



US DOT National
University Transportation Center for Safety

Carnegie Mellon University



**Project #642: “Advancing Accessible Bus Transit:
Collaborative Design of Bus Transit Schedules”**

Sarah Fox (0000-0002-7888-2598) and Nikolas
Martelaro (0000-0002-1824-0243)

Final Report – August 31, 2026

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, under [grant number 69A3552344811 / 69A3552348316] from the U.S. Department of Transportation's University Transportation Centers Program. The U.S. Government assumes no liability for the contents or use thereof.

Technical Report Documentation Page

1. Report No. 642	2. Government Accession No. 	3. Recipient's Catalog No.
4. Title and Subtitle Advancing Accessible Bus Transit: Collaborative Design of Bus Transit Schedules		5. Report Date August 31, 2026
		6. Performing Organization Code Enter any/all unique numbers assigned to the performing organization, if applicable.
7. Author(s) Sarah Fox (0000-0002-7888-2598); Nikolas Martelaro (0000-0002-1824-0243)		8. Performing Organization Report No. Enter any/all unique alphanumeric report numbers assigned by the performing organization, if applicable.
9. Performing Organization Name and Address Carnegie Mellon University 5000 Forbes Avenue Pittsburgh, PA 15213		10. Work Unit No.
		11. Contract or Grant No. Federal Grant # 69A3552344811 / 69A3552348316
12. Sponsoring Agency Name and Address Safety21 University Transportation Center / U.S. Department of Transportation, University Transportation Centers Program		13. Type of Report and Period Covered Final Report (July 1, 2025 – July 31, 2026)
		14. Sponsoring Agency Code USDOT
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract

Bus schedules shape both the service riders receive and the working conditions under which operators provide it. Concerns about scheduling emerged through preliminary research with operators, who described time pressure and the erosion of breaks, and disability advocates, who identified schedule reliability as essential to inclusive bus service. The study combined an interdisciplinary evidence review with 24 semi-structured interviews: eight schedulers and scheduling experts, six union representatives or operator-leaders, five vendors and transit-data specialists, and five transit IT professionals. Findings show that schedule quality cannot be evaluated solely through cost, running time, and on-time performance. Participants described schedules as negotiated sociotechnical artifacts shaped by resource constraints, collective bargaining agreements, software, fragmented data, local expertise, and translations among operational and passenger-information systems. They distinguished schedule recovery from meaningful rest; identified run construction, reliefs, spread, days off, and bidding as central to operators' quality of life; and emphasized that service reliability and operator well-being are usually interdependent. Preliminary recommendations from this research include separating operating recovery from protected breaks, evaluating whole workdays rather than isolated trips, establishing consequential worker-feedback processes, making scheduling objectives and tradeoffs visible, and using both operational data and situated knowledge to evaluate schedule changes.

17. Key Words

public transit; bus scheduling; accessibility; bus operators; worker well-being; co-design; service reliability; human-centered scheduling

18. Distribution Statement

No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)

Unclassified.

20. Security Classif. (of this page)

Unclassified.

21. No. of Pages

1-25

22. Price

N/A

Executive Summary

Public bus schedules do more than tell riders when a vehicle should arrive. They determine how service capacity is distributed, how operators' workdays are assembled, how agencies interpret performance data, and how much time is available for the human work of safe and accessible service. Scheduling emerged as a shared concern through two strands of preliminary research: operators described unrealistic running times, lost breaks, and workdays organized around constant time pressure, while disability advocates identified dependable schedules and trustworthy service information as prerequisites for reliable, inclusive bus service. Together, these accounts reframed scheduling as a foundational accessibility and work-design problem: even a well-designed communication tool cannot produce accessible service if the bus does not arrive reliably or the schedule does not provide time for an operator to see, communicate with, board, secure, and assist a passenger safely.

The project therefore focused on the question: How might transit schedules be designed to better incorporate factors that support operator well-being while sustaining accessible, reliable service for passengers? The study combined a structured review with 24 interviews spanning schedulers, union representatives and operator-leaders, vendors and transit-data specialists, and transit IT professionals. This multi-stakeholder design made it possible to compare how different actors define efficiency, interpret data, allocate recovery and break time, construct work assignments, translate schedules into public information, and understand the relationship between operator and rider needs.

Core findings

- Scheduling is a coupled worker-rider system. Time allocated to passenger assistance is simultaneously an accessibility resource, a safety resource, and an element of operator workload.
- "On-time" service can conceal displaced costs. When running and dwell times are insufficient, operators absorb variability through shortened breaks, delayed restroom access, rushed driving, and difficult interactions with riders.
- Accessibility labor is variable but predictable at the system level. Wheelchair boarding, securement, wayfinding, communication, and support during disruptions cannot be treated as exceptional deviations from normal service.
- Scheduling expertise is distributed. Schedulers combine software, performance data, service standards, labor agreements, budgets, and local knowledge; operators and riders hold additional knowledge that is rarely represented in formal scheduling inputs.

- Optimization objectives encode institutional priorities. When models privilege platform hours, cost, and punctuality while omitting well-being and accessibility, the omitted burdens do not disappear; they are transferred to workers and passengers.
- The unit of analysis changes the conclusion. A trip can appear feasible while the run built from many trips produces excessive spread, unstable reliefs, lost breaks, or undesirable days off.
- Worker participation varies from recurring joint review to consultation without follow-through. Participants distinguished being heard from having a consequential role in schedule decisions.
- Scheduled service is repeatedly translated across operational and public-facing systems. Reliability depends not only on producing a workable schedule but also on publishing and updating it accurately for operators and riders.
- Humane scheduling requires organizational processes, not a single metric. Protected time, feedback channels, cross-stakeholder review, and monitoring for unequal effects are mutually reinforcing.

Priority recommendations

1. Treat accessible boarding and passenger assistance as ordinary scheduling requirements, using route- and stop-specific evidence to calibrate dwell and recovery time.
2. Protect meaningful layover, meal, and restroom time rather than allowing these periods to function as schedule-recovery buffers.
3. Create recurring, auditable channels through which operators can identify chronically infeasible segments and passengers and advocates can identify accessibility failures.
4. Evaluate schedules with a balanced scorecard that includes reliability, safety, accessibility, operator well-being, missed service, and distributional impacts.
5. Use optimization as decision support. Make objectives, constraints, tradeoffs, and overrides visible to schedulers and affected stakeholders.

1. Introduction

Schedules are the backbone of transit agencies. They provide riders with roadmaps to their destinations; shape service capacity, operating costs, and service quality; determine operator workdays; and frame data produced by automated vehicle location, automated passenger counting, trip-planning, real-time information, and annunciation systems [19]. A schedule is therefore structures both the service riders receive and the conditions under which operators work.

Bus operators are responsible for translating schedules into service under variable, real-world conditions. In addition to driving, they answer questions, make judgments about boarding and alighting, deploy ramps, secure mobility devices, monitor passenger safety, respond to emergencies, and adapt to

traffic, weather, crowding, construction, and equipment failure [4, 13]. These tasks are central to accessible service, but the time they require is often represented only indirectly in schedules.

When schedules are unrealistic, the consequences are shared but unevenly distributed. Riders experience missed connections, long waits, pass-ups, hurried boarding, and unreliable access. Operators experience time pressure, shortened breaks, lack of restroom access, conflict with passengers, stress, fatigue, and pressure to adopt unsafe driving practices [16, 24]. The same schedule may therefore appear efficient at the level of planned vehicle movement while producing inaccessibility and occupational strain in practice.

1.1 Project origin and evolution

This project was originally framed around human-machine interfaces that would help passengers with disabilities communicate their intent to board and their assistance needs. The proposed work emphasized participatory design, hazard analysis, prototyping, and simulated evaluation of rider-to-operator communication. Preliminary research, however, surfaced scheduling as an upstream concern from two directions. Operators described schedules that left insufficient time for breaks, passenger assistance, and ordinary variability. Disability advocates emphasized that reliable arrival, adequate boarding time, and accurate schedule information are fundamental to inclusive service; an interface for signaling assistance cannot solve a trip that arrives unpredictably, departs before a rider can board, or is represented inaccurately in passenger-information systems.

Scheduling therefore emerged not as a departure from the accessibility focus, but as a more foundational site where driver and passenger needs converge. Communication is valuable only if operators have sufficient time and organizational support to act on it safely, and if riders can trust that scheduled service will be delivered and represented accurately. The project therefore shifted upstream, examining how scheduling and operational decisions shape the conditions for accessible service.

This report documents that revised focus. It treats accessible transit not as a feature added at the point of boarding, but as an operational capacity that must be designed into service plans, running times, dwell assumptions, recovery periods, work assignments, policies, and feedback systems.

1.2 Objectives

- Explain how bus schedules are produced and which forms of knowledge shape them.
- Identify how scheduling affects operator health, safety, morale, and retention.
- Clarify how operator well-being and passenger accessibility are interdependent rather than competing concerns.
- Synthesize existing interventions and identify gaps in current scheduling research and practice.

- Develop principles and an empirical research plan for collaborative, worker- and rider-centered schedule design.

2. Project Scope and Research Questions

The project was guided by an overarching question: What would it mean to design a humane bus schedule? “Humane” is used here to describe schedules that recognize bodily needs, variable operating conditions, accessibility work, professional judgment, and the distribution of burdens across workers and riders. It does not imply that schedules can eliminate every delay or tradeoff. Rather, it asks whether operational plans make necessary human work possible without routinely transferring system variability onto frontline workers or passengers with the least flexibility.

2.1 Research questions

6. How are bus schedules constructed, and which institutional, technical, contractual, and experiential inputs shape them?
7. How do schedule design and day-to-day schedule performance affect operator well-being and safe work?
8. Where do the scheduling needs of operators and passengers - especially passengers with disabilities - align, and where do genuine tradeoffs arise?
9. What organizational processes, metrics, and design interventions could support more collaborative and humane scheduling?

2.2 Scope

The analysis focuses primarily on fixed-route public bus transit in the United States while drawing on international evidence where it illuminates organizational interventions. It considers strategic, tactical, and operational scheduling, with primary attention to timetable construction, running and dwell times, layover and recovery, vehicle blocking, runcutting, rostering, and real-time adaptation. It does not attempt to produce a universal optimization model or prescribe a single minimum layover percentage across agencies; local service conditions, labor agreements, route geometry, climate, infrastructure, and passenger demand require contextual calibration.

3. Research Approach

3.1 Study design

The project used a qualitative, multi-stakeholder interview study supplemented by an interdisciplinary evidence review and informed by preliminary research with bus operators and disability advocates. The preliminary work established scheduling as a shared concern: operators foregrounded time pressure

and workability, while disability advocates foregrounded reliability, boarding time, and the dependability of passenger information. The subsequent interviews examined how schedules are created, evaluated, communicated, negotiated, and experienced. The sampling strategy intentionally crossed organizational positions because schedule design is distributed. No single participant group sees the full path from service goals and software configuration to operator work and rider experience.

3.2 Participants

The research team conducted 24 semi-structured interviews between March and August 2026. Participants were assigned role-based pseudonyms in the research record and are identified here only by stakeholder category. Several participants had worked across multiple roles - for example, as operators, schedulers, consultants, agency managers, software developers, or advocates - providing insight into how scheduling priorities change across organizational positions.

Stakeholder group	n	Relevant perspectives represented
Schedulers and scheduling experts	8	Current and former agency schedulers, scheduling managers, consultants, and an expert with operator, planning, accessibility, and scheduling experience.
Union representatives and operator-leaders	6	Current or former operators, scheduling-committee members, local union officers, and a national labor representative.
Vendors and data specialists	5	Scheduling-software and consulting expertise, transit-data platforms, GTFS production and quality, runtime analysis, and applied scheduling research.
Transit IT professionals	5	Agency and contractor experience spanning AVL/APC, GTFS and GTFS-Realtime, passenger-information systems, scheduling-tool development, data publication, and schedule production.
Total	24	Multi-stakeholder interview corpus.

Table 1. Interview sample by primary stakeholder category. Categories reflect the role through which each participant was recruited; many participants had experience in more than one category.

3.3 Data collection

Interviews followed a semi-structured protocol tailored to each stakeholder group. Common topics included the scheduling workflow; use and limits of AVL, APC, GTFS, and other operational data; running-time and layover decisions; blocking, runcutting, rostering, bidding, and reliefs; collective bargaining agreements and work rules; operator and union input; software capabilities; service changes

and disruptions; and possible improvements for operator well-being and rider experience. Interviews typically lasted approximately one hour. The analytic materials included verbatim transcripts and detailed interview notes.

Participants were recruited through transit labor unions, LinkedIn, personal and professional connections within the transit and software industries, and subsequent snowball sampling. All participants provided informed consent prior to participation. We conducted semi-structured interviews and compensated participants \$40 per interview. Interviews were audio recorded with participants' consent and automatically transcribed; members of the research team subsequently reviewed and corrected the transcripts for accuracy. The study protocol was reviewed and approved by Carnegie Mellon University's Institutional Review Board.

3.4 Analysis

Analysis proceeded iteratively. The team first organized material by stakeholder group and stage of the scheduling process. It then compared recurring concerns across groups, attending both to convergence and disagreement. Codes focused on definitions of efficiency and schedule quality; data and local knowledge; running time, layover, and breaks; run and roster construction; seniority and choice; staffing and resource constraints; participation and trust; technology and interoperability; and effects on riders. Themes were refined by returning to full interview contexts and checking claims across multiple participant categories. Quotations in this report are attributed only by stakeholder category to protect confidentiality.

3.5 Evidence synthesis

The completed work consisted of a structured, interdisciplinary synthesis of transit scheduling practice and operator well-being. Sources included the Transit Cooperative Research Program scheduling manual; peer-reviewed work on routing, timetabling, vehicle scheduling, crew scheduling, and rescheduling; occupational-health research on bus operators; studies of disability and operator-passenger interaction; federal and state policy materials; industry data standards; and documented organizational interventions.

The review followed the scheduling process from strategic network design through tactical timetable and crew construction to operational adaptation. Evidence was then organized using a social-ecological framework that distinguishes, while connecting, individual characteristics, interpersonal relations, working conditions, organizational policy, infrastructure, and broader economic and regulatory systems [1]. This enabled the research team to move beyond a narrow account of running time and identify how scheduling mediates health, accessibility, and service quality across levels.

3.6 Scheduling-role landscape scan

To characterize the work of schedulers, the team conducted a preliminary scan of 174 job listings across TransitTalent, Mass Transit, the American Public Transportation Association, and the American Association of State Highway and Transportation Officials. Fifteen listings with direct scheduling responsibilities were screened in detail. The scan was used to identify the range of job titles and functions associated with scheduling, including timetable and run development, service planning, community and government relations, and analysis of automated passenger count and vehicle-location data.

3.7 Integrative analytic strategy

The analysis compared what scheduling systems formally represent with work that operators and passengers must perform in practice. Particular attention was given to omitted or weakly represented variables: passenger-assistance time, access to restrooms and meals, the cumulative effects of delay, uneven shift quality, operator discretion, equipment failure, weather, crowding, and the interpersonal consequences of lateness. Findings were developed as design requirements and translated into agency, software, policy, and research recommendations.

3.8 Limitations

The study provides depth across a set of heterogeneous experts but is not representative of U.S. transit agencies or operators. Participants were recruited for relevant experience, and several had worked in large agencies or specialized technical roles. Although preliminary research with disability advocates shaped the project focus, the 24-interview corpus did not include a comparable dedicated sample of disabled riders or rider advocates; future work will extend the study to engage these groups directly. The study also did not compare participant accounts against agency schedule, AVL, APC, absence, or retention datasets. The findings therefore identify recurring mechanisms, tensions, and design requirements rather than estimating their prevalence. In the coming year, we will extend this work through co-design workshops with relevant stakeholders, using the findings reported here to inform the development and refinement of potential design interventions.

4. Foundations of Transit Scheduling

4.1 Strategic, tactical, and operational decisions

Transit scheduling is not a single calculation. Strategic decisions establish networks, route alignments, stops, and broad service goals. Tactical decisions determine frequencies and timetables, assign vehicles to blocks, divide vehicle work into runs, and assemble weekly rosters. Operational decisions respond to disruption through dispatching, holding, stop-skipping, short turns, vehicle substitution, or schedule regeneration [8, 15, 17, 19]. Decisions at each level constrain the next: a timetable cannot fully

compensate for stop placement that creates inaccessible boarding, and real-time control cannot sustainably repair a master schedule that is routinely infeasible.

4.2 Timetables, blocks, runs, and rosters

The master timetable assigns planned departure and arrival times to routes. It must account for round-trip running time, passenger demand, dwell, layover, recovery, transfers, service standards, labor agreements, and operational preferences [19]. Vehicle blocking links trips into work for individual buses. Runcutting decomposes vehicle blocks into pieces of work for operators, while rostering assembles daily runs into weekly assignments. These processes jointly shape both the public service and the quality of individual jobs.

Scheduling algorithms commonly minimize operating cost subject to demand, capacity, safety, and contractual constraints. Research has extended these formulations to energy, eligibility, complex break constraints, and fatigue balance [6, 9, 10, 18]. Yet operator well-being and accessibility are often represented as hard minimum constraints, indirect proxies, or not at all. This matters because optimization tends to use every unprotected margin. A nominal break can become recovery time; recovery can disappear after a delayed trip; and a legally compliant shift can still be physiologically or socially difficult.

4.3 Schedulers as organizational integrators

Software automates important subtasks, but producing a workable schedule remains an expertise-intensive organizational process. Schedulers interpret ridership and vehicle-location data, understand route geometry and local traffic, reconcile budgets and labor rules, anticipate public response, and negotiate with operations staff. Their role is less that of a neutral operator of an optimization tool than an integrator of heterogeneous evidence and competing institutional priorities.

This makes scheduler discretion an important point of intervention. More inclusive tools should not simply add another automated score. They should help schedulers see who bears the cost of a proposed schedule, trace the evidence behind assumptions, compare alternatives, and document why local judgment overrides a model.

4.4 Data infrastructures

The General Transit Feed Specification supports publication and exchange of static schedule and real-time vehicle data [29]. Automated vehicle location and passenger counting provide substantial evidence about actual running time, dwell, crowding, and adherence. These data can support better schedules, but they are not self-interpreting. A stopped bus may reflect passenger assistance, a restroom need, a safety event, traffic, or equipment failure. When interaction logs are read only as lateness or time off route, data intended for planning can become a disciplinary infrastructure and can discourage the very discretion required for safe and accessible service [4].

5. Findings: Scheduling as a Shared Accessibility and Work System

Across stakeholder groups, participants challenged the idea that a schedule is simply a timetable generated from demand and travel time. They instead described a layered artifact shaped by service goals, fleet and staffing constraints, collective bargaining agreements, software configurations, local conventions, and repeated judgments about acceptable tradeoffs. The findings presented here are preliminary; analysis and writing are ongoing, with the aim of developing this work for submission to ACM CSCW or a comparable peer-reviewed venue. At this stage, we identify several recurring patterns across the interviews, distinguishing areas of broad agreement from points where stakeholder perspectives diverged.

5.1 Schedule time is an accessibility resource

Accessible service requires time with operators needing to position the vehicle carefully, deploy a ramp or lift, clear a securement area, communicate with a passenger, secure a mobility device, provide wayfinding, wait for a passenger to sit or stabilize, and manage interactions among riders. Weather, crowding, stop design, device type, communication needs, and equipment condition affect how long these tasks take. Treating this work as an exception makes accessibility contingent on spare time that may not exist.

The central finding is therefore that passenger assistance should be modeled as part of ordinary service delivery. This does not require assigning a fixed penalty to every stop. It requires using distributions and local evidence to recognize predictable variation, protecting recovery capacity, and avoiding performance rules that penalize operators for providing needed assistance.

Interviewees repeatedly connected rider conditions to trip-level running time. Schedulers described moving from broad time-of-day averages toward trip-by-trip analysis because a school dismissal, heavy boarding activity, crowding, or a particular stop can make adjacent trips on the same route behave differently. Union representatives similarly emphasized that operators see passenger patterns and recurring boarding conditions not visible in a systemwide average. A former operator and scheduler summarized the practical ethic of the work: even changing a schedule by one minute can affect both an operator's day and a rider's connection.

This finding also reflects the preliminary disability-advocacy research that motivated the project shift. Advocates identified schedule reliability as part of accessibility itself, not merely a general service-quality concern. Unpredictable arrival, insufficient boarding time, a missed connection, or inaccurate information can have heightened consequences for riders who require accessible vehicles or stops, assistance, additional travel time, or careful coordination with other services. Inclusive scheduling must therefore address both the time available to deliver assistance and the reliability with which that time and service are communicated.

5.2 Time pressure moves risk across the system

Time pressure is associated with fewer rest breaks, higher stress, fatigue, and increased risk of unsafe behaviors such as speeding, abrupt acceleration, or incomplete stops [16]. It also affects riders. An operator who is already late has less practical capacity for patient communication and careful boarding; riders may experience rushed interactions or missed connections; and passenger frustration may be directed at the operator, increasing interpersonal strain [4, 13].

A tight schedule can thus create a feedback loop. Variable conditions generate delay; operators absorb delay by sacrificing breaks or increasing pace; fatigue and conflict make service harder to deliver; and the resulting instability appears as an individual performance problem rather than evidence that the schedule is under-resourced.

Union participants described “living and dying by the clock” and contrasted management definitions of efficiency, often centered on cost, with operator definitions centered on realistic running time, spacing, and freedom from constant rushing. Schedulers and technical participants did not dispute the mechanism. Several described efficient blocking or tighter cycle times reducing layover, while one IT participant observed that agencies ultimately “pay for it” either through scheduled capacity or through recurring, unpredictable service failures when operators must stop mid-route for basic needs.

5.3 Layover and recovery are not interchangeable with rest

Recovery time allows a late vehicle to return to schedule. Layover may also provide opportunities for restroom use, meals, movement, decompression, and preparation for the next trip. When the same minutes are expected to serve both functions, operational variability routinely displaces bodily needs. A schedule that includes a nominal layover but produces no usable break under common conditions should not be considered adequate.

Restroom access illustrates the issue. Although access is required, operators may lack either a facility or sufficient time to use it [24]. Effective planning must connect time and place: a break is meaningful only if it occurs near a usable facility, allows for walking and waiting, and is protected from routine erosion.

This distinction was one of the clearest empirical findings. Vendors described agencies using the same time both to recover late service and to satisfy operator needs, even though runtime variability determines how much of that time survives. One vendor stated plainly, “breaks are included in the layover,” then rejected that formulation: layover protects the next departure, whereas a break serves a person. Union representatives added that the location must be safe and have an accessible restroom; time at a terminal without a usable facility is not meaningful recovery. Participants differed on whether a universal minimum was feasible, but converged on evaluating realized break time rather than the printed schedule alone.

5.4 Shift structure affects health and life beyond the vehicle

Early, night, rotating, irregular, overtime, and split shifts can disrupt sleep, eating, family life, and social support [16]. Seniority-based selection offers a degree of worker choice but may concentrate undesirable or physiologically difficult work among newer operators and may not accommodate medical or caregiving needs. Humane scheduling therefore includes both the feasibility of individual trips and the distribution of runs and rosters across a workforce.

Interviewees consistently argued that trip feasibility is an inadequate unit for evaluating quality of life. They pointed to split or swing shifts, total spread, report and travel time, street versus garage reliefs, consecutive days off, four-day workweeks, weekend work, and the predictability of rosters. Examples showed that a change that appears less efficient at the vehicle level - such as pulling a bus into the garage for a relief - can improve operator safety and quality of life. Conversely, a set of individually feasible trips can produce an unattractive or exhausting day when combined into a run.

Seniority was treated ambivalently but not simplistically. Participants recognized that it concentrates poor work among newer operators, contributing to turnover. Yet schedulers and union representatives also described seniority as a transparent protection against favoritism and as a benefit earned through years of undesirable assignments. The most credible alternative was not abolishing seniority, but improving the baseline quality and legibility of all work while giving operators adequate time and information to choose.

5.5 Accessibility and well-being are usually aligned

Operator and passenger needs are sometimes framed as competing demands: more assistance time may appear to threaten on-time performance, while more recovery may appear to reduce service. The synthesis suggests that this framing is often misleading. Sufficient dwell and recovery time improves the conditions for safe boarding, patient communication, reliable connections, and safer driving. Better information about passenger needs can also reduce uncertainty for operators if it is paired with schedule capacity and carefully designed workflows.

Genuine tradeoffs remain. Increasing running time may require more vehicles, labor hours, or lower frequency under a fixed budget. The design challenge is not to hide these tradeoffs inside operator effort. It is to make them explicit, evaluate who is affected, and identify whether additional resources, network changes, operational control, or targeted schedule adjustments are most appropriate.

Participants supplied concrete examples of alignment. Interlining a chronically delayed high-ridership route with a route that regularly returned early created a dependable break while stabilizing service. Increasing schedule consistency enabled operators to learn routes and passengers, improving rider experience. Adding realistic running time reduced pressure to rush and made the next departure more reliable. These examples complicate a simple cost-versus-well-being frame: some changes require resources, while others reallocate slack already present elsewhere in the system.

5.6 Formal metrics omit distributed expertise

Operators know where left turns routinely fail, where school dismissal changes traffic, where ramps are difficult to deploy, where restrooms are inaccessible, and which scheduled connections create repeated conflict. Riders and advocates know where published access diverges from usable access. Schedulers know contractual, fleet, budgetary, and network interactions that may be invisible to any one route. A credible schedule-design process requires all three forms of knowledge.

Occasional complaint collection is insufficient. Feedback must be structured, linked to schedule versions and locations, reviewed on a known cadence, and closed with an explanation of what changed or why change was not feasible. Otherwise, participation generates information without accountability.

The interviews revealed a wide range of participation arrangements. Some agencies held recurring union meetings, garage sessions, or operator roundtables; others invited input only after a draft run cut existed. Union participants frequently distinguished cordial meetings from influence. One explained that the agency listened and praised suggestions but “very rarely” implemented them. Schedulers, in turn, described the emotional and technical difficulty of receiving generalized criticism after investing substantial effort under tight constraints. Both accounts point to the same design failure: feedback arrives without shared evidence, decision rules, or a traceable response.

A labor representative described a more collaborative model in which agency and union participants jointly pursued two outcomes: “quality of service” and “quality of work.” This arrangement depended on phased implementation, evaluation, and willingness to revise. The contrast suggests that participation is most consequential when it occurs before decisions harden, uses an open account of constraints, and includes an explicit feedback-to-action loop.

5.7 Technology can support or intensify the problem

Automated ticketing, passenger information, and driver-assistance technologies can reduce some tasks but can also create new alerts, breakdown work, monitoring, and role overload [4]. Similarly, schedule-optimization tools can expand the alternatives a scheduler can consider while narrowing attention to variables the system can quantify. The appropriate goal is not maximal automation. It is legible decision support that represents human requirements and preserves professional judgment.

Technical participants characterized scheduling as “art and science.” AVL and APC data can reveal distributions of running time, dwell, passenger loads, and recurring volatility, but participants warned that data show what happened more readily than why. Login errors, geofences, manual entry, inconsistent identifiers, and mismatches among scheduling, operations, and human-resource systems can distort analysis. Smaller agencies may lack service planners, data staff, or integrated platforms altogether, leaving schedules to be adjusted through spreadsheets, vendor exports, or informed guesswork.

The expanded IT sample showed that a schedule is repeatedly transformed after schedulers finish constructing it. Data may move from HASTUS, Trapeze, or another planning platform into CAD/AVL systems, vehicle databases, operator communication interfaces, GTFS and GTFS-Realtime feeds, agency websites and apps, third-party trip planners, printed timetables, and stop displays. Each transformation introduces validation, synchronization, and ownership problems. Participants described custom scripts and notebooks used to add missing accessibility fields, reconcile calendars, merge current and future service, correct stop and headsign information, and make data usable by public-facing tools.

These translations are consequential for inclusion. One IT participant described adding accessibility information that the core vendor export omitted; another described station-pathway data intended to support “street to seat” navigation. Participants also described delays between an identified error and the next formal schedule release, inconsistent representations of temporary service, and operations improvements that did not automatically reach customer-information systems. A schedule can therefore be operationally valid yet publicly misleading. For riders who depend on precise accessibility and real-time information, that gap can determine whether service is practically usable.

Software vendors emphasized that contemporary tools can encode collective bargaining rules, generate many alternatives, support trip-level runtimes, and score aspects of operator quality of life. Yet the system cannot decide which outcomes deserve protection. Configuration is policy: whether a break is a hard constraint or an optimization preference, how spread is penalized, and which forms of undesirable work are visible all shape the resulting schedule. Several participants therefore favored open-deck processes in which assumptions, rules, and consequences are inspectable rather than a single opaque “optimized” answer.

5.8 Existing interventions point toward system-level change

Documented interventions suggest that changing the work environment can improve outcomes. A Stockholm project combined bus priority, infrastructure improvements, and passenger information, reducing several measures of stress and job hassles. Copenhagen’s HealthyBus initiative used more than 200 interventions across work organization, organizational support, training, and the physical environment; follow-up indicated perceived improvements in working conditions [27, 28]. These examples reinforce that schedule changes work best as part of a broader system involving infrastructure, staffing, communication, and organizational support.

5.9 Staffing shortages turn schedule defects into cascading service failures

Participants treated operator availability as both an input to and an outcome of scheduling. When a trip is uncovered, the following bus inherits more passengers and longer dwell, producing a compounding delay. Overtime and extra-board reliance can then increase fatigue, while poor days off, long spreads, and unpredictable work contribute to turnover. A scheduler described adequate staffing as the largest immediate improvement because gaps create a “domino effect.” This reciprocal relationship means that

recruitment and retention cannot be separated from schedule design: agencies need operators to deliver service, but the quality of scheduled work helps determine whether operators stay.

5.10 Efficiency is plural and politically negotiated

The deepest disagreement concerned what counts as efficiency. Vendors and schedulers often used the term to describe lower cost, improved vehicle utilization, or schedules that satisfy more constraints. Union representatives used it to describe service that runs consistently without forcing operators to rush or surrender basic needs. These definitions are not mutually exclusive, but they prioritize different denominators. A schedule can use vehicles efficiently while using human time poorly; it can protect generous margins while delivering too little service; or it can improve both through better interlining, data, and work design.

Accordingly, the empirical material does not support a universal formula for humane scheduling. It supports a governance requirement: agencies should state which forms of efficiency they are pursuing, identify who bears the downside of each alternative, and make protected human requirements explicit before optimization begins.

6. Design Principles and Recommendations

6.1 Define a humane schedule as a multi-dimensional standard

A humane schedule should be operationally feasible under ordinary variability; provide usable time for passenger assistance and bodily needs; distribute desirable and undesirable work fairly; preserve safe discretion; and be revisable through evidence and stakeholder input. No single measure captures these properties. Agencies should adopt a balanced set of indicators.

Dimension	Example indicators	Diagnostic question
Service reliability	On-time performance; headway regularity; missed trips; connection success	Does the schedule work consistently for riders, not only on average?
Accessibility	Boarding completion; pass-ups; lift/ramp events; assistance-related delay; rider reports	Does the schedule make accessible boarding ordinary and reliable?
Operator well-being	Usable break time; restroom access; overtime; fatigue and stress reports; absenteeism	Can operators meet bodily needs and complete work without chronic strain?

Safety	Harsh events; preventable incidents; speeding pressure; passenger falls	Does the schedule avoid incentives to rush?
Feasibility	Running-time percentiles; terminal arrival distribution; recurrent delay segments	Are planned times robust to common variability?
Equity	Run quality by seniority and demographic group; route-level burden; disability impacts	Who receives flexibility and who absorbs instability?

Table 2. Illustrative dimensions for evaluating schedule quality. Measures should be interpreted together and disaggregated by route, time, run, and affected population.

6.2 Build accessibility-sensitive time into schedules

- Use observed dwell-time distributions rather than a single systemwide average where data quality permits.
- Identify stops and time periods with recurring ramp, securement, crowding, or wayfinding needs and calibrate time accordingly.
- Include sufficient recovery to absorb common variation without consuming protected breaks.
- Do not count assistance-related delay as operator noncompliance without contextual review.

6.3 Protect breaks and restroom access

- Distinguish schedule recovery from minimum usable rest in planning rules and reporting.
- Map operating facilities to runs, including walking time, access restrictions, maintenance, and hours of availability.
- Monitor realized rather than scheduled break time and identify routes where breaks are repeatedly lost.
- Use extra-board, surge, interlining, terminal, and route-design strategies to address recurrent infeasibility rather than relying on operator sacrifice.
- Encode recovery and protected rest as separate scheduling concepts, even when they occur within the same terminal interval.

6.4 Evaluate the whole workday

- Assess run quality using total platform time, paid time, spread, split duration, relief type and location, report and travel time, consecutive days off, weekend burden, and schedule predictability.

- Report how undesirable work is distributed by seniority and depot rather than relying only on the quality of the average run.
- Provide operators with timely, accessible information about available work so bidding represents informed choice.
- Test four-day workweeks, straight runs, pull reliefs, alternative interlining, or roster arrangements as explicit pilots, evaluating service and workforce outcomes together.

6.5 Institutionalize collaborative schedule review

Agencies should establish a recurring schedule-review process involving scheduling, operations, operators or union representatives, accessibility staff, and rider/disability advocates. Review should occur early enough to influence service changes, not only after a schedule has been finalized.

10. Map recurrent pain points using schedule-adherence data, operator reports, rider complaints, accessibility events, and field observation.
11. Separate structural problems from isolated incidents and identify which level - route design, timetable, blocking, runcutting, policy, infrastructure, or dispatch - can address each issue.
12. Generate alternatives and make their resource and distributional implications explicit.
13. Pilot changes on selected routes or runs with pre-specified reliability, accessibility, safety, and well-being measures.
14. Report back to participants, document the disposition of each material concern, and incorporate evidence into the next service-change cycle.

6.6 Design transparent scheduling tools

- Expose objectives, constraints, weights, confidence intervals, and local overrides rather than presenting a single “optimal” schedule.
- Allow schedulers to compare alternatives across cost, reliability, accessibility, break protection, and run-quality indicators.
- Attach qualitative annotations from operators and riders to locations, trips, and schedule versions.
- Preserve an audit trail showing how feedback and data affected decisions.
- Use automated flags to prompt investigation, not automatic discipline.

6.7 Improve data integration without erasing context

- Create stable identifiers and documented links among scheduling, AVL/APC, operations, bidding, and workforce systems.

- Track data provenance and known failure modes, including missing logins, geofence errors, manual corrections, and coverage gaps.
- Pair quantitative anomalies with operator, dispatcher, and field observations before changing runtimes or evaluating performance.
- Provide lower-capacity agencies with scalable methods that do not assume a large analytics staff or enterprise software stack.
- Validate accessibility fields, pathways, stop locations, headsigns, calendars, and temporary service across agency and third-party passenger-information channels before each release.
- Treat the timely publication of schedule corrections and service changes as an accessibility requirement, with clear ownership and escalation paths when operational and public-facing representations diverge.

6.8 Evaluate distribution, not only averages

System averages can conceal routes, shifts, and workers that bear disproportionate burdens. Agencies should examine tails of running-time and break-loss distributions, compare run quality across seniority groups and depots, and assess whether accessibility failures cluster at particular stops or service periods. Evaluation should also ask whether schedule changes shift burdens from one group to another.

6.9 Align policy and funding with human requirements

Agencies cannot schedule their way out of every resource constraint. Persistent infeasibility may require additional operating funds, staffing, bus-priority infrastructure, accessible stops, restroom agreements, fleet maintenance, or service redesign. Policy should define accessibility and operator well-being as performance requirements and fund the capacity needed to meet them, rather than treating them as unfunded additions to a fixed schedule.

7. Conclusions and Future Work

The project's shift from communication interfaces to scheduling reveals an important systems insight: accessible transit depends not only on whether riders can communicate a need, but on whether the service plan gives operators the capacity to respond. Schedules coordinate vehicle movement, passenger expectations, and working conditions. They are therefore a central site for safety and accessibility design.

A humane schedule is not simply a slower schedule. The interviews show that it is a schedule developed through an accountable process that recognizes variation, distinguishes recovery from rest, evaluates complete workdays, represents distributed expertise, makes tradeoffs visible, and monitors how

burdens are allocated. Such schedules can support operator health and retention while improving the reliability and dignity of passenger service.

7.1 Priority future research

- Conduct a dedicated next-stage study with disabled riders and disability advocates, extending the preliminary research that identified reliability and schedule information as accessibility concerns; also include dispatchers, accessibility staff, frontline operators without union roles, and agencies underrepresented in this study.
- Link the interview findings to de-identified schedule, AVL, APC, dwell, lift/ramp, complaint, absence, overtime, bidding, and turnover data where available.
- Co-design feedback mechanisms and scheduling-tool features, then test whether they improve decision quality and stakeholder trust.
- Develop and validate measures of usable recovery, accessibility-sensitive dwell, schedule feasibility, and run-quality distribution.
- Pilot schedule changes and examine effects on reliability, accessibility, safety, operator well-being, and resource use over multiple service periods.

8. Research Products, Data, and Outcomes

8.1 Products and outputs

The materials supplied for this report document the following project outputs:

- A structured review and conceptual synthesis, “Towards Humane Bus Scheduling.”
- A qualitative dataset consisting of 24 semi-structured interviews and interview notes across four stakeholder categories.
- A cross-stakeholder analysis of schedule creation, data practices, work design, participation, and definitions of efficiency.
- Design principles and recommendations for collaborative, accessibility-sensitive, worker-centered scheduling, consolidated in this final report.

8.2 Data and data management

The project generated interview transcripts and notes containing potentially identifiable information about participants, agencies, labor relations, and software practices. These raw qualitative data are not appropriate for unrestricted public release. They have been secured, de-identified, and archived in accordance with the approved Data Management Plan, consent materials, and institutional

requirements. A de-identified codebook, interview protocol, aggregate sample description, or analytic memo may be suitable for public sharing, if it should be requested.

8.3 Matching funds

Matching funds were provided through in-kind teaching and staff research time. Within Carnegie Mellon University's Human-Computer Interaction Institute, Sarah Fox's course, Design and/of Policy, included a unit on autonomous vehicle technology, and Nikolas Martelaro's rapid prototyping course included a focus on autonomous vehicle interfaces. The Transport Workers Union of America (TWU) and Amalgamated Transit Union (ATU) contributed in-kind staff research time supporting engagement with transit labor expertise and worker-centered scheduling concerns.

8.4 Documented outcomes and anticipated impact

The project reframed accessible transit technology as an operational and organizational design problem. Its primary contribution is a set of requirements for ensuring that technologies and schedules do not ask operators to absorb accessibility work through personal time, rushed driving, or informal workarounds. The recommendations are relevant to transit agencies, scheduling-software vendors, labor organizations, accessibility advocates, and public funders.

References

1. Agency for Toxic Substances and Disease Registry. n.d. "Models and Frameworks." Principles of Community Engagement. https://www.atsdr.cdc.gov/communityengagement/pce_models.html.
2. Bertsimas, D. J. "A Vehicle Routing Problem with Stochastic Demand." *Operations Research* 40(3): 574-585. <https://doi.org/10.1287/opre.40.3.574>.
3. Wang et al. 2022. "Shuttle Bus Rerouting and Rescheduling Problem Considering Daily Demand Fluctuation." *Mathematical Problems in Engineering*. <https://doi.org/10.1155/2022/2917240>.
4. Akridge, H., B. Fan, A. X. Tang, C. Mehta, N. Martelaro, and S. E. Fox. 2024. "The Bus Is Nothing Without Us: Making Visible the Labor of Bus Operators amid the Ongoing Push Towards Transit Automation." *Proceedings of CHI 2024*. <https://doi.org/10.1145/3613904.3642714>.
5. Chitty, D., J. Lewis, and E. Keedwell. 2023. "An Adaptive Sequence-Based Selection Hyper-Heuristic for Application to Electric Bus Scheduling." *GECCO Companion*. <https://doi.org/10.1145/3583133.3590669>.
6. Cortés, C. E., C. Gil, A. Gschwender, and P. A. Rey. 2023. "The Bus Synchronization Timetabling Problem with Dwelling Times." *Transportation Research Part B* 174: 102773. <https://doi.org/10.1016/j.trb.2023.05.010>.
7. Gkiotsalitis, K. "Bus Operations Optimization: A Literature Review on Bus Holding, Rescheduling and Stop-Skipping."
8. Guo, H., B. Deng, W. Li, J. Huang, J. Li, and K. Tang. 2023. "Crew Rostering Problem with Fatigue Balance." In *Advanced Computing*, 45-63. https://doi.org/10.1007/978-3-031-35641-4_4.
9. Kletzander, L., T. M. Mazzoli, and N. Musliu. 2022. "Metaheuristic Algorithms for the Bus Driver Scheduling Problem with Complex Break Constraints." *GECCO 2022*, 232-240. <https://doi.org/10.1145/3512290.3528876>.
10. Liu, Z., Y. Yan, X. Qu, and Y. Zhang. 2013. "Bus Stop-Skipping Scheme with Random Travel Time." *Transportation Research Part C* 35: 46-56. <https://doi.org/10.1016/j.trc.2013.06.004>.
11. Das Neves, B., and C. Unsworth. 2024. "Occupational Encounters: The Interpersonal Impact of Bus Drivers' Engagement With Disabled Passengers." *OTJR* 44(3): 488-499. <https://doi.org/10.1177/15394492241237744>.
12. Öztöp, H., U. Eliyi, D. T. Eliyi, and L. Kandiller. 2017. "A Bus Crew Scheduling Problem with Eligibility Constraints and Time Limitations." *Transportation Research Procedia* 22: 222-231. <https://doi.org/10.1016/j.trpro.2017.03.029>.
13. Spliet, R., A. F. Gabor, and R. Dekker. 2014. "The Vehicle Rescheduling Problem." *Computers & Operations Research* 43: 129-136. <https://doi.org/10.1016/j.cor.2013.09.009>.

14. Tse, J. L. M., R. Flin, and K. Mearns. 2006. "Bus Driver Well-Being Review: 50 Years of Research." *Transportation Research Part F* 9(2): 89-114. <https://doi.org/10.1016/j.trf.2005.10.002>.
15. Yang, Y., J. Cheng, and Y. Liu. 2024. "An Overview of Solutions to the Bus Bunching Problem in Urban Bus Systems." <https://doi.org/10.1007/s42524-024-0297-1>.
16. Transportation Research Board. 2009. TCRP Report 135: Controlling System Costs: Basic and Advanced Scheduling Manuals and Contemporary Issues in Transit Scheduling. <https://nap.nationalacademies.org/read/14257/chapter/3>.
17. American Public Transportation Association. 2010. Impacts of the Recession on Public Transportation Agencies. https://www.apta.com/wp-content/uploads/Resources/resources/reportsandpublications/Documents/Impacts_of_Recession_March_2010.pdf.
18. Healthy Work Campaign. 2020. Bathroom Access for Bus Drivers in the United States and Canada. <https://www.healthywork.org/wp-content/uploads/2020/09/Bathroom-Access-for-Bus-Drivers-in-US-and-Canada.pdf>.
19. Healthy Work Campaign. 2020. Intervention to Reduce Job Stress among Bus Drivers in Stockholm. <https://www.healthywork.org/wp-content/uploads/2020/01/HWC-Website-Page-Content-Resources-Healthy-Work-Strategies-Intervention-to-reduce-job-stress-bus-drivers-Sweden-v1-011720.pdf>.
20. Healthy Work Campaign. 2020. HealthyBus: Action Research Intervention among Urban Bus Drivers in Denmark. <https://www.healthywork.org/wp-content/uploads/2020/01/HWC-Website-Page-Content-Resources-Healthy-Work-Strategies-Action-research-intervention-urban-bus-drivers-Denmark-v1-011720.pdf>.
21. General Transit Feed Specification. n.d. "Overview." <https://gtfs.org/documentation/overview/>.
22. Federal Transit Administration. "Transit Worker and Rider Safety." <https://www.transit.dot.gov/assaults>.