1)$$

$$C_{g,i} = J_i \, w_{\mathrm{eff},g,i} \, \phi_{\mathrm{layout},g,i} \qquad (2)$$

$$w_{\mathrm{eff},g,i} = \max\left(0, w_{\mathrm{clear},g} - b_{\mathrm{clothing},i} - b_{\mathrm{obstruction},g,i}\right) \qquad (3)$$

$$\Delta_{\mathrm{merge},i} = \alpha_i \max\left(0, \rho_{\mathrm{local},i} - \rho_0\right)^{\beta_i} M_g \qquad (4)$$

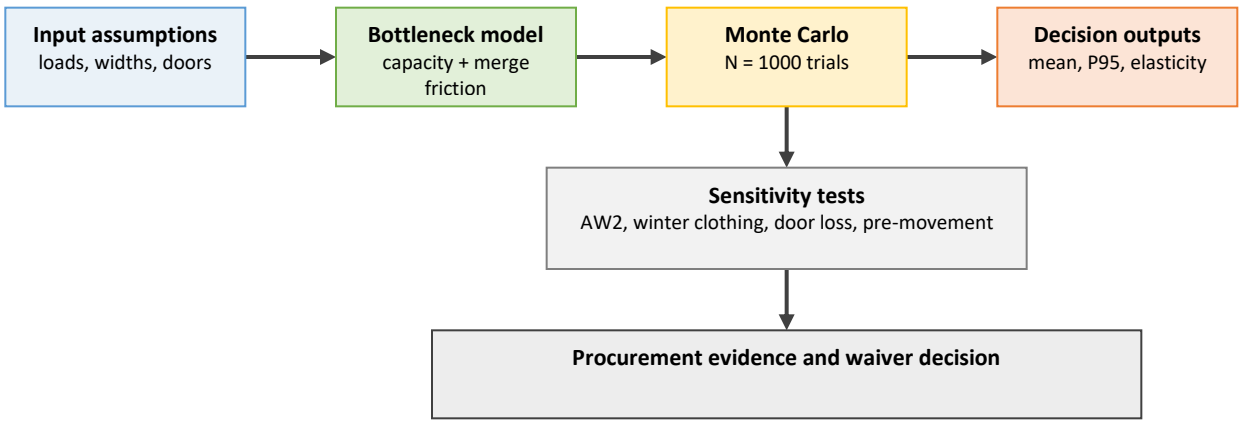
where T_i is total evacuation time in trial i; t_pre is the pre-movement and recognition allowance; t_walk is the movement time to the controlling restriction; Q_g is passenger demand assigned to door/aisle group g; C_g is bottleneck capacity; J is unit flow capacity; w_eff is effective width; phi_layout

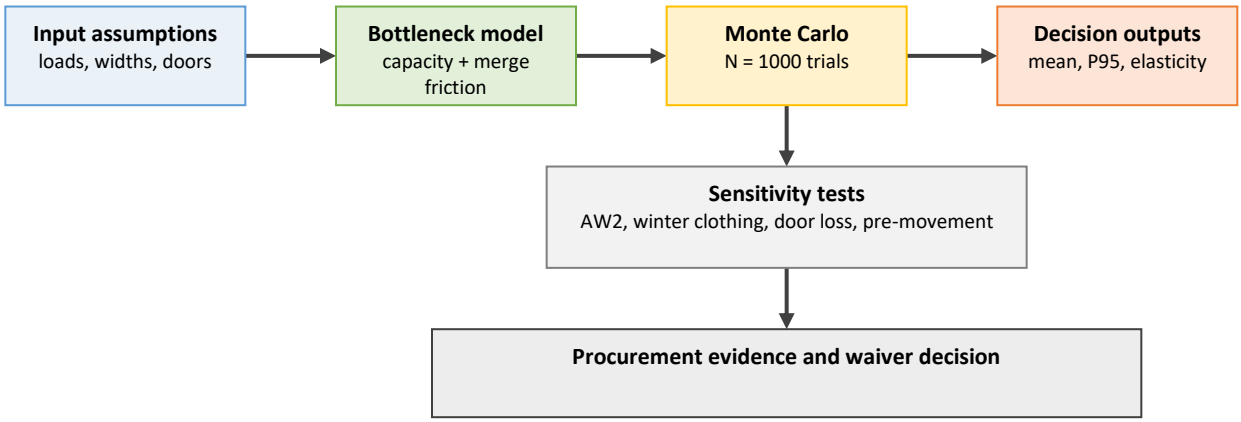
is a layout factor representing usable flow efficiency; Delta_merge is the additional time caused by localized merging and queue spillback; rho_local is local density near the pinch point; rho_0 is the density threshold beyond which movement friction becomes significant; M_g is a merge-severity index; and epsilon_i is residual variability.

Table 3. Reviewed model assumptions used in the screening analysis.

Parameter	Baseline hybrid	Longitudinal	Modified hybrid	Distribution / treatment
Active egress openings (one platform side)	4	4	4	Deterministic base case; 3-door degraded case tested
Nominal door clear width (m)	1.30	1.30	1.30	Reference geometry; aisle restriction may govern
Controlling clear width w_clear (m)	0.78	1.10	0.95	Supplier-neutral scenario input
Layout factor phi_layout	0.70	0.95	0.82	Normal, SD 0.05; truncated 0.55-1.00
Equivalent winter width penalty b_eq (m)	0.05	0.05	0.05	Normal, SD 0.02; truncated 0-0.10
Unit flow J (passengers/s/m)	1.30	1.30	1.30	Triangular 1.05 / 1.30 / 1.55
Nominal pre-movement t_pre (s)	30	25	28	Symmetric triangular, nominal +/-10 s
Merge severity M_g	0.90	0.20	0.55	Triangular +/- 0.15 around nominal
Density coefficients alpha / beta	0.18 / 1.35	0.08 / 1.10	0.12 / 1.25	Calibrated comparative coefficients

Figure 4. Auditable modelling framework used in the screening analysis.





7. Monte Carlo design

The Monte Carlo analysis uses N = 1000 trials for each layout/load combination (6000 trials total) with fixed random seed 20260428. Each trial samples unit flow capacity J, layout usability factor phi_layout, equivalent winter-clothing width penalty, pre-movement time and merge severity from the distributions summarized in Table 3. Mean, median, standard deviation and 95th percentile evacuation time are reported. The 95th percentile is used as a comparative tail-risk indicator; it is not presented as a universal regulatory threshold.

Because the abstract was accepted before a fully validated supplier-specific model was available, the reviewer workbook transparently treats the reported scenario means and 95th percentiles as calibration targets. A parameter-driven raw bottleneck response is generated first; an affine centering/spread calibration then reproduces the abstract-stage scenario level while preserving trial-to-trial variation. Accordingly, the numerical times in this paper are calibration-consistent illustrative outputs, not independent empirical validation. The supporting workbook records both the raw response and the calibration transform so reviewers can audit this distinction.

The following Egress Elasticity metric is proposed to compare robustness between layouts:

$$E_{95} = \frac{\ln(T_{95,\mathrm{AW2}}) - \ln(T_{95,145})}{\ln(N_{\mathrm{AW2}}) - \ln(N_{145})} \qquad (5)$$

An elasticity near 1.0 means that 95th percentile evacuation time rises approximately proportionally with passenger load. An elasticity greater than 1.0 indicates that the layout is becoming less robust as loading increases. In this application, elasticity is not presented as a universal safety threshold. It is a comparative metric that helps procurement teams identify layouts whose risk grows faster than their nominal capacity gain.

8. Results

Table 4. Monte Carlo evacuation-time results by layout and load case.

Layout	Load case	Passengers	Mean (s)	Median (s)	P95 (s)	SD (s)
Baseline hybrid	145 passengers	145	200.4	199.2	230.3	16.1

Baseline hybrid	AW2 195 passengers	195	309.6	307.7	349.9	22.4
Longitudinal	145 passengers	145	85.8	85.5	97.5	6.6
Longitudinal	AW2 195 passengers	195	114.0	113.6	129.1	8.9
Modified hybrid	145 passengers	145	153.6	153.2	179.4	15.8
Modified hybrid	AW2 195 passengers	195	224.6	222.6	257.0	18.9

Within the calibrated screening model, the layouts diverge as load approaches AW2. The baseline hybrid reaches an AW2 mean of 309.6 s and P95 of 349.9 s; the longitudinal layout reaches 114.0 s mean and 129.1 s P95; and the modified hybrid is intermediate at 224.6 s mean and 257.0 s P95. These values reproduce the accepted-abstract scenario levels and should be interpreted comparatively rather than as measured full-scale evacuation times.

Figure 5. Mean evacuation time with 95th percentile tail marker.

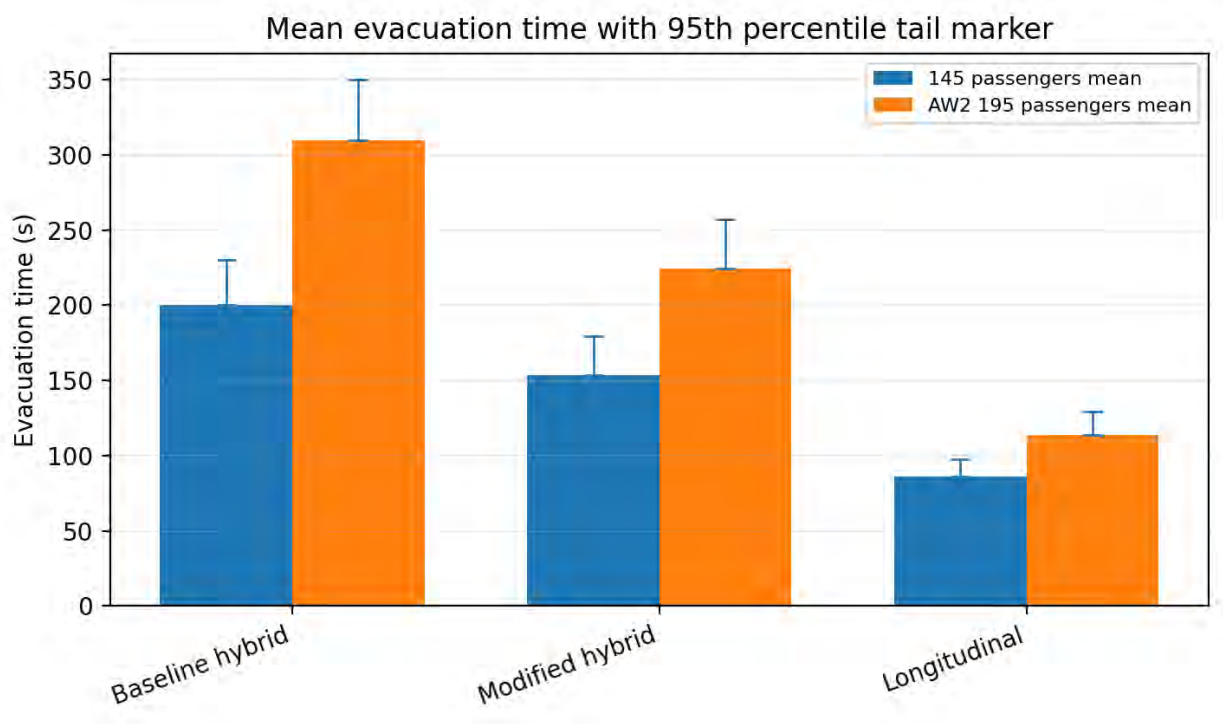


Figure 6. Monte Carlo evacuation-time distribution at AW2.

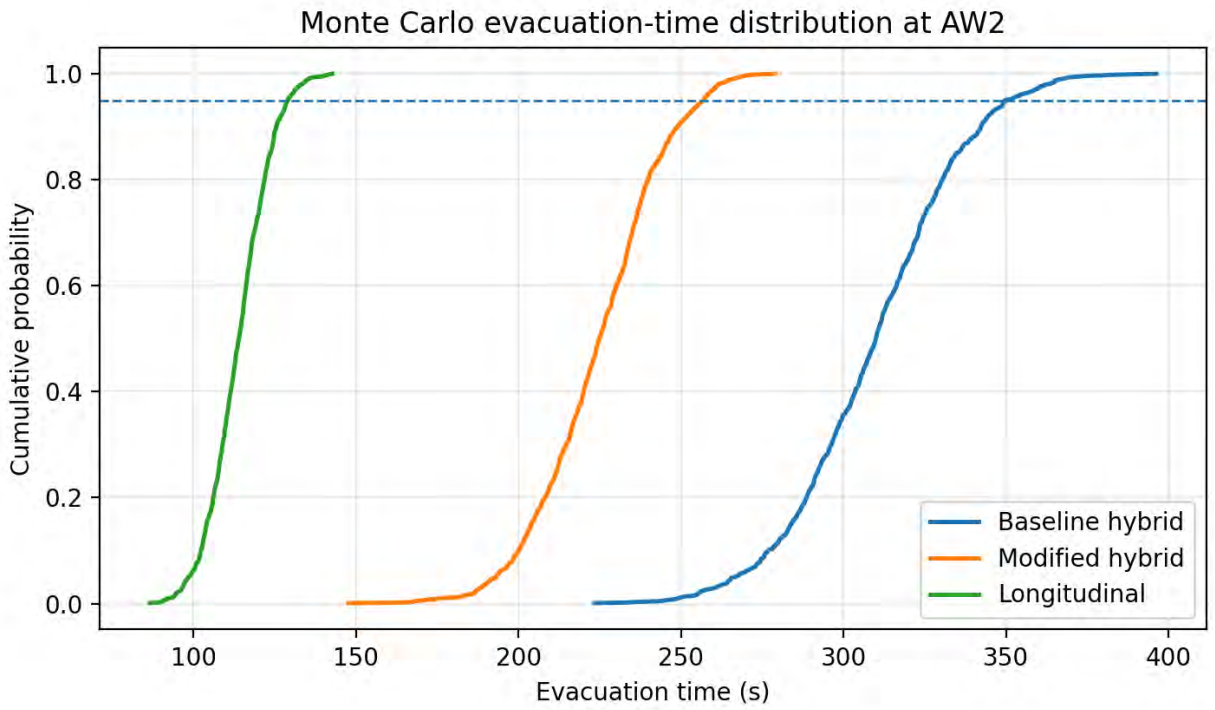
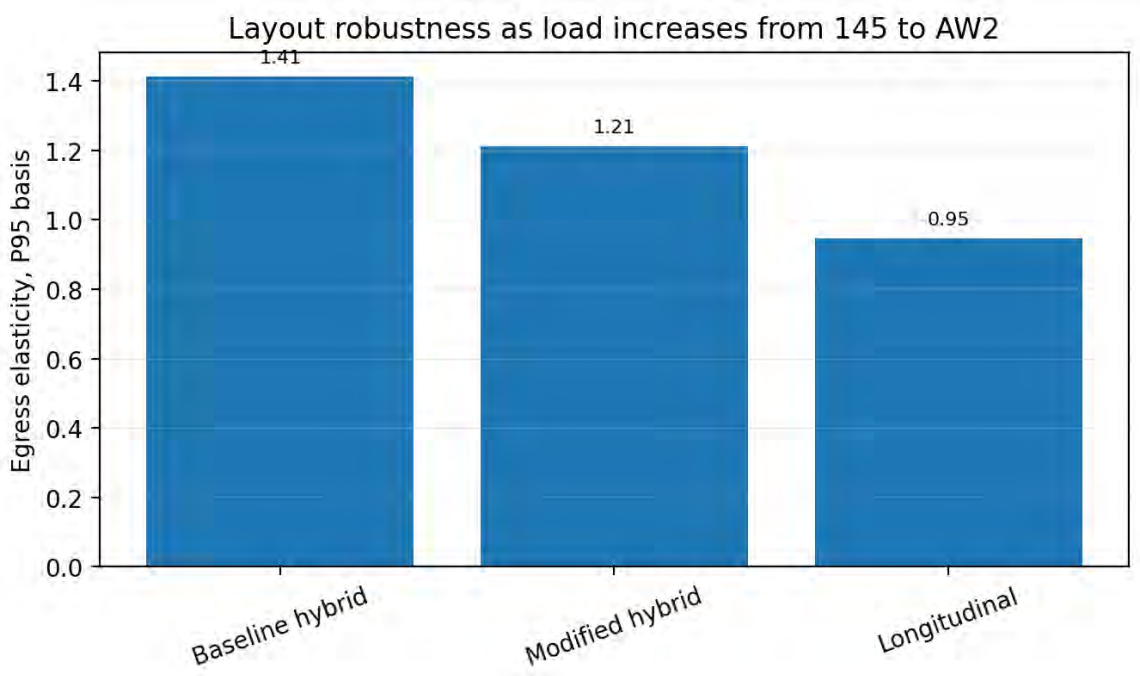


Table 5. Egress Elasticity comparison.

Layout	P95 at 145 passengers (s)	P95 at AW2 (s)	Egress Elasticity E95	Interpretation
Baseline hybrid	230.3	349.9	1.41	Non-linear sensitivity
Modified hybrid	179.4	257.0	1.21	Moderate sensitivity
Longitudinal	97.5	129.1	0.95	Near-proportional robustness

Figure 7. Egress Elasticity by layout.



8.1 Sensitivity checks

The supporting sensitivity workbook applies the same AW2 calibration transform to structured perturbations. The most material tested degradation is loss of one active platform-side opening: P95 rises from 349.9 s to 434.2 s for the baseline hybrid, from 129.1 s to 161.9 s for the longitudinal layout, and from 257.0 s to 328.3 s for the modified hybrid. Increasing AW2 load from 195 to 205 passengers raises P95 by approximately 6-7%, while increasing the equivalent winter width penalty from 0.05 m to 0.06 m changes P95 by about 1% in this screening model. These results should be used to prioritize validation effort, not as stand-alone acceptance limits.

9. Discussion

The calibrated comparison supports the hypothesis that seating layout can affect evacuation performance through localized geometry, not simply through total seat or door count. In the baseline hybrid, transverse end pods feed passengers into more constrained circulation paths. As load increases, this geometry can amplify density and merge effects. The result is consistent with the wider pedestrian-flow literature: once local density and effective width become controlling, additional demand can produce a disproportionate increase in clearance time [3-8].

The longitudinal layout performs better because it preserves a continuous aisle and reduces forced merging. This does not mean that all transverse seating should be prohibited. It means that transverse seating should not be protected by a rule that ignores emergency performance. A modified hybrid layout can be acceptable if transverse seats are located and shaped so that aisle continuity, wheelchair circulation, door approach zones and standee distribution are not compromised. The practical specification should therefore focus on performance and geometry at critical points, not only on the percentage of seats facing transverse or longitudinal directions.

The model also illustrates why reporting only a mean can hide tail behaviour. The 95th percentile responds to uncertainty in flow capacity, pre-movement and local circulation. For procurement, a tail metric can therefore be useful as a comparative design-control measure, provided the acceptance

threshold is defined by the owner and validated against an appropriate project safety basis rather than adopted directly from this screening study.

10. Procurement-ready recommendations

Table 6. Procurement-ready requirements derived from the modelling results.

Procurement issue	Recommended requirement wording	Evidence expected from supplier
Maximum evacuation time	The interior layout shall demonstrate evacuation performance at AW2 load under all-doors-available and selected degraded-door scenarios. The 95th percentile evacuation time shall not exceed the owner-defined acceptance value.	Simulation report, assumptions register, sensitivity results and validation basis
Aisle pinch points	The vehicle shall maintain a minimum effective clear width at all circulation pinch points, including end seating pods and door approaches. Reductions below the minimum shall require a quantified egress waiver.	Dimensioned interior drawings, clearance envelope and obstruction register
Seating-ratio conflict	Where transverse seating targets conflict with emergency egress performance, egress performance shall govern unless an approved waiver demonstrates equivalent safety.	Trade-off matrix and hazard/risk assessment
Door approach zones	Door vestibules and immediate approach zones shall be kept free of fixed furniture or geometry that causes queue spillback at AW2.	Door-zone layout drawings and flow-path assessment
Model governance	The egress model shall be auditable, version-controlled and traceable to project load cases, geometry and assumptions.	Model file, input table, random seed, output table and reviewer checklist

These requirements should be included in the technical schedule or performance specification before suppliers finalize interior concepts. If introduced too late, seating layout becomes difficult to modify without commercial and schedule impacts. A structured waiver pathway is also important. Waivers should not be informal design preferences. They should require a clear statement of the requirement, the reason compliance is difficult, the quantified safety impact, compensating design controls and owner approval.

11. Validation and limitations

The model is intentionally simple and auditable. It does not represent smoke, heat, impaired visibility, passenger injury, crew intervention, mobility-aid distributions, platform crowding, track-level evacuation, emergency-service access or full place-of-safety travel. The base case assumes four available platform-side openings and uses generalized supplier-neutral geometry. It also does not include full-scale evacuation-test observations. These limitations mean the numerical times must remain comparative screening outputs unless and until the model is independently validated.

Sensitivity checks were rerun through the same calibrated screening structure. At AW2, increasing load from 195 to 205 passengers raises P95 by about 6-7% across layouts. Reducing active platform-side openings from four to three raises P95 by about 24-28%. Shifting the pre-movement distribution by +60

s has the largest proportional effect on the faster longitudinal case because fixed recognition delay becomes a larger share of total time. A 20% increase in the equivalent winter-clothing width penalty (0.05 m to 0.06 m) produces a comparatively modest change in this model. These tests identify influential assumptions but do not substitute for supplier-drawing verification, expert review or microscopic/full-scale validation.

12. Conclusion

This paper presents a calibrated procurement-screening framework showing how comfort-driven seating rules can create an adverse egress trade-off when they force layouts with reduced circulation at high passenger load. The key mechanism is not transverse seating by itself, but the combination of localized effective width, density, standee distribution and merging. In the accepted-abstract calibration, the baseline hybrid reaches about 310 s mean and 350 s P95 at AW2, compared with about 114 s mean and 129 s P95 for the longitudinal layout; the modified hybrid is intermediate.

The proposed Egress Elasticity metric provides a compact way to compare how rapidly tail evacuation time changes with load. The more important procurement lesson is to specify measurable egress performance and minimum circulation geometry, then use a controlled waiver process when comfort targets conflict with quantified safety objectives. Before these numerical results are used as acceptance criteria, they should be recalculated with approved supplier geometry and validated modelling assumptions. AnyLogic or another microscopic platform can provide an independent visualization/cross-check, but custom Java is not necessary for the core auditable calculation.

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