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Conceptual Design of a Dual-Function Bus Handle Rail System for Wheelchair Boarding and Interior Support: A Preliminary Scoping and Analysis Study

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ABSTRACT

Low-floor buses improve physical access to public transportation, but wheelchair users may still encounter gaps in reachable support while boarding, moving through the bus interior, and positioning within the designated wheelchair space. This study presents the conceptual design of a dual-function ceiling-mounted rail intended to serve as a conventional handrail for non-disabled passengers and as a supplementary guidance and support element for wheelchair users during boarding, circulation, and positioning.

A structured field audit was conducted on a convenience sample of 18 low-floor buses across nine Seoul routes. No dedicated wheelchair-user support handle was observed in the sampled vehicles, and the nearest fixed graspable support adjacent to the wheelchair space was a vertical pole in all 18 buses. The horizontal distance to this support ranged from 49 to 71 cm, with a mean of 61.9 cm, while the maximum unsupported gap along the boarding-to-wheelchair-space path ranged from 200 to 223 cm, with a mean of 214.7 cm. These measurements informed the requirement for more continuous and reachable interior support.

Simplified engineering analyses were then used to test specific features of the proposed concept against external criteria. Under an assumed pivot torque of 12 N·m, lever lengths from 0.10 to 0.30 m required 40 to 120 N of operating force, all exceeding the 22.2 N accessibility reference for operable parts. Estimated contact forces ranged from about 1.5 to 60 N across the sensitivity range and were compared with ISO/TS 15066 body-region limits as non-transit-specific screening references. Published city-bus hard-braking data reaching 0.75 g correspond to an estimated inertial load of approximately 660 N for the assumed 90 kg wheelchair-and-occupant mass, which is used only as a structural reference for the rail mounting. Four preliminary design requirements were derived, covering continuous support along the boarding path, mounting strength, controlled handle movement, and reachable low-force operation.

The proposed rail should therefore be understood as a preliminary boarding, circulation, and positioning aid rather than an occupant-restraint system. Prototype testing, user evaluation, and validation of the

mechanism, actuation method, structural mounting, and safety features are required before accessibility improvements can be established.

Keywords: *universal design; low-floor bus; handrail design; wheelchair accessibility; transit accessibility*

INTRODUCTION

Low-floor buses have improved physical access to public transportation for mobility-disadvantaged passengers, including wheelchair users, but access to the vehicle does not necessarily ensure accessible movement within it. In Korea, low-floor bus services have expanded nationwide since 2004, yet wheelchair users continue to report barriers affecting independent mobility and the practical use of public transportation.[1,2]

Previous research has examined these challenges from several perspectives. Studies of transportation services for disabled users have addressed mobility, disability acceptance, and quality of life, while research on low-floor bus interiors has identified vehicle layout, handrail placement, seating, aisle circulation, and wheelchair space as important elements of accessibility and universal design.[3,4,5] Video-observation studies have further shown that passenger movement within actual low-floor buses can reveal usability problems that may not be apparent from policy or infrastructure analysis alone.[6]

Wheelchair transportation research has also emphasized the importance of dedicated securement and occupant-restraint systems during vehicle travel.[7,8] These systems address occupant protection once a wheelchair user is positioned for travel and should remain distinct from supplementary interior support features. Within the literature reviewed for this study, less attention has been given to how shared interior support structures might assist wheelchair users during the continuous process of boarding, moving through the aisle, and reaching the designated wheelchair area while remaining usable by other passengers. This question is relevant to universal design principles of equitable and flexible use across different user groups.[9]

Several existing systems address parts of this problem. In healthcare facilities, ceiling-mounted track lifts move a suspended load along an overhead rail to transfer patients between positions, and a review of this technology concluded that ceiling lifts can improve the musculoskeletal safety of both caregivers and patients.[10] The mechanical principle is directly analogous to the proposed rail, since a carriage travels along a fixed overhead track and delivers support to a person below it. What does not transfer is the operating context. A ceiling lift carries the full body weight of a stationary patient under the control of a trained caregiver, whereas a bus rail must be usable by passengers without assistance, share space with standing passengers, and tolerate vehicle motion.

In public transit, wheelchair securement has also moved beyond manual four-point tiedowns. Turkovich et al. compared a four-point tiedown, an automatic docking system, and a rear-facing wheelchair passenger

station during city-bus maneuvers.[11] Commercial automatic rear-facing securement stations now allow a wheelchair user to back against a padded backrest and activate securement with a single accessible button.[12] These systems address occupant protection once the wheelchair is parked. They do not provide graspable support along the path from the door to the wheelchair space, and the rear-facing approach is designed so that the occupant does not need to hold on during braking. The concept proposed here is therefore intended to complement these securement systems by addressing the boarding and positioning movement that precedes securement, not to replace them.

Patent literature also contains movable and wheelchair-oriented transit handholds. One Korean patent describes a ceiling-mounted transfer rail with a movable carriage and downward handle intended to assist passengers, including older and disabled users, in moving through a vehicle, while another public-transport design uses a sliding block within a roof-mounted guide rail.[13,14] A separate bus handrail patent provides a foldable support positioned specifically for a wheelchair passenger.[15] These precedents show that neither movable overhead handholds nor wheelchair-specific bus supports are themselves new. The distinction of the present concept is therefore narrower: it combines a shared-use conventional rail with a movable, lowered support intended specifically to bridge the path from boarding to wheelchair positioning while remaining separate from occupant securement.

This study therefore explores the conceptual design of a dual-function ceiling-mounted rail system for low-floor buses. The proposed system is intended to function as a conventional handrail for non-disabled passengers while providing wheelchair users with a reachable guidance and support element during boarding, circulation, and positioning. The study combines preliminary design scoping, field observation, ergonomic reach considerations, and simplified engineering analysis to develop and evaluate early-stage design requirements. The proposed rail is not intended to replace certified wheelchair tiedown or occupant-restraint systems.

METHODS

1. Research Approach

This study was conducted as a preliminary design-scoping and engineering analysis study to develop and evaluate a conceptual dual-function rail system for low-floor buses. The study focused on supplementary support during wheelchair boarding, interior circulation, and positioning rather than occupant restraint during vehicle travel.

The research process consisted of four stages. First, a structured field audit of low-floor buses was conducted to examine existing support geometry, wheelchair-space configuration, and the continuity of graspable support between the boarding area and the designated wheelchair position. Second, published research on low-floor bus interiors and wheelchair-user reach was reviewed to establish ergonomic and accessibility reference conditions. Third, relevant transportation accessibility standards were used to identify external design criteria for graspable support, circulation, wheelchair positioning, and operable

components. Finally, simplified engineering analyses were used to evaluate specific features of the proposed mechanism, including vehicle-deceleration loading, moving-handle behavior, and the operating force required for the pivoting handle.

The field observations, literature-based ergonomic references, accessibility criteria, and engineering analyses were then used to derive preliminary design requirements for the proposed ceiling-mounted rail system. The system is intended as a supplementary boarding, circulation, and positioning aid and is not intended to replace certified wheelchair tiedown or occupant-restraint systems used for passenger protection during vehicle travel.

2. Structured Field Audit

2.1 Sampling and Audit Procedure

A structured field audit was conducted on 18 low-floor buses on September 25, 2026, beginning at approximately 5:00 p.m. Three student observers took part, namely the author and two additional students, Yeonwoo Jang and Jaehu Lee of Valor International School. Each observer examined six vehicles by sampling three bus routes accessible from his or her local area and two different physical buses on each route, producing a total sample of 18 vehicles. Routes and vehicles were selected by convenience rather than at random.

The routes included 440, 472, and 3011 for the first observer; 463, 301, and 147 for the second observer; and 400, 148, and 141 for the third observer. For reporting purposes, the two vehicles sampled on each route were labeled A and B. These labels are used only to distinguish different physical buses on the same route and do not indicate travel direction.

Each vehicle was observed during a ride of three to five stops. All three observers followed the same measurement definitions (Table 1) and recorded the same set of physical characteristics. Measurements were obtained using the LiDAR-based Measure function on Apple devices and recorded in centimeters. For each vehicle, photographs were taken of the wheelchair space, the nearest vertical pole, and the nearest overhead handhold as a record of the measurements. These photographs were used only to check the recorded values and are not reproduced in this paper. Because the audit was conducted in an operating transit environment rather than with calibrated surveying equipment, the values are treated as approximate field measurements, and small measurement errors should be expected.

2.2 Measurement Variables and Operational Definitions

For each vehicle, the designated wheelchair area was identified using the marked wheelchair-positioning space within the bus interior. The audit recorded the wheelchair-space dimensions and location, the type of the nearest graspable support element, the presence or absence of a dedicated wheelchair-user support handle, the height of the nearest overhead passenger handhold, the horizontal distance to the nearest

graspable vertical support, and the maximum unsupported gap along the movement path from the boarding area to the wheelchair space. Wheelchair-space dimensions were measured along the marked floor boundary in each vehicle.

The overhead handhold height was defined as the vertical distance from the bus floor to the nearest overhead passenger handhold located adjacent to the wheelchair area. The horizontal support distance was defined as the horizontal distance from the nearest edge of the marked wheelchair space to the nearest graspable vertical pole. The maximum unsupported gap was defined as the longest interval along the boarding-to-wheelchair-space movement path without an intervening graspable support element.

The audit examined vehicle geometry and interior support features rather than passenger behavior. No passengers were interviewed, physically measured, or evaluated, and no individual passenger behavior was recorded as research data.

Table 1. Variables and operational definitions used in the structured field audit

Variable	Operational definition	Recording
Wheelchair-space dimensions	Width and length of the marked wheelchair-positioning area	cm
Wheelchair-space location	Position of the designated area relative to the interior layout and exit door	Categorical / field note
Dedicated wheelchair support handle	Presence or absence of a graspable element specifically positioned for the wheelchair area	Yes / No
Nearest support type	Closest graspable fixed support adjacent to the wheelchair area	Vertical pole / other
Overhead handhold height	Vertical distance from the bus floor to the nearest overhead passenger handhold adjacent to the wheelchair area	cm
Horizontal support distance	Horizontal distance from the nearest edge of the marked wheelchair space to the nearest graspable vertical pole	cm

Maximum unsupported gap	Longest interval along the boarding-to-wheelchair-space path without an intervening graspable support element	cm

3. Ergonomic and Accessibility Reference Criteria

Published wheelchair-user reach data were used to interpret the physical measurements obtained during the field audit. Das and Kozey's measurements of normal and maximum reach among adult wheelchair users were treated as external ergonomic reference data rather than measurements of participants in the present study.[16] No wheelchair users were recruited or physically measured as part of the field audit.

Transportation accessibility standards and guidelines were also reviewed to establish external comparison criteria for graspable support elements, interior circulation, wheelchair positioning, and operable components. These criteria were used as design benchmarks rather than as evidence that the proposed system satisfies regulatory certification requirements.

For the pivoting-handle analysis, an operating-force reference of 22.2 N (5 lbf) from the ADA Standards for operable parts was used as an accessibility comparison criterion.[17] Other vehicle and accessibility standards were used where relevant to distinguish supplementary interior support from certified wheelchair securement and occupant-restraint requirements.[18,19,20]

4. Engineering Analysis

The engineering analysis was used to test specific assumptions of the proposed concept rather than to confirm a predetermined design. Three simplified analyses were conducted: (1) a vehicle-deceleration load analysis used as a preliminary structural reference, (2) a moving-handle analysis examining speed, momentum, and estimated contact force, and (3) a lever analysis comparing required operating force with an external accessibility criterion.

These calculations are screening-level analyses rather than validated design calculations. Where prototype properties had not yet been measured, assumed values were identified explicitly and their influence on the results was considered. The analyses were used to identify design limitations and conditions requiring redesign or further testing.

The assumed input values, their basis, and the range used for sensitivity checks are summarized in Table 2.

Table 2. Assumed input values, their basis, and ranges used in sensitivity checks.

Parameter	**Baseline**	**Basis**	**Range tested**
Combined wheelchair and occupant mass	90 kg	Assumed (75 kg occupant and 15 kg manual wheelchair). Powered wheelchairs, which are considerably heavier, were not analyzed	80 - 110 kg
Bus deceleration	7.4 m/s² (0.75 g)	Maximum vehicle deceleration measured during city-bus hard braking[11]	2.1 - 7.4 m/s²
Rail-block travel distance	0.6 m	Assumed reference travel segment used only to compare movement times and speeds; it does not represent the full boarding-to-wheelchair-space travel distance or a finalized mechanism specification.	Speed varied directly
Rail-block movement speed	0.30 m/s	Conservative intermediate prototype condition for horizontal rail-block movement; to be limited mechanically by a damper	0.15 - 0.60 m/s
Moving mass of block and handle	3 kg	Assumed estimate, not measured	2 - 5 kg
Contact duration	0.1 s	Assumed, no measured value available	0.05 - 0.2 s
Target pivot torque	12 N·m	Assumed scenario value, not measured	Torque meeting 22.2 N calculated (Table 5)
Pull angle relative to lever	90°	Idealized perpendicular pull	45 - 90°

4.1 Vehicle-Deceleration Structural Load Reference

Bus deceleration was analyzed because sudden stops can create forward inertial movement for wheelchair users. Previous city-bus maneuver testing has examined wheelchair movement during normal driving, hard braking, and rapid turning, using vehicle acceleration measurement and wheelchair movement tracking.[11] Deceleration is therefore used here to estimate the inertial load that the rail mounting may need to resist, not the force a passenger should be expected to hold.

Turkovich et al. used a low-tech movement-tracking system to record wheelchair displacement during city-bus maneuvers, including hard braking and rapid turning.[11] Their results showed substantial

movement of unsecured wheelchairs during sudden vehicle maneuvers, supporting the use of bus deceleration as a relevant structural loading scenario for the proposed rail system.

Based on Newton's second law, a simplified inertial load can be estimated using F = ma, where F represents the estimated inertial force in the scenario, m represents the assumed effective forward-shifting mass, and a represents the bus deceleration. The estimated inertial load increases in direct proportion to the bus deceleration.

Figure 1. Estimated inertial load as a function of bus deceleration for a combined wheelchair and occupant mass of 90 kg (F = ma). Marked points show the four deceleration scenarios in Table 3. The figure is a structural loading reference for the rail mounting and does not represent a force to be held by a passenger.

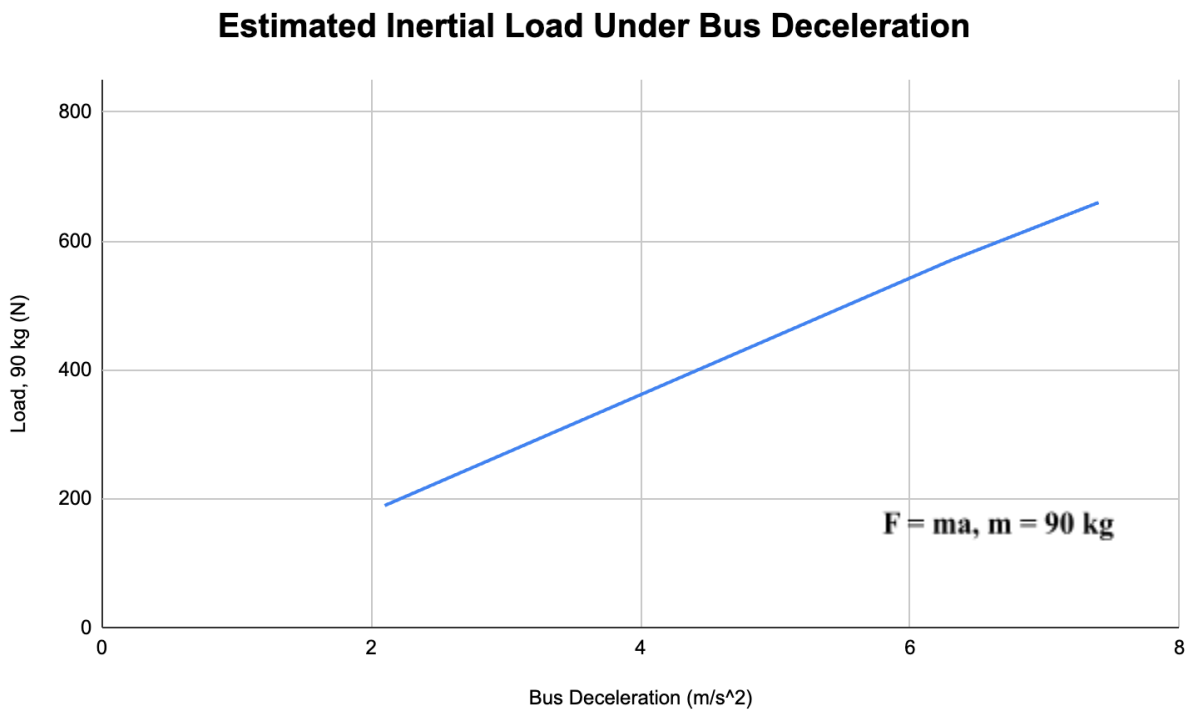


Figure 1 shows that the inertial load rises linearly with deceleration. The measured hard-braking cases produce loads about 3 to 3.5 times larger than the original service-stop scenario, which is why the service stop was not used as the design case.

4.1.1 Deceleration scenarios

Rather than assuming a comfortable service stop, the analysis used decelerations reported for real city-bus hard braking. In the city-bus maneuver testing by Turkovich et al., hard braking from about 32 km/h to

rest took approximately 3 seconds, while the peak vehicle deceleration averaged 0.64 g (SD 0.1) across trials and reached a maximum of 0.75 g.[11] As a regulatory cross-check, the FMVSS No. 121 requirement that a loaded bus stop from 30 mph within 70 ft implies an average deceleration of at least 4.2 m/s² (about 0.43 g).[21] The original service-stop scenario of 30 km/h to rest in 4 seconds (2.1 m/s², about 0.21 g) is retained in Table 3 only for comparison.

The inertial load was estimated as F = ma, where m is the assumed combined mass of a 75 kg occupant and a 15 kg manual wheelchair (90 kg). Using the maximum measured deceleration of 0.75 g (7.4 m/s^2),

$$F = 90 \text{ kg} \times 7.4 \text{ m/s}^2 \approx 660 \text{ N}$$

Results for all four scenarios and for a mass range of 80 to 110 kg are given in Table 3. The illustrative factor of 2 used in the earlier version has been removed. A factor of safety applies to material strength relative to a known load, whereas the purpose here is to identify a realistic load scenario, which the measured hard-braking data provide directly.

Table 3. Estimated inertial load of a wheelchair and occupant under four deceleration scenarios. Values are rounded to two significant figures and are used only as structural references for the rail mounting.

Scenario	**Deceleration (m/s²)**	**Deceleration (g)**	**Load, 80 kg (N)**	**Load, 90 kg (N)**	**Load, 110 kg (N)**
Service stop, 30 km/h to rest in 4 s (original scenario)	2.1	0.21	170	190	230
FMVSS No. 121 minimum braking performance[21]	4.2	0.43	340	380	460
City-bus hard braking, mean peak[11]	6.3	0.64	500	570	690
City-bus hard braking, maximum peak[11]	7.4	0.75	590	660	810

These values are not certified structural design loads. Wheelchair occupant protection in public transit buses relies on dedicated securement and restraint systems and on broader protection requirements that lie outside the scope of a single support rail.[7,18,22] Bus dynamics have also been characterized specifically for the purpose of securement design.[23] Structural testing would be required to establish the actual load capacity of the proposed rail and its mounting.

4.1.2 Limits of the model

This free-body model treats the full 90 kg as a single mass moving horizontally. It ignores the wheelchair's wheel locks and rolling resistance, tire friction against the floor, and the pitching moment

created when a restraining hand force acts at about shoulder height while the mass decelerates at floor level. That moment acts about the front caster contact and makes forward tipping, together with shoulder and wrist loading, a more likely limiting case than horizontal force alone. A moment analysis would require wheelchair geometry that was not measured in this study. The horizontal values in Table 3 should therefore be interpreted only as simplified gross inertial-load references for the rail and its mounting. They do not predict the force transmitted through a user's upper limb, wheelchair stability, or occupant biomechanics.

4.1.3 Comparison with human capability

The loads in Table 3 are not forces that a passenger could reasonably be expected to provide through a handhold. Recent population-specific data from 338 Korean wheelchair users with spinal cord injury showed substantial variability in hand strength, and 8.3% of male participants produced no measurable grip force.[24] The same study recommends low-force, non-grasp interfaces where possible. These findings reinforce the conclusion that a handhold should not be relied upon as an occupant-restraint mechanism during hard braking. The proposed rail is therefore scoped as a boarding, circulation, and positioning aid, while certified securement and occupant-restraint systems remain responsible for passenger protection during travel.

4.2 Moving Rail-Block Speed and Contact Analysis

The movement speed of the rail block and attached hanging handle was examined as a preliminary mechanism-design variable. During boarding and positioning, the assembly is intended to move horizontally along the overhead rail as the user progresses toward the wheelchair space. Slower movement may delay access to the support element, whereas faster movement increases the momentum of the moving assembly and the potential contact force if it strikes a passenger or obstruction.

A horizontal travel distance of 0.60 m was used as a simplified comparison scenario. This distance is an assumed reference segment used to convert movement time into speed and does not represent the full travel of the rail block from the boarding area to the wheelchair space.

Movement speed was calculated as:

$$v_b = \frac{d_b}{t_b}$$

In this equation, v_b represents the rail-block movement speed, d_b represents the horizontal rail-block travel distance, and t_b represents the movement time. A shorter movement time results in a higher rail-block movement speed. For a 0.60 m reference travel distance, movement times of 4, 2, and 1 s correspond to rail-block speeds of 0.15, 0.30, and 0.60 m/s, respectively.

The momentum of the moving assembly was estimated using:

$$p = m_b \cdot v_b$$

In this equation, p represents the momentum of the moving handle, m_b represents the moving assembly of the handle, and v_b represents the handle movement speed. Under the baseline moving-assembly assumption of 3 kg, the corresponding momentum values are 0.45, 0.90, and 1.80 kg·m/s.

Impulse was used to explain the possible impact-related risk of fast handle movement. The average impact force can be estimated using the change in momentum over the contact time.

$$F_{avg} = \Delta p / \Delta t$$

assuming that the moving assembly comes to rest during contact. With the baseline contact-duration assumption of 0.10 s, the estimated contact forces are 4.5, 9.0, and 18 N at speeds of 0.15, 0.30, and 0.60 m/s, respectively.

Because both moving mass and contact duration are unverified prototype parameters, these baseline values are not sufficient to establish a safe operating speed. Their influence was therefore examined through the sensitivity analysis shown in Table 4.

4.3 Comparison with External Contact-Force References

Because ISO/TS 15066 was developed for collaborative robotics rather than transit vehicles, its body-region limits are used here only as screening references.[25] The specification also distinguishes quasi-static from transient contact; therefore, comparison with these values does not establish that the proposed mechanism is safe. Because an overhead moving handle could contact the head or hand, the quasi-static values of 65 N for the face, 130 N for the forehead, and 140 N for the hand are used only to indicate the scale of human-contact forces against which the simplified estimates can be compared. Under the baseline assumptions, the three movement scenarios produce estimated contact forces of 4.5, 9.0, and 18 N, respectively.

This comparison depends strongly on the assumed moving mass and contact duration, and the estimated force is inversely proportional to contact time. Table 4 shows the contact force across the plausible range of each assumption. At 0.30 m/s, the estimate ranges from 3 to 30 N and remains below the cited quasi-static reference values. At 0.60 m/s, the upper sensitivity case of a 5 kg moving mass and 0.05 s contact duration produces an estimated force of 60 N, close to the 65 N face reference. The 0.30 m/s condition, for which the corresponding upper estimate is 30 N, was therefore retained as a conservative prototype speed cap that provides greater margin below the comparison criterion. This value should not be interpreted as a demonstrated safe or optimal speed. The actual moving mass, contact duration, and

contact behavior must be measured using a physical prototype before an operating speed can be validated. Future prototype testing should also examine whether the mechanism preserves interior circulation, remains graspable, and can be stopped or manually controlled at any point. Vehicle accessibility guidelines treat handrails, stanchions, and circulation space as important elements of accessible vehicle interiors.[26]

Table 4. Sensitivity of estimated contact force (N) to moving mass and contact duration, calculated as F = mv/Δt. The baseline case is shown in bold. ISO/TS 15066[25] quasi-static limits for comparison are 65 N (face), 130 N (forehead), and 140 N (hand).

Moving mass (kg)	**Contact time (s)**	**0.15 m/s**	**0.30 m/s**	**0.60 m/s**
2	0.05	6.0	12	24
2	0.1	3.0	6.0	12
2	0.2	1.5	3.0	6.0
3	0.05	9.0	18	36
3	**0.1**	**4.5**	**9.0**	**18**
3	0.2	2.3	4.5	9.0
5	0.05	15	30	60
5	0.1	7.5	15	30
5	0.2	3.8	7.5	15

4.3 Lever Operating-Force Analysis

Torque was analyzed because the proposed handle system includes a lever-assisted pivoting component. In this mechanism, the hanging handle is connected to the rail block through a pivot joint, and user-applied force causes the handle to rotate around this pivot. This rotational movement was considered as a possible way to reposition or operate the support element within the rail system. Because the pivoting handle is intended to be used from a seated position, its operation must be considered together with wheelchair reachability, graspability, and interior circulation requirements. Previous reach research provides normal and maximum reach measures for adult wheelchair users, while transportation accessibility standards and Korean mobility-convenience regulations identify handrails, graspable support elements, and interior circulation as important vehicle-accessibility factors.[16,26,27]

In this context, increasing the lever arm length can reduce the force needed to generate the same torque. This is relevant to ergonomic design because a lower required operating force may make the handle easier to use for people with different physical abilities.

The torque relationship can be expressed as follows:

$$\tau = \boldsymbol{rF} \cdot \boldsymbol{sin\theta}$$

In this equation, τ represents torque, r represents the lever arm length, F represents the applied force, and θ represents the angle between the force direction and the lever arm. In this simplified model, the force was considered to act perpendicular to the lever arm. Therefore, $\boldsymbol{sin\theta = 1}$, and the equation can be simplified as follows:

$$\tau = \boldsymbol{rF}$$

The equation can then be rearranged to calculate the required user force:

$$\boldsymbol{F = \tau / r}$$

For this preliminary comparison, the target torque was set at 12 N·m as an assumed scenario value (Table 2). Because the pivoting handle is an operable part used by seated passengers, the required force was compared with the 22.2 N (5 lbf) maximum operating force for operable parts in the 2010 ADA Standards.[17]

Table 5. Required operating force (N) for the pivoting handle at a target torque of 12 N·m, for three pull angles.

Lever arm length (m)	**Pull at 90° (N)**	**Pull at 60° (N)**	**Pull at 45° (N)**	**Meets 22.2 N?**
0.10	120	140	170	No
0.15	80	92	110	No
0.20	60	69	85	No
0.25	48	55	68	No
0.30	40	46	57	No
0.54 (minimum length for 22.2 N at 90°)	22	26	31	At 90° only

4.4 Result

Every lever length in the original 0.10-0.30 m design range fails the 22.2 N criterion (Table 5, Figure 2). Even the longest original lever, 0.30 m, requires 40 N under a perpendicular pull, nearly twice the

reference value, while the shortest requires more than five times the reference value. Extending the lever to approximately 0.54 m would meet the criterion only under the idealized 90° pull condition.

4.5 Limits of the torque model

The relationship $F = \tau/r$ states only that a longer lever reduces force. It cannot show whether a design is usable unless the result is compared with a criterion, and it rests on simplifications that make the real force higher than predicted. First, it assumes the user pulls exactly perpendicular to the lever. A seated user reaching upward is more likely to pull at an angle, and at 60° or 45° the required force rises by about 15% and 41% respectively (Table 5). Second, it treats the 12 N·m torque as fixed, although the real torque will depend on the handle's own weight about the pivot and on friction in the joint, neither of which has been measured. Third, it is a static model and ignores the additional force needed to start the handle moving.

4.6 What would have to change

Solving $F = \tau/r$ for the 22.2 N limit shows two routes. At 12 N·m, the lever would need to be at least 0.54 m long for a perpendicular pull, or 0.62 m at 60°. A lever of that length would sweep a large arc through the aisle and would itself create a head-strike hazard for standing passengers (Table 9). Alternatively, the torque that the user must supply would have to fall to about 6.7 N·m or less with a 0.30 m lever, or 5.8 N·m at 60°. This could be achieved by counterbalancing the handle with a gas spring or counterweight so that the user only overcomes friction, by reducing the handle's mass, or by powered actuation, which would bring its own control and fail-safe requirements. Counterbalancing is adopted as the preferred direction in the design requirements, and a bench mock-up measuring the actual operating force with a spring scale is identified as the most direct next test.

5. Design Requirements

Based on the preliminary design scoping, field observations, literature review, and physics-based design calculations, four main design requirements were defined for the proposed universal bus handle rail system. These requirements were developed by translating previously identified accessibility issues, wheelchair reach considerations, vehicle interior support standards, and scenario-based engineering calculations into preliminary design criteria.[4,5,6,16,26,27]

First, the rail system should provide continuous support from the boarding area to the wheelchair space. Previous low-floor bus studies have identified interior layout, handrail placement, aisle movement, passenger circulation, and wheelchair space as important accessibility factors inside bus environments.[4,5,6] Based on these findings and the preliminary field observations, the proposed system should connect the boarding area, interior circulation path, and wheelchair space as one support route, rather than functioning only as a fixed handle at a single location.

Second, the rail and its ceiling mounting should be designed to resist the inertial loads associated with hard braking, even though the rail is not intended to restrain a passenger. If a passenger holds the rail or handle during an unexpected stop, the mounting must not fail. Based on the measured hard-braking data, a reference load of approximately 660 N (Table 3) was adopted for early-stage mounting design. This is a structural reference, not a certified design load, and occupant protection during travel remains the role of certified tiedown, occupant-restraint, or rear-facing securement systems.[7,18,22]

Third, the moving element should become available quickly enough to be useful while limiting contact risk. A conservative prototype speed cap of approximately 0.30 m/s was adopted for further development. This value is a prototype scenario, not an experimentally verified optimal speed, and it must be confirmed once the actual moving mass and contact behavior are measured.

Fourth, the handle geometry should reduce the force required from the user while remaining reachable from a seated position. Previous reach research provides normal and maximum reach measures for adult wheelchair users, while bus accessibility guidelines and Korean mobility-convenience regulations identify handrails, graspable support elements, and interior circulation as important vehicle-accessibility factors.[16,26,27] Similar requirements in rapid rail and commuter rail accessibility standards further show that handrail and stanchion placement should be coordinated with wheelchair or mobility-aid circulation routes and interior positioning space across public transportation vehicle types.[28,29] The torque analysis showed that no lever length between 0.10 and 0.30 m meets the 22.2 N operating-force reference at the assumed 12 N·m. The handle should therefore be counterbalanced so that the force a seated user must apply stays at or below 22.2 N, and its grip position in the lowered state should fall within the 38 to 122 cm reach range used as a reference in this study.[17]

5.1 Target Vehicle and Preliminary Construction Assumptions

The concept is intended primarily as a retrofit for Korean low-floor city buses with a centrally located wheelchair space adjacent to the middle exit door, matching the configuration observed in the field audit. The audited wheelchair spaces measured approximately 750 × 1300 mm. The present design does not assume a specific bus manufacturer or model and therefore should not be interpreted as installation-ready. No manufacturing-cost estimate was developed because the concept has not yet been detailed to production level; retrofit feasibility would require vehicle-specific roof-structure assessment and installation quotes.

6. Actuation and Control Concept

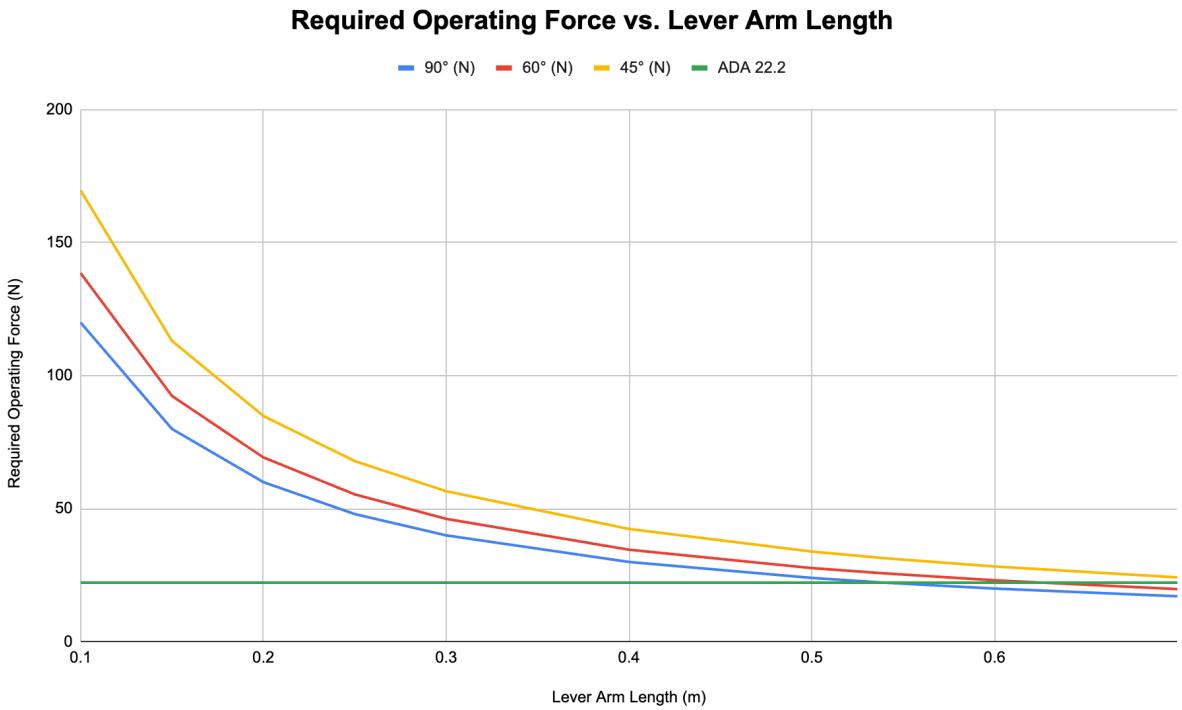
The proposed mechanism is manually operated, and the rail block and hanging handle are moved without motors. At the boarding door, the user pulls the counterbalanced hanging handle downward from its stowed position to a reachable operating height. The required vertical deployment stroke has not yet been fixed and will depend on the final ceiling height, stowed position, and seated-reach target. The user then holds the handle while moving toward the wheelchair space, and the rail block travels along the rail with

the user. A rotary damper in the rail block limits its speed to about 0.30 m/s regardless of how hard it is pushed.

The only powered component is an electric lock on the rail block that is engaged whenever power is absent. The lock releases only while the doors used for wheelchair boarding are open, when the vehicle is stationary. When the doors close, the block locks in place, so the moving mass cannot travel along the track during vehicle motion or in a collision. The driver can also lock the block from the driver's position, and a mechanical key release allows staff to move the block if power fails.

Each wheelchair space is served by one movable block. If a second wheelchair user boards while the block is in use, the fixed sections of the rail remain available as a conventional handrail. After use, the block is manually returned to its stowed position. Because the block is locked during travel, the handle can be used for positioning before securement but is not intended to be held while the bus is moving. This keeps the rail consistent with tiedown and rear-facing securement practice, in which the occupant is protected without needing to hold on.

Figure 2. Required operating force as a function of lever-arm length under the assumed 12 N·m torque condition. The horizontal reference line represents the 22.2 N maximum activation-force criterion for operable parts in the ADA Standards.[17] All lever lengths in the original 0.10-0.30 m design range exceed the comparison criterion at every evaluated pull angle.



Lever (m)	90° (N)	60° (N)	45° (N)	ADA 22.2
0.10	120.0	138.6	169.7	22.2
0.15	80.0	92.4	113.1	22.2
0.20	60.0	69.3	84.9	22.2
0.25	48.0	55.4	67.9	22.2
0.30	40.0	46.2	56.6	22.2
0.40	30.0	34.6	42.4	22.2
0.50	24.0	27.7	33.9	22.2
0.54	22.2	25.7	31.4	22.2
0.60	20.0	23.1	28.3	22.2
0.70	17.1	19.8	24.2	22.2

RESULTS AND DISCUSSION

1. Structured Field-Audit Results

The structured audit identified recurring gaps in reachable support around the designated wheelchair area and along the movement path within the sampled buses.

Across all 18 vehicles, the designated wheelchair space measured approximately 75 x 130 cm and was located in the central portion of the bus immediately forward of the exit door. No dedicated wheelchair-user support handle was observed in any of the 18 buses. In every vehicle, the nearest fixed graspable support adjacent to the wheelchair space was a vertical pole.

The nearest overhead passenger handhold was positioned 160-167 cm above the floor, with a mean height of 163.3 cm and a median of 163.5 cm. The horizontal distance from the nearest edge of the marked wheelchair space to the closest graspable vertical pole ranged from 49 to 71 cm, with a mean of 61.9 cm and a median of 62.0 cm. For comparison, the 2010 ADA Standards set 122 cm (48 in) as the maximum height for an unobstructed forward or side reach from a wheelchair.[17] The nearest overhead handhold exceeded this reference in all 18 vehicles, by 38 to 45 cm. Das and Kozey also reported that the reach envelopes of adult wheelchair users are much smaller than those of non-wheelchair users.[16] Although these references were developed for buildings and workspaces rather than vehicles, the comparison supports the observation that existing overhead handholds are positioned for standing passengers.

These recurring conditions were observed across nine routes sampled by three observers in different parts of the Seoul metropolitan area. The sample was not randomly selected and should not be interpreted as

representative of the entire Seoul bus fleet. Nevertheless, the consistency of the measured configurations provides empirical support for examining a more continuous interior support system.

The measurements alone do not establish whether a particular wheelchair user can or cannot reach an existing support element. Reach depends on wheelchair configuration, body dimensions, seated posture, and upper-limb function. Published wheelchair-user reach data are therefore used as external ergonomic references rather than treating the field measurements as direct evidence of individual reach capability.[16]

Table 6. Measured support geometry across 18 sampled low-floor buses.

Route	Wheelchair Space (marked dimensions)	Nearest Support	Overhead handhold height (cm)	Horizontal distance to nearest support (cm)	Maximum unsupported gap (cm)
440A	75 x 130 cm	Vertical pole	165	49	203
440B	75 x 130 cm	Vertical pole	164	53	200
472A	75 x 130 cm	Vertical pole	162	61	220
472B	75 x 130 cm	Vertical pole	163	55	215
3011A	75 x 130 cm	Vertical pole	165	58	220
3011B	75 x 130 cm	Vertical pole	164	61	218
463A	75 x 130 cm	Vertical pole	162	59	215
463B	75 x 130 cm	Vertical pole	164	62	220
301A	75 x 130 cm	Vertical pole	161	65	210
301B	75 x 130 cm	Vertical pole	164	62	214
147A	75 x 130 cm	Vertical pole	162	68	212
147B	75 x 130 cm	Vertical pole	161	71	210
400A	75 x 130 cm	Vertical pole	162	68	213
400B	75 x 130 cm	Vertical pole	165	70	220
148A	75 x 130 cm	Vertical pole	160	65	210

148B	75 x 130 cm	Vertical pole	167	65	220
141A	75 x 130 cm	Vertical pole	163	62	221
141B	75 x 130 cm	Vertical pole	165	60	223

Note. A and B identify two different physical buses sampled on the same route.

Table 7. Summary statistics for the measured support geometry across the 18 sampled vehicles.

Measure	**Mean**	**Median**	**Range**
Overhead handhold height	163.3 cm	163.5 cm	160 - 167 cm
Horizontal distance to nearest support	61.9 cm	62.0 cm	49 - 71 cm
Maximum unsupported gap	214.7 cm	215 cm	200 - 223 cm

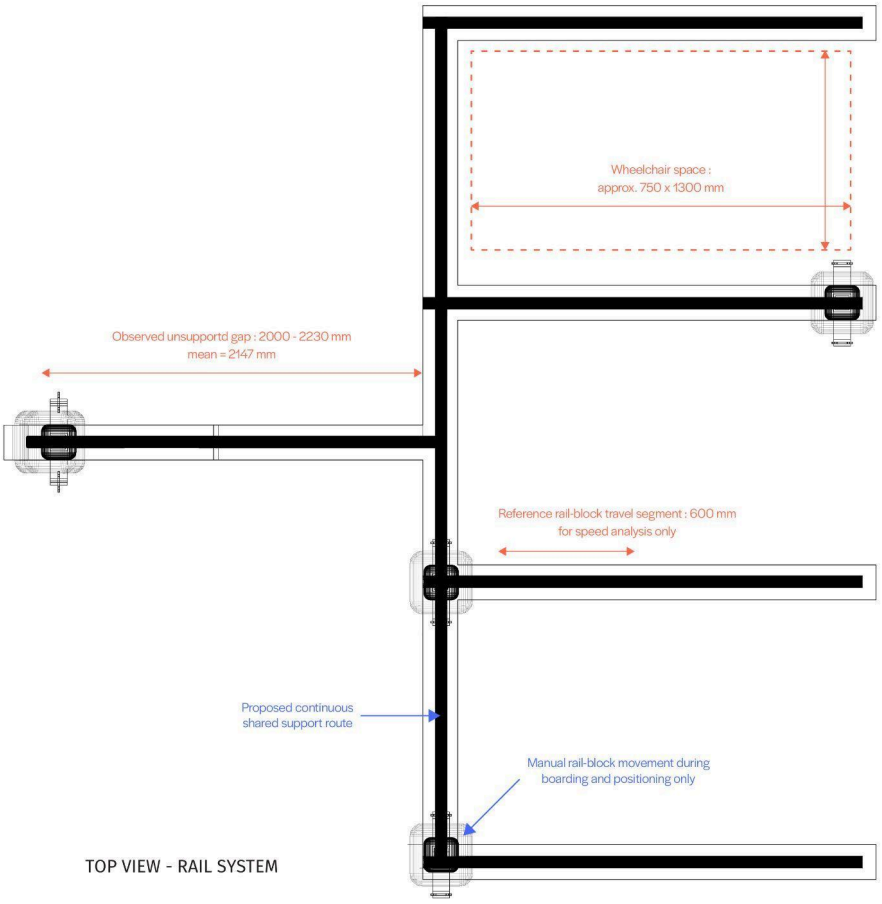
Table 8 summarizes which conditions recurred. Five of the six conditions were identical in all 18 vehicles, while the horizontal distance to the nearest pole varied by up to 22 cm between vehicles and was the least consistent measure.

Table 8. Recurring conditions observed across the 18 sampled vehicles.

Condition	**Vehicles (n = 18)**	**Consistency across vehicles**
No dedicated wheelchair-user support handle	18	Consistent across all routes and observers
Nearest fixed support was a vertical pole	18	Consistent
Wheelchair space immediately forward of the exit door	18	Consistent
Nearest overhead handhold above the 122 cm high-reach reference	18	Consistent (160-167 cm)
Unsupported gap of 200 cm or more along the boarding path	18	Consistent (200-223 cm)
Horizontal distance from wheelchair space to nearest pole	All measured	Varied between vehicles (49-71 cm)

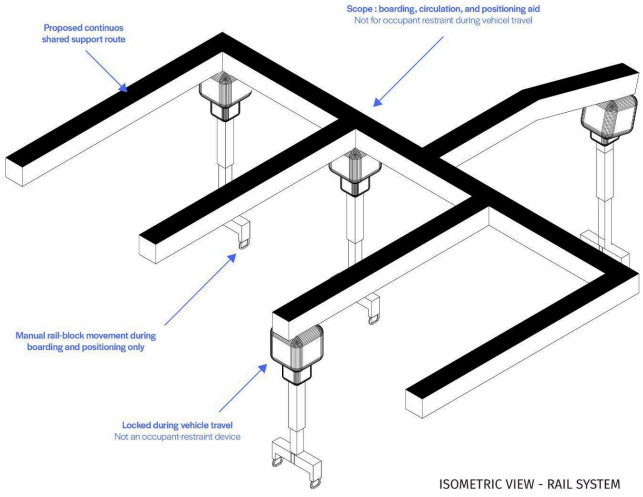
2. Proposed Rail System

Figure 3. Dimensioned side, top, and pivot-detail views of the proposed rail system within the wheelchair area. Dimensions are in millimeters.



The isometric view in Figure 4 shows how the ceiling-mounted rail and vertical handle components are organized as one connected support system. This configuration responds to the design requirement for continuous support by distributing support points across the bus interior. As a result, the rail system is intended to be accessed from multiple positions during boarding, movement, and positioning, while also remaining usable as a general handrail for non-disabled passengers. This shared-use direction is consistent with universal design principles that emphasize equitable use and flexible use across different user groups.[9]

Figure 4. Isometric view of the proposed rail system. Annotations indicate the intended support route and operating constraints of the movable rail block. Diagram created using Rhinoceros 3D and Adobe Illustrator.



The top view in Figure 5 further clarifies the spatial logic of the rail system, where the path was arranged to connect the boarding area, interior circulation path, and wheelchair space. This layout reflects the idea that accessibility should be considered as a continuous movement process, not only as a fixed wheelchair parking area. By extending the support system along the user's path of movement, the design attempts to reduce the gap between boarding assistance and interior stabilization. This design decision was informed by previous low-floor bus studies that identified passenger movement, aisle circulation, handrail placement, and wheelchair space layout as important factors in accessible bus interiors.[4,5,6]

Figure 5. Front view of the rail system. This diagram was created using Rhinoceros 3D and Adobe Illustrator.

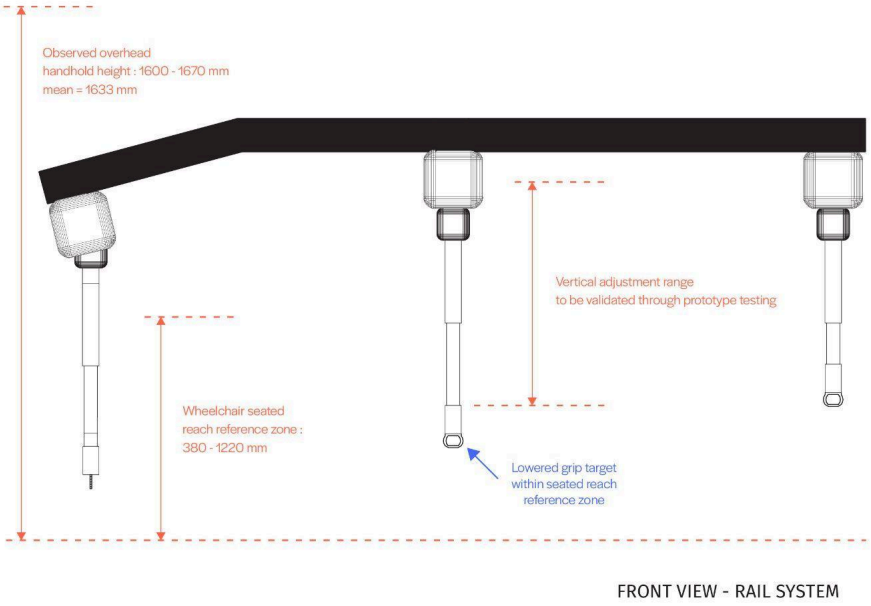
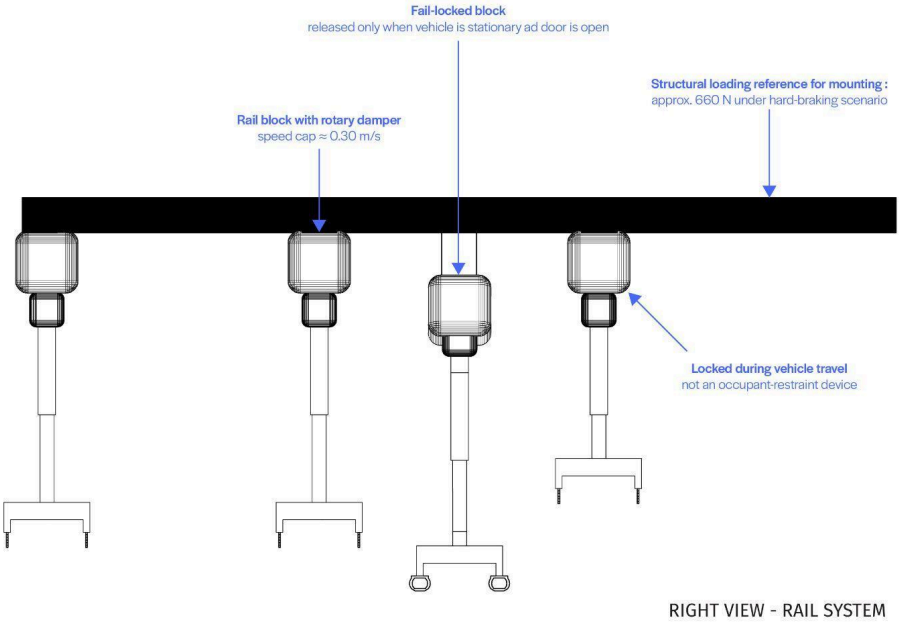


Figure 6. Right-side view of the rail system. This diagram was created using Rhinoceros 3D and Adobe Illustrator.



The front and right-side views in Figures 6 and 7 were used to examine the vertical relationship between the ceiling-mounted rail and the hanging support elements. These views show how the height, spacing, and placement of the handles affect the user's ability to reach and interact with the system. Previous reach research provides normal and maximum reach measures for adult wheelchair users, while bus accessibility guidelines and Korean mobility-convenience regulations identify handrails, graspable support elements, and interior circulation as important vehicle-accessibility factors.[16,26,27] Rapid rail and commuter rail accessibility standards also connect handrail or stanchion placement with wheelchair or mobility-aid circulation routes and interior positioning space, suggesting that reachability and circulation should be considered together across accessible vehicle interiors.[28,29] Therefore, the rail must be designed as an ergonomic interface that responds to different seated positions, reach ranges, and mobility conditions.

Figure 7. Detailed view of the rail system connection. This image was created using Rhinoceros 3D.

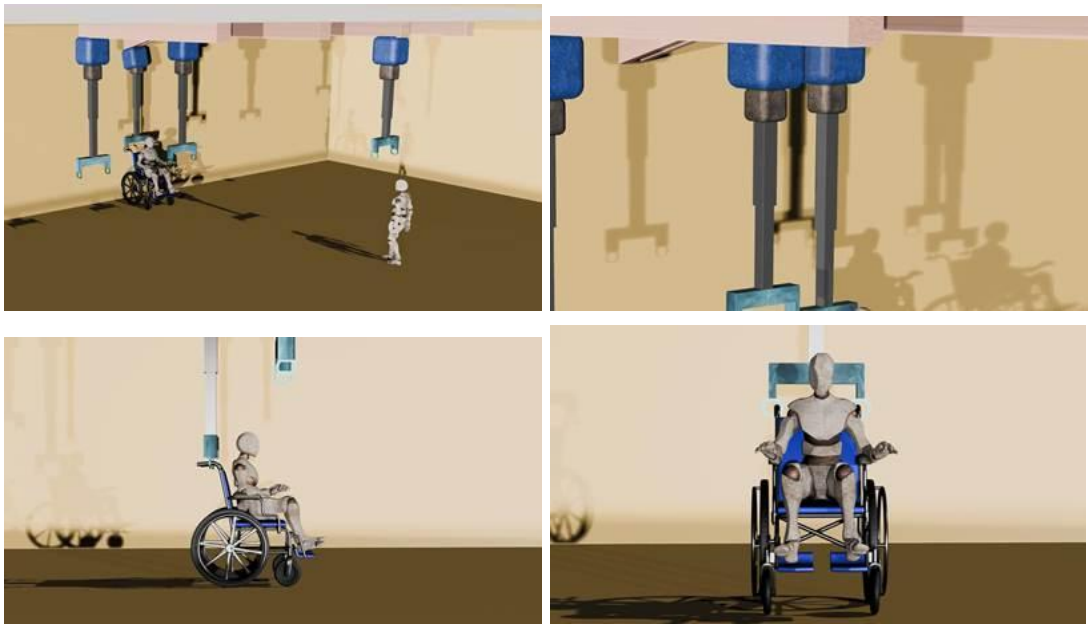


The connection detail in Figure 8 focuses on how the rail, support block, and vertical handle element are joined. The proposed system includes a pivoting handle component connected to the rail block through a pivot joint. When the user pulls the hanging handle, the component rotates around the pivot and assists operation or repositioning of the support element. This detail is important because the connection point would need to transfer user-applied force to the ceiling-mounted rail structure during movement and, if a passenger holds the handle during an unexpected stop, under the inertial loads in Table 3. However, wheelchair occupant protection in public transit buses involves dedicated securement and restraint systems beyond a single support rail.[7,18,22] Therefore, the connection detail should be understood as a preliminary support and operation concept, not as a certified restraint or structural safety solution.

In the current concept, this lever-assisted motion is intended to improve the usability of the handle for users who may have limited strength or reach. The torque analysis showed that lever geometry alone cannot bring the operating force below the accessibility reference, so the handle is counterbalanced

(Section 5). The locking and fail-safe behavior of this connection is described in the actuation concept and in Table 9, and has not yet been tested on a prototype.

Figure 8. Renderings of the rail mechanism in a neutral setting, created by the author using Rhinoceros 3D. (a) Overall shared rail configuration with a wheelchair user and a standing passenger. (b) Detail of the movable rail block and hanging handle. (c) Side view of the handle adjacent to a wheelchair user. (d) Front view of the lowered support position. These renderings show the mechanism only, and its position relative to the bus interior is shown in Figure 3.



The scenario renderings in Figures 9 illustrate how the rail system may operate within the bus interior. The same rail structure is intended to support wheelchair users during boarding and positioning while also serving as a handrail for non-disabled passengers, consistent with the universal design principle of equitable use.[9] A further design hypothesis is that a shared rail may be less stigmatizing than a support structure used only by disabled passengers. This hypothesis was not tested in this study and would need to be evaluated with wheelchair users.

3. Hazards Introduced by the Proposed System

A moving element suspended from the ceiling of a crowded bus introduces risks of its own. Table 9 lists the hazards identified for the current concept, their causes, and the proposed mitigations. Several mitigations depend on the actuation concept described above, in particular the door-interlocked lock that prevents the rail block from moving while the vehicle is in motion. The mitigations are design intentions and have not been tested.

Table 9. Hazards introduced by the proposed rail system, their causes, and proposed mitigations.

Hazard	**Cause**	**Proposed mitigation**
Head strike to standing passengers	Handle or rail block at head height; a long lever sweeping through the aisle	Stowed handle kept at or above the existing handhold height (about 163 cm); movement only while doors are open; speed limited to about 0.30 m/s; padded, rounded handle ends
Finger or hand entrapment	Gaps at the pivot joint, rail slot, and block end stops	Covered pivot; closed rail slot with a brush seal; gaps designed to avoid finger entrapment
Loss of power	Failure of the supply to the electric lock	Lock engaged when unpowered so the block stays fixed; mechanical key release for staff
Moving mass becoming a projectile	Unlocked block during hard braking or a collision	Block locked whenever doors are closed; block captive in the track with end stops; mounting designed for the Table 3 reference load
Obstruction of the aisle and emergency exit	Lowered handle or block left in the aisle	Handle returns to stowed height when released; lowered position limited to the zone beside the wheelchair space
Conflict with crowding at peak times	Standing passengers holding the movable block; competition for the handle	Fixed rail sections serve standing passengers; movable block reserved for the wheelchair space
Use as a restraint during travel	Passenger holds the handle instead of relying on securement	Block locked during travel; signage; certified securement remains the primary protection
Added roof mass	Rail, block, and brackets mounted high in the vehicle	Total added mass has not yet been calculated from finalized material specifications
Cleaning and maintenance burden	Debris in the rail track; wear of the damper and lock	Enclosed track; scheduled inspection of the lock and damper; surfaces compatible with routine cleaning
Conflicting requests from two users	A second user pulling a block already in use	One movable block per wheelchair space; fixed rail sections available to other passengers

Overall, the design outcome shows how supplementary support, reachable geometry, and shared use can be combined in a single interior element, while the analyses show where the current concept falls short. The operating force of the pivoting handle exceeds the accessibility reference at every evaluated lever

length, the contact-force estimate depends on unmeasured parameters, and the hazards in Table 9 remain untested. Rethinking existing bus handles as shared support systems may help wheelchair users during boarding and positioning, but this benefit has not been measured and should be treated as a hypothesis for prototype and user testing.

4. Limitations

This study has several limitations. The field audit used a convenience sample of 18 vehicles on nine routes, observed on a single day, and its measurements were taken with a smartphone LiDAR tool rather than calibrated equipment. No wheelchair users were involved, so reach and usability were assessed only against published references, and those references were developed for buildings and workspaces rather than vehicles. The engineering analyses rely on assumed parameters that have not been measured on a prototype, the braking model does not include the tipping moment, and powered wheelchairs were not analyzed. Finally, the prior-art review was targeted rather than systematic and may not capture all relevant patents or commercial transit handhold systems.

CONCLUSION

This study developed and preliminarily evaluated a conceptual dual-function rail system intended to address gaps in reachable support during wheelchair boarding, interior circulation, and positioning in low-floor buses.

A structured audit of 18 buses provided an empirical basis for the design problem. No dedicated wheelchair-user support handle was observed in the sampled vehicles, the nearest fixed support adjacent to the wheelchair space was a vertical pole in all 18 buses, and the maximum unsupported interval along the boarding-to-wheelchair-space path averaged approximately 215 cm.

The engineering analyses also identified limitations in the current concept rather than simply confirming the proposed design. Under an assumed pivot torque of 12 N·m, all evaluated lever lengths required more than the 22.2 N accessibility reference for operable parts, indicating that the mechanism would require substantial redesign or mechanical assistance. The moving-assembly analysis further showed that estimated contact force depends strongly on unverified prototype parameters, particularly contact duration and moving mass. Under the upper sensitivity case, the 0.60 m/s scenario approached the 65 N ISO/TS 15066 quasi-static facial screening reference. A conservative prototype speed cap of approximately 0.30 m/s was therefore retained for further testing; this value does not establish a safe or optimal operating speed.

The proposed rail should therefore be understood as a conceptual boarding, circulation, and positioning aid rather than as a wheelchair restraint or occupant-protection system. The present study establishes preliminary design requirements and identifies several conditions that the current concept does not yet satisfy.

Future work should include construction of a physical prototype, measurement of actual mechanism mass and operating torque, definition and testing of the actuation and fail-safe system, dimensional and structural evaluation within a representative low-floor bus interior, and user testing with wheelchair users under an appropriate human-subject research protocol.

ETHICS STATEMENT

This study did not recruit human participants or collect identifiable personal, medical, or behavioral data. The structured field audit examined the physical configuration of bus interiors rather than individual passengers. No passengers were interviewed, measured, or evaluated as part of the study, and no identifiable passenger information is reported.

This study did not constitute human subjects research. Because the empirical component was limited to measurements of vehicle interiors and did not involve the collection or analysis of data about individuals, no ethical review was sought or required.

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No external funding was received for this study.

CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

The vehicle-level measurements used in the structured field audit are reported in Table 6, and the calculation inputs and sensitivity analyses are reported in Tables 2-5. No separate public dataset was created for this study.

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During the preparation of this manuscript, ChatGPT was used for feedback on manuscript organization, language clarity, and citation formatting. AI tools were not used to generate the field data or the

quantitative results reported in this study. All calculations, sources, figures, and final text were reviewed by the author, who takes full responsibility for the content of the manuscript.

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