TRANSPORTATION RESEARCH BOARD
SPECIAL REPORT 341

Technical Feasibility of a Wheelchair Securement Concept for Airline Travel

A Preliminary Assessment

Committee for a Study on the Feasibility of
Wheelchair Restraint Systems in Passenger Aircraft

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRB
TRANSPORTATION RESEARCH BOARD

THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

Transportation Research Board Special Report 341

Subscriber Categories: Aviation; society

Transportation Research Board publications are available by ordering individual publications directly from the TRB Business Office, through the Internet at www.TRB.org or nationalacademies.org/trb, or by annual subscription through organizational or individual affiliation with TRB. Affiliates and library subscribers are eligible for substantial discounts. For further information, contact the Transportation Research Board Business Office, 500 Fifth Street, NW, Washington, DC 20001 (telephone 202-334-3213; fax 202-334-2519; or e-mail TRBsales@nas.edu).

Printed in the United States of America

This publication was reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the National Academy of Medicine.

This study was sponsored by the U.S. Access Board.

International Standard Book Number-13: 978-0-309-09396-5
International Standard Book Number-10: 0-309-09396-1
Digital Object Identifier: https://doi.org/10.17226/26323
Library of Congress Control Number: 2021946532

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org.**

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to provide leadership in transportation improvements and innovation through trusted, timely, impartial, and evidence-based information exchange, research, and advice regarding all modes of transportation. The Board's varied activities annually engage about 8,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state departments of transportation, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

Consensus Study Reports published by the National Academies of Sciences, Engineering, and Medicine document the evidence-based consensus on the study's statement of task by an authoring committee of experts. Reports typically include findings, conclusions, and recommendations based on information gathered by the committee and the committee's deliberations. Each report has been subjected to a rigorous and independent peer-review process and it represents the position of the National Academies on the statement of task.

Proceedings published by the National Academies of Sciences, Engineering, and Medicine chronicle the presentations and discussions at a workshop, symposium, or other event convened by the National Academies. The statements and opinions contained in proceedings are those of the participants and are not endorsed by other participants, the planning committee, or the National Academies.

For information about other products and activities of the National Academies, please visit www.nationalacademies.org/about/whatwedo.

COMMITTEE FOR A STUDY ON THE FEASIBILITY OF WHEELCHAIR RESTRAINT SYSTEMS IN PASSENGER AIRCRAFT

Alan M. Jette (NAM), Boston University, Boston, Massachusetts, *Chair*
Naomi Armenta, Nelson\Nygaard, Oakland, California
Peter W. Axelson, Beneficial Designs, Inc., Minden, Nevada
Rory A. Cooper, University of Pittsburgh, Pittsburgh, Pennsylvania
Karen J. Erazo, Sun Country Airlines (retired), Eagan, Minnesota
Francis S. Heming, Jr., Goodrich Interiors (retired), Colorado Springs, Colorado
Kevin L. Hiatt, Alexandria, Virginia
Katharine M. Hunter-Zaworski, Oregon State University, Corvallis
George A. Lesieutre, The Pennsylvania State University, University Park
Miriam A. Manary, University of Michigan Transportation Research Institute, Ann Arbor
Clinton V. Oster, Jr., Indiana University, Troy, Montana
Gary M. Weissel, Tronos Aviation Consulting, Woodstock, Georgia

Staff

Melissa Welch-Ross, Study Director, Consensus and Advisory Studies, Transportation Research Board
Tracy Lustig, Senior Program Officer, Health and Medicine Division
Anusha Jayasinghe, Associate Program Officer, Consensus and Advisory Studies, Transportation Research Board
Claudia Sauls, Program Coordinator, Consensus and Advisory Studies, Transportation Research Board
Thomas R. Menzies, Jr., Director, Consensus and Advisory Studies, Transportation Research Board

NOTE: See Appendix C, Disclosure of Unavoidable Conflicts of Interest.

Preface

Section 432 of the Federal Aviation Administration Reauthorization Act of 2018 (Public Law 115-254) calls on the U.S. Access Board, in consultation with the Secretary of Transportation and other expert and interested parties, to conduct a study to determine the feasibility of wheelchair securement and restraint systems for use in the passenger cabins of airplanes. If the systems are deemed feasible, the study is expected to examine the ways in which individuals with significant disabilities who use wheelchairs, including power wheelchairs, can be accommodated using the systems.

The U.S. Access Board commissioned the National Academies of Sciences, Engineering, and Medicine (the National Academies) to convene an expert committee to conduct the study under the auspices of its Transportation Research Board (TRB). A 12-member committee was appointed from the fields of airplane interior design and engineering; airplane crashworthiness standards, testing, and certification; airline operations and safety; wheelchair and assistive technology design, performance, and crashworthiness; transportation accessibility for people with disabilities; and economics and policy analysis. This report represents the consensus efforts of these 12 individuals, who served uncompensated in the public interest. Their biographical information is provided in Appendix B.

ACKNOWLEDGMENTS

The committee met 10 times from February 2020 through May 2021 to gather information relevant to the study and to deliberate on the report's

contents, findings, and recommendations. Three of the meetings, which were open to the public, included briefings by experts in the following areas: difficulties that nonambulatory people face when flying; wheelchair design, technologies, and standards; wheelchair securement and occupant restraint systems; airplane structures and interiors; federal safety requirements for passenger airplanes; airline operations; and passenger service for people with disabilities.

The committee thanks the following individuals for participating in these briefings and making other contributions to the committee's work: William Ammer, Ammer Consulting, LLC; Heather Ansley and Lee Page, Paralyzed Veterans of America; Kelly Buckland, National Council on Independent Living; Oli Davalos, Q'STRAINT; Paul Doell, National Air Carrier Association; Jonathan Duvall, University of Pittsburgh; Michele Erwin, All Wheels Up; Gregg Fesenmyer, American Airlines; Cindy Ford, G2 Secure Staff; Hans-Gerhard Giesa and Ralf Schliwa, Airbus; Jon Gondeck and Mike Kulig, Calspan; Mark Greig, Sunrise Medical; Karen Holmes, JetBlue; Raki Islam, SAFRAN; Glenn Johnson, Collins Aerospace; Andrew Keleher, Boeing; John Kloosterman, United Airlines; William Meier, Quantum Rehab; Doug Mullen, Airlines for America; Nichole Orton, University of Michigan; Bryan Parker and Johanna Reimer, Southwest Airlines; Ray Prentice and Ronda Ruderman, Alaska Airlines; Ramakant Rambhatla, Invacare Corporation; John Shelden, Federal Aviation Administration; Jo Ann Storie, Prospect Airport Services; and Chris Wood, Flying Disabled.

Melissa Welch-Ross directed the study and assisted the study committee in the preparation of this report with the assistance of Tracy Lustig and under the guidance of Thomas R. Menzies, Jr. Anusha Jayasinghe provided support to the committee by arranging meetings, and Claudia Sauls assisted with manuscript preparation. The committee thanks Benjamin Hubbard, graphic artist, for creating many of the figures in the report.

The report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

The National Academies thanks the following individuals for their review of this report: Ben Berman, Berman Aviation Associates, LLC; Cathy Bodine, University of Colorado Denver; William Borucki (National Academy of Sciences), National Aeronautics and Space Administration Ames Research Center (retired); Dianne Chong (National Academy of Engineering), Boeing Research and Technology (retired); Bill Cotney, Cotney Aerospace,

Inc.; Zahra Mohaghegh, University of Illinois at Urbana-Champaign; Gerardo Olivares, National Institute for Aviation Research at Wichita State University; Victor Paquet, University at Buffalo; Larry Schneider, University of Michigan Transportation Research Institute (retired); Tom Strganac, Texas A&M University; and Gary Talbot, Gary Talbot ADA Consulting.

Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the committee's conclusions and recommendations, nor did they see the final version of the report before its release. The review of this report was overseen by Chris T. Hendrickson (National Academy of Engineering), Carnegie Mellon University (emeritus), Pittsburgh, Pennsylvania; and Walter Frontera (National Academy of Medicine), University of Puerto Rico, San Juan, Puerto Rico. They were responsible for making certain that an independent review of the report was conducted in accordance with institutional procedures and that all review comments were carefully considered by the committee. Responsibility for the final content of the report rests solely with the authoring committee and the institution. Karen Febey, Senior Report Review Officer, TRB, managed the report review process.

Contents

Acronyms and Abbreviations

ABA	Architectural Barriers Act of 1968
AC	Advisory Circular
ACAA	Air Carrier Access Act
ADA	Americans with Disabilities Act
ADAAG	ADA Accessibility Guidelines
ANSI	American National Standards Institute
ATD	anthropomorphic test dummy
CMS	Centers for Medicare & Medicaid Services (U.S. Department of Health and Human Services)
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
HIC	head injury criterion
IATA	International Air Transport Association
IFE	in-flight entertainment
ISO	International Organization for Standardization
NRE	non-recurring engineering
PDAC	CMS Pricing, Data Analysis and Coding
PSU	passenger service unit

RESNA	Rehabilitation Engineering and Assistive Technology Society of North America
RJ	regional jet
SAE	Society of Automotive Engineers
SSR	special service request
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation
WTORS	wheelchair tiedown and occupant restraint systems

Executive Summary

Congress mandated in Section 432 of the Federal Aviation Administration Reauthorization Act of 2018 (Public Law 115-254) that the U.S. Access Board examine the feasibility of wheelchair securement systems for passenger use in airplane cabins and the ways in which people with significant disabilities who use wheelchairs can be accommodated by such systems if feasible. This study, commissioned by the U.S. Access Board and conducted by an expert committee, reviews technical issues pertaining to the concept of an in-cabin wheelchair securement system; provides a preliminary assessment of whether the technical issues suggest that the concept is feasible or potentially infeasible; and recommends actions to fill gaps in technical information needed for more definitive assessments of feasibility and for public policy considerations about the systems and their potential to expand air travel opportunities for people with significant disabilities.

A wheelchair securement system for passenger use in an airplane cabin is an intuitively appealing solution to many of the impediments to air travel faced by people who are nonambulatory. While no securement systems of this type exist in scheduled airline service, the norm for most other modes of transportation is for people to be able to board a vehicle in their personal manual or power wheelchair, stay seated in that wheelchair for the duration of the trip, and wheel off the vehicle at the destination. Airline transportation, however, is an exception because it invariably requires people who are nonambulatory to fly in an airplane seat. For reasons explained in this report, this requirement can greatly complicate access to airline service by making flying uncomfortable, painful, injurious, and sometimes impossible. Of interest, therefore, is whether the technical challenges associated with the development and implementation of in-cabin wheelchair securement systems are so formidable that the service that wheelchair users have grown accustomed to in other transportation settings is infeasible for airline travel.

This report identifies and examines potential technical challenges to the development and implementation of an in-cabin wheelchair securement system that could be installed on enough airplanes to provide nonambulatory people with airline flight offerings in enough markets to provide meaningful (and not niche) service availability. The focus is on a securement system concept that can accommodate personal wheelchairs, as opposed to wheelchairs designed and optimized specifically for airplane travel. Personal wheelchairs are often customized to the physical and medical needs of the occupant, and are often considered essential for the person's comfort, health, and well-being during travel and when at the destination. In particular, the following three major technical considerations were deemed most relevant to this preliminary assessment of concept feasibility:

- Whether airplanes common to airline service have enough doorway and interior space to enable a power or manual wheelchair to enter and exit the passenger cabin and maneuver to and from a securement location that provides sufficient room for the functioning of the securement system and medically essential wheelchair position adjustments;
- Whether an airplane floor and its structure can accommodate the loadings imparted by an occupied power wheelchair; and
- Whether a secured personal wheelchair can meet the crashworthiness, occupant injury protection, and other relevant air transportation safety requirements of the Federal Aviation Administration (FAA).

In addition to these technical issues, the report identifies several important airline operational and passenger accommodation issues that would warrant careful consideration as part of any initiative to develop and introduce an in-cabin wheelchair securement system intended to provide reliable and meaningful levels of flight service to people who are nonambulatory and have significant disabilities.

KEY FINDINGS ON TECHNICAL FEASIBILITY

With respect to these major technical considerations, the study findings suggest the following:

- Airplane boarding door clearances and cabin aisle space should not present major physical impediments to personal wheelchairs entering and exiting an airplane and maneuvering to and from a securement area located near the boarding door. A large majority of airplanes have a main boarding door with sufficient width to enable a large majority of personal wheelchairs to pass through. While it was not possible to examine the cabin interior dimensions and layouts of all airplanes in the U.S. airline fleet, the most common interior layouts for the two most ubiquitous families of airplanes, the Boeing 737 and the Airbus A320, should require only modest interior modifications to create a wheelchair securement area located at the front of the cabin near the turn from the main boarding door.

- The removal of two successive rows of seats in a cabin location near the boarding door should provide sufficient room in most airplanes for a securement location spacious enough to allow the occupant of a wheelchair to maneuver into and out of the location and, once secured, to use physically and medically essential wheelchair position functions without impinging on the space of other passengers.
- The removal of two successive rows of seats in most airplanes should free up enough airplane floor structure to accommodate the load imparted by the heaviest of occupied power wheelchairs using load distribution systems that are commonly employed for seat assembly attachments, including pallet systems.
- The removal of two successive rows of seats should provide sufficient clear space to satisfy FAA criteria that the wheelchair occupant and nearby passengers do not risk serious head and leg injuries from striking objects or structure during a survivable crash or emergency event as long as the wheelchair remains secured and its occupant restrained.
- Many personal wheelchairs, including power wheelchairs, comply with motor vehicle transportation safety and crash performance standards (WC19) for wheelchairs established by the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA). Because WC19 wheelchairs have four brackets for securing tiedown straps and anchor points for a lap safety belt, this can provide a widely available and standardized interface for an in-cabin wheelchair tiedown and occupant restraint system.
- RESNA's crash performance test for WC19 wheelchairs has some similarities with one of FAA's two dynamic crash tests for airplane seats in which the predominant impact vector is horizontal. FAA's horizontal test requires an airplane seat to demonstrate the ability to avoid severe deformation, retain items of mass, and protect the occupant from severe head and leg injuries from a 16-*g* peak

dynamic loading along the airplane's longitudinal axis, such as from a survivable crash or emergency landing impact when the airplane is primarily moving forward. To meet the WC19 standard, secured wheelchairs must demonstrate crashworthiness, occupant restraint, and battery and component retention in a frontal motor vehicle crash occurring at 30 mph. The horizontal test condition in this case creates a dynamic loading that averages 20 *g*, which is higher than the peak 16-*g* loading of the FAA test, and also assumes a nearly instantaneous deceleration from 30 to 0 mph.

- RESNA's WC19 standard does not include a test condition comparable to FAA's second dynamic crash test in which the predominant impact vector is vertical. This second test is also intended to demonstrate the seat structure's ability to avoid severe deformation, retain items of mass, and protect the occupant from spinal injury but under vertical loadings characteristic of a survivable airplane crash during an attempted takeoff or emergency landing with a high descent rate. In the absence of a WC19 vertical test, technical evaluations are needed to determine the crash and injury protection performance of wheelchairs when subject to such vertical forces, which seldom occur in motor vehicle crashes. Likewise, RESNA's flammability testing standards for wheelchairs differ from FAA's standards for airline seats, and thus technical evaluations are needed to gauge the ability of wheelchairs to satisfy FAA criteria for resistance to post-crash fires.

Future efforts to fill these gaps in technical information will benefit from RESNA's crashworthiness standards for wheelchairs. The standards provide a performance minimum, or widely applicable baseline, for wheelchair evaluations on the basis of FAA test criteria, as many commonly used wheelchairs comply with the RESNA standards today and more wheelchairs could be designed to comply with them in the future. If the WC19 and other RESNA standards did not exist to provide such a common baseline, the job of evaluating a heterogeneous population of personal wheelchairs for compliance with FAA criteria could be technically daunting and potentially impractical.

KEY FINDINGS ON OPERATIONAL AND ACCOMMODATION ISSUES

The implementation of an in-cabin wheelchair securement system, if technically feasible, would require airlines to address a range of operational and passenger accommodation issues, including assurance of the system's safe and proper use by passengers, the provision of adequate airline passenger support and equal service treatment, and a reasonable and reliable level of securement system availability on scheduled flights. This study's assessment of technical issues provides insight into how some of these requirements could be addressed. Notably, the technical assessment of cabin space requirements suggests that designating a securement location in the passenger seating area near the left forward boarding door would require only modest physical changes to the interiors of many common airplanes. Another potentially important operational and accommodation benefit of this securement location is that the left forward door is widely used for general passenger boarding; therefore, users of wheelchairs could enter and exit the airplane through the same boarding bridge and cabin door used by all other passengers. The use of a single door for all boarding would minimize airline operational impacts and result in more equal service treatment among passengers.

Ensuring operational practicality and equitable treatment of all passengers is necessary; however, in only having a securement system concept to evaluate, as opposed to a fully defined system, the committee had limited ability to assess airline operational and passenger accommodation issues. Nevertheless, the report does point to potential challenges associated with providing needed passenger assistance and service, fare reservation system capabilities, procedures for validating wheelchair boarding eligibility, and protocols and power management for controlling wheelchair seating functions in flight. These issues are discussed in Chapter 5 of this report, recognizing that specific measures to address many of them would depend on system designs and on any relevant implementation requirements established by the U.S. Department of Transportation (U.S. DOT), FAA, and individual airlines.

The committee's deliberations did surface some general operational and accommodation issues that would require careful consideration during the planning and implementation of any wheelchair securement system. An operational issue that could be particularly vexing concerns the ability of an airline to ensure that passengers with significant disabilities traveling in their wheelchairs do not become stranded en route, such as during connecting service, due to the unplanned substitution of an airplane that lacks in-cabin wheelchair service. For some people with significant disabilities, unreliable or disrupted service could be more serious than an inconvenience. Airlines would need to find solutions to this potential problem and ensure that trained service agents are available to provide passenger assistance in all of the airports that they serve with airplanes equipped with wheelchair securement systems.

The extent to which the assurance of reliable and sufficiently available securement systems on airplanes could create operational and accommodation challenges will depend in part on the level of passenger demand for in-cabin wheelchair service and the nature of this demand—for instance, if many more people who use wheelchairs choose to fly and whether people with significant disabilities constitute a smaller or larger share of securement system users. The level and nature of demand will affect an airline's motivation to equip more airplanes with securement systems and affect service agent training requirements. Passenger demand, however, is difficult to gauge at this point, because it would presumably depend in large part on whether people who do not fly now because of difficulties sitting in and transferring to and from an airplane seat would be willing to fly if they could remain seated in their personal wheelchairs. Passenger demand would also depend on interest from people who are nonambulatory and fly occasionally now but who might fly more often if they did not face the risks and difficulties of seat transfer or worries about their personal wheelchairs being lost or damaged when checked. Assessing demand for in-cabin wheelchair service is therefore a complicated but potentially critical step for making decisions about equipping airplanes with wheelchair securements and understanding and addressing ensuing operational and accommodation needs.

The committee was not asked to advise whether wheelchair securement systems should be installed on airplanes, which is a choice that would entail considerations that go beyond a system's technical feasibility and operational and accommodation implications to include airline implementation costs and economic impacts. Passenger airplane interiors are space constrained and airlines generate revenue in accordance with seating capacity and fare classes. The implementation of a wheelchair securement system would require the redesign of interior space in ways that would affect airplane seating capacity in total and by fare class, which are all likely to impact airline economics. The committee was well aware of this likelihood, but an assessment of airline economics was not part of the study charge. It is reasonable to presume that Congress too was aware that in-cabin wheelchair securement systems would probably affect airline seating capacity and revenue, but the request for this study does not state that a determination of feasibility should be predicated on a system having no or minimal impacts on airline economics.

CONCLUSIONS AND RECOMMENDATIONS

After reviewing the available information, as summarized in the findings above, the committee did not identify any issues in this preliminary assessment that seem likely to present design and engineering challenges so formidable that they call into question the technical feasibility of an in-cabin wheelchair securement system and the value of exploring the concept further. While the report's analyses and findings suggest that equipping enough airplanes with securement systems to provide meaningful levels of airline service would require substantial effort, the types of cabin modifications required to provide the needed space and structural support would likely be of moderate technical complexity for many individual airplanes. Further assessments, including efforts to fill the information gaps identified in this report, would appear to be warranted, particularly to understand how secured personal wheelchairs are likely to perform relative to FAA's safety criteria in restraining and protecting occupants during a survivable airplane crash or emergency landing. The committee believes that such follow-on assessments are warranted because the many feasibility issues that could indeed be assessed using the information at hand appear to be manageable from a technical perspective. Concerted efforts to understand the remaining technical uncertainties through more focused analysis and testing, as described in the recommendations offered next by the committee, would enable more informed public policy decisions about the feasibility and desirability of in-cabin wheelchair securement systems.

- **The U.S. Department of Transportation and the Federal Aviation Administration (FAA) should establish a program of research, in collaboration with the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) and the assistive technology industry, to test and evaluate an appropriate selection of WC19-compliant wheelchairs in accordance with applicable FAA crashworthiness and safety performance criteria.** The research program should address, but not be limited to, assessing the performance of WC19 wheelchairs secured in an airplane cabin during a survivable crash, an emergency landing, and severe turbulence by maintaining their form, restraining their occupants and protecting them from injury, retaining batteries and other items of mass, and providing adequate fire resistance. Consideration should be given to different conditions experienced in flight, such as the occurrence of unexpected severe turbulence while a wheelchair's seat position functions are activated (e.g., leg elevation, recline, and tilt). The research should be conducted to inform decisions that may need to be made by U.S. DOT and FAA in response to petitions and other requests for in-cabin wheelchair securement systems to be allowed or even required on passenger airplanes; by RESNA and the assistive technology industry to identify opportunities to align existing wheelchair transportation safety standards with performance criteria required for airplane transportation; and by the airline and aircraft industries to more fully understand the implications of and opportunities for providing travelers who are nonambulatory and have significant disabilities with the ability to remain seated in their personal wheelchairs during flight.
- **The U.S. Access Board should sponsor studies that assess the likely demand for air travel by people who are nonambulatory if they could remain seated in their personal wheelchairs in flight.** The

studies should estimate the total demand for this service as well as the nature of this demand, including the demand by people with varying degrees of impairment. The studies should assess both the extent to which and how people with different disabilities are likely to use the securement systems, which could better define the space needed in the airplane cabin for wheelchair maneuvering and securement, provide insight into passenger support and service assistance requirements, and inform airline decisions about needed levels of fleet coverage and flight availability.

Ideally these recommended next steps of research, testing, and evaluation would be planned and programmed in a systematic manner—or in accordance with a high-level "roadmap"—that takes into account the series of follow-on decisions and work that would be needed depending on the research, testing, and evaluation results. Numerous issues would need to be addressed in concert and stepwise. For instance, it would be important to find ways to ensure that wheelchairs brought on board an airplane cabin do not create security issues and are kept crashworthy as they age and are potentially modified. A fuller understanding of the training requirements of airline personnel will be needed, along with testing and simulations to confirm the actual amount of cabin space required for wheelchair maneuvering and securement and the in-flight use of essential wheelchair seat position functions. A more in-depth understanding of the likely travel experience of passengers using the systems will be needed, along with the implications of their installation and use on airline operations and economics.

A strategic roadmap that identifies and connects these issues and follow-on requirements could be important for sustained progress toward the realization of in-cabin wheelchair securement systems should evaluations indicate continued promise. The roadmap could contain key decision points where information from the results of testing and analyses can be assessed for confidence and on the basis of risk analysis to define and prioritize next steps for information gathering and for furthering engineering and design activities, standards and regulation development, and practical requirements for implementation (e.g., personnel training requirements). U.S. DOT would be the logical lead for the development of such a roadmap in collaboration with the agencies and entities identified in the recommendations above and with consultation and input from a wide range of interests and experts, including the airlines and their passenger service personnel, airframe manufacturers and interior component suppliers, people with disabilities and their advocates, and the assistive technology industry.

Inasmuch as Congress called for this study, the committee trusts that Congress will consider these recommendations and the need for agency resources to execute them.

1

Introduction

Wheelchair securement systems for passenger use in airplane cabins are intuitively appealing as a solution to many of the hardships that people with disabilities and who are nonambulatory face when flying. Such systems are currently used and designed in accordance with widely accepted safety standards for public and private modes of surface transportation, including cars, vans, and transit buses. In using these systems, people who are nonambulatory can board the vehicle in their personal wheelchair, stay seated in the wheelchair for the duration of the trip, and wheel off the vehicle upon reaching the destination. Indeed, the ability of people to travel while seated in their personal wheelchairs has been the norm for several decades, facilitated by public policies to ensure that people who are nonambulatory are afforded similar access as people who are ambulatory to employment, medical services, education, shopping, family and social events, and other activities and opportunities.[1]

A major exception to this norm has been airline transportation, which invariably requires that every passenger travel in an airplane seat. This requirement can greatly complicate access to air travel because of the need for passengers to transfer from and back to their personal wheelchairs and to use an airplane seat that does not accommodate their physical and medical needs for the duration of a flight. For some people with significant disabilities, this requirement can make air travel so inconvenient,

[1] Accommodation and access laws, regulations, and design standards for individuals using paratransit vans, buses, taxis, and other passenger vehicles for surface transportation can be found at https://adata.org/ada-law-regulations-and-design-standards.

uncomfortable, and unsafe that they fly rarely, if at all. If wheelchair securement systems could be installed in airplane cabins and made sufficiently safe and available by scheduled airlines, more people who are nonambulatory would be able to benefit from air travel, and when doing so, they would retain more independence and dignity while experiencing less discomfort and risk of injury.

Air travel has differed from other transportation modes with regard to passengers being able to travel seated in their personal wheelchairs for several reasons. Perhaps more than the vehicles of some other passenger modes such as trains, airplanes have severe space constraints and are held to different safety performance requirements. The space constraints complicate wheelchair movements within the airplane cabin and limit the room available for a securement location. Modifications to typically configured airplane interiors, including the reconfiguration or removal of tightly spaced passenger seats and other cabin features, would be needed to create the requisite room. The airplane cabin and its seating systems must meet exacting government standards for safety assurance, including crashworthiness and fire resistance. Safety assurance is a challenge because wheelchairs, unlike airplane seats, are not designed purposefully to perform safely in a survivable airplane crash. However, the introduction and use of wheelchair securement systems has presented space, safety, and other technical challenges in all modes of passenger transportation.[2] A valid question, therefore, is whether the technical challenges associated with air transportation are so formidable that accommodations comparable to those that are now commonplace in the other modes are infeasible.

In Section 432 of the Federal Aviation Administration Reauthorization Act of 2018 (Public Law 115-254), Congress mandated that the U.S. Access Board examine the feasibility of in-cabin wheelchair securement systems and the ways in which people with significant disabilities who use wheelchairs, including power wheelchairs, can be accommodated by such systems provided they are feasible.[3] This study, commissioned by the U.S. Access Board in response to the legislative mandate and conducted by an expert committee, reviews the various technical issues pertaining to in-cabin wheelchair securement systems. It then assesses the available information to gauge whether any of the identified issues suggest that these systems could be feasible, or potentially infeasible, to design and implement. The emphasis, therefore, is on providing a preliminary technical assessment that can

[2] Hunter-Zaworski, K.M., and J.R. Zaworski. 2002. "Progress in Wheelchair Securement: 10 Years Since the Americans with Disabilities Act." *Transportation Research Record,* no. 1779: 197–202; Hunter-Zaworski, K.M., D.G. Ullman, and J.R. Zaworski. 1993. "The Mechanics of Mobility Aid Securement/Restraint on Public Transportation Vehicles." *Transportation Research Record,* no. 1378: 45–51.

[3] This legislative request is presented in Appendix A.

inform choices about whether and how to plan follow-on evaluations of this concept, with the goal of expanding air travel opportunities for people with significant disabilities.

Congress's specific motivations for mandating a feasibility study are not clear, but public interest in extending transportation accommodations to people who have significant disabilities has been growing since the enactment of the Americans with Disabilities Act (ADA) of 1990.[4] The fulfillment of the ADA's requirements has led people who use wheelchairs to become accustomed to—and often dependent on—being able to travel in their personal wheelchairs, which are optimized for their own physical and medical needs. As the popularity of long-distance travel has grown, and indeed become essential to some jobs and family gatherings, the burdensome nature of air travel for people who depend on their personal wheelchairs for mobility, health, and well-being has become increasingly problematic.[5]

The kinds of burdens that people who are nonambulatory face when seeking to travel on scheduled airlines, as explained to the study committee by people with disabilities, are discussed next. An appreciation of these issues is essential for understanding why there is interest in the concept of an in-cabin wheelchair securement system and why an assessment of the technical challenges associated with its development and implementation is important.

Following this discussion, the remainder of the chapter presents the study's Statement of Task and the committee's decisions about how to frame and assess the technical feasibility of an in-cabin wheelchair securement system that remains largely conceptual. The chapter ends with an overview of the organization of the report.

BURDENS PEOPLE WHO ARE NONAMBULATORY FACE WHEN FLYING

People who are nonambulatory and use wheelchairs experience several burdens that can make air travel inconvenient, uncomfortable, unhealthy, and unsafe. For people with significant disabilities who need to remain seated in their customized personal wheelchair, travel by scheduled airlines in a

[4] See https://www.ada.gov/pubs/adastatute08.htm.

[5] The ADA accessibility requirements apply to airport terminals, and the Architectural Barriers Act of 1968 (ABA) requires all buildings and facilities designed, built, or altered with federal funds, including airport terminals, to be accessible to people who use wheelchairs. However, the ADA and the ABA no longer apply at the point of proceeding down the passenger boarding bridge. While the Air Carrier Access Act (ACAA) of 1986 specifies obligations of airlines in accommodating passengers with disabilities, it has no provisions for use of personal wheelchairs in the cabin because no airline provides in-cabin wheelchair securements.

passenger seat is not possible at all. For some of these individuals, and for some others who can fly but avoid doing so because of the risks and problems encountered, long-distance trips for work, family gatherings, medical care, and recreation may need to be made using other modes of passenger transportation that are more time-consuming and potentially less safe.[6]

Boarding and Deplaning Problems

Based on a survey by the U.S. Department of Transportation (U.S. DOT), an estimated 25.5 million people (8.5 percent of the U.S. population age 5 and older) have disabilities that limit their travel.[7] More than 11 percent of these individuals, or an estimated 2.8 million people nationally, identify as wheelchair users.[8] According to data from the *Air Travel Consumer Report*, 381,792 wheelchairs or scooters were checked on scheduled flights by U.S. airlines during the second half of 2019, from July to December.[9] Wheelchairs or scooters were checked on about 11 percent of scheduled airline departures. During this half-year period, airlines enplaned nearly 460

---

[6] See National Transportation Safety Board. n.d. "U.S. Transportation Fatalities in 2019—by Mode." https://www.ntsb.gov/investigations/data/Documents/US-Transportation-Fatalities-2019.pdf; National Safety Council Injury Facts. n.d. "Deaths by Transportation Mode." https://injuryfacts.nsc.org/home-and-community/safety-topics/deaths-by-transportation-mode.

[7] See FHWA. 2018. "National Household Travel Survey." https://www.bts.gov/travel-patterns-with-disabilities. The Federal Highway Administration (FHWA) conducts this survey, the National Household Travel Survey, which is the primary source of data on household travel behavior in the United States. FHWA conducted the latest version in 2017 and earlier versions in 2001 and 2009.

[8] Among those with disabilities who responded to the FHWA National Household Travel Survey, 11.6 percent reported using wheelchairs, and 3.9 percent reported using power wheelchairs. Other devices used included walking canes (36.7 percent), walkers (22.9 percent), motorized scooters (4.4 percent), crutches (2.6 percent), white canes for visual impairments (1.3 percent), and seeing-eye dogs (1.1 percent). Respondents could report using more than one mobility device. See FHWA. 2018. "National Household Travel Survey." https://www.bts.gov/travel-patterns-with-disabilities.

[9] *Air Travel Consumer Report* is a monthly series of reports issued by U.S. DOT's Office of Aviation Enforcement and Proceedings. These reports were first issued at the beginning of 2019 and contain information on the combined number of wheelchairs and scooters stowed on the 17 U.S. airlines with at least 0.5 percent of total domestic scheduled flight service revenues. The data that these airlines report include both domestic and international travel. During the first few months of these reports, there appear to have been some reporting issues; therefore, the data used in this report encompass the reporting period from July 1, 2019, through December 31, 2019. On average, 63,632 wheelchairs or scooters were checked monthly during this period. While these data do not cover the entire scheduled passenger airline industry, these 17 airlines enplaned 96 percent of all passengers carried by all U.S. scheduled airlines and accounted for 86 percent of all scheduled airline departures. See https://www.transportation.gov/airconsumer/air-travel-consumer-reports-2019.

million passengers in total;[10] hence, passengers who checked wheelchairs and scooters accounted for about 0.1 percent of all enplaned passengers.

People who use wheelchairs differ in their ability to board and deplane an airplane. Some people who are ambulatory and use wheelchairs are able to walk a short distance through the passenger boarding bridge to and from their airplane seat. For passengers who are nonambulatory, the narrow width of an airplane aisle means that before boarding, they will need to transfer out of the wheelchair to an airline-provided boarding chair that is sufficiently narrow to pass through the cabin aisle. The boarding chair is usually no more than 13 in. wide, as is necessary to clear an aisle that may be only 15 in. in width.[11]

Passengers must transfer themselves or be lifted into the boarding chair by service agents. The boarding chair is then wheeled through the passenger boarding bridge and cabin aisle to the passenger's seat. Once at the seat, the passenger must transfer from the boarding chair into the seat. Some passengers can transfer on their own and others will require assistance. Passengers requiring assistance are usually lifted into the seat by one or more service agents. If the passenger cannot transfer independently or be lifted by service personnel, then a mechanical lift may be used for the transfer, but such devices are not widely available.[12] This entire process is reversed when the passenger deplanes upon arrival.

As a result of these transfers, people who use wheelchairs can encounter the following problems, as explained to the study committee by the study sponsor and people who use wheelchairs[13]:

---

[10] FAA. "Commercial Service Airports (Rank Order) Based on Calendar Year 2019 (issued 9/26/2020)." https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger. Derived also from U.S. Department of Transportation, Bureau of Transportation Statistics. "T100 Data for Scheduled Passenger Service July 1–December 31, 2019." https://www.transtats.bts.gov/databases.asp?Z1qr_VQ=E&Z1qr_Qr5p=N8vn6v10&f7owrp6_VQF=D.

[11] The current FAA standard for aisle width was last updated in the 1954 Civil Air Regulations code, which was re-codified by FAA as Title 14 Part 25 of the Code of Federal Regulations, titled "Airworthiness Standards: Transport Category Airplanes." The regulation states that "the main passenger aisle at any point between seats shall not be less than 15 inches wide up to a height above the floor of 25 inches and not less than 20 inches wide above that height."

[12] Lifts are not routinely available in the United States, but a few U.S. airports provide lifts at a passenger's request.

[13] This section of the report draws on presentations to the committee at its first public meeting from the U.S. Access Board (the study sponsor) and advocates for individuals with disabilities (the Preface of this report provides a list of invited presenters), and is also informed by congressional testimony. See "The Airline Passenger Experience: What It Is and What It Can Be, Hearings Before the House Committee on Transportation and Infrastructure, Subcommittee on Aviation, 116th United States Congress, March 3, 2020 (Testimony of Lee Page, Paralyzed Veterans of America)." https://www.congress.gov/116/meeting/house/110600/witnesses/HHRG-116-PW05-Wstate-PageL-20200303.pdf.

- The transfer at the gate to and from the boarding chair can cause strain, discomfort, and in some cases injury to the occupant.
- Boarding chairs frequently lack sufficient back support for the passenger and can be unstable on passenger boarding bridges. The narrowness of the boarding chair combined with the slope of the passenger boarding bridge can lead to lateral instability and risk a passenger falling in or from the chair, causing injury. Injury to arms, legs, and hips can also occur as passengers are pushed in the boarding chair through the narrow cabin aisle.[14] The seating surface of the boarding chair may also place some people at risk of pressure injuries.
- The transfer between the boarding chair and the airplane seat creates a risk of injury as the passenger is lifted, moved, and placed into the seat through a tight space and over protruding armrests and safety belt buckles.[15]

Airplane Seat Limitations

Some people who have significant disabilities may lack the flexibility, range of motion, physiological ability (e.g., tissue integrity, respiratory reserve, circulatory capacity), or postural stability to sit in an airplane seat. For these individuals, travel by scheduled airlines is not an option today. In other cases, passengers who are transferred from a boarding chair to an airplane seat may not be able to sit without pain or discomfort for even short periods of time, much less for the duration of a long-distance flight. Often these passengers will have personal wheelchairs that are equipped with seating and positioning systems tailored to meet their specific support, restraint, and other physical needs. Their wheelchairs, for instance, will usually have seat cushions and back, head, neck, and foot supports to address their medical needs and minimize risk of pressure injuries.[16] Fur-

[14] The committee could not verify with data on frequency of occurrence or other statistics.

[15] The service provider also risks serious lifting injuries. According to federal guidelines established by the National Institute for Occupational Safety and Health, the maximum recommended weight for a single person to lift is 51 lb; thus, two service providers risk serious back injuries when lifting passengers heavier than about 100 lb over the backs of boarding devices and airplane seats in such tight spaces. (See U.S. Department of Health and Human Services. 1994. *Applications Manual for the Revised NIOSH Lifting Equation.* http://www.cdc.gov/niosh/docs/94-110.)

[16] Some of the problems that nonambulatory passengers experience with airplane seats, and the problem described earlier with boarding via narrow aisles, stem from FAA specifications for airplane seats and aisle widths that assume that the average passenger is 170 lb (a weight that many ambulatory and nonambulatory passengers currently exceed), standing, and ambulatory.

thermore, many power wheelchairs, and some manual wheelchairs, can tilt, recline, and elevate the leg rests. A passenger airplane seat, of course, does not offer these seating functions, which are necessary for pressure relief and other medical reasons.

Lost and Damaged Wheelchairs

In the case of some manual wheelchairs and all power wheelchairs, they must be stowed in the airplane cabin or in the cargo hold. A concern of many passengers is that their checked wheelchairs will be mishandled or improperly secured and damaged when stowed or moved to and from the loading area and cargo hold.[17] According to U.S. DOT consumer complaint statistics, of the 381,792 wheelchairs and scooters stowed from July through December 2019, 5,637 (or 1.5 percent) were "mishandled," which includes devices that were "lost, damaged, delayed, and pilfered as reported by or on behalf of the passenger."[18,19]

Power wheelchairs are sensitive, complex, and expensive pieces of equipment that can be heavily customized. A damaged or lost wheelchair can result in a severe loss of mobility for the passenger arriving at the destination, followed by a potentially long period of reduced mobility, discomfort, pain, and injury during the time it takes for the wheelchair to be repaired or replaced.[20] Ordering a replacement wheelchair that is highly customized can take weeks or months, leaving the passenger dependent on a manual wheelchair or with no mobility at all. For some people, these risks are not worth taking, and they avoid flying.

Care and Dignity

The leading complaint among passengers with disabilities who file a complaint report with U.S. DOT is failure to provide passengers who use

[17] For example, see Miranda, G. 2021. "'This Is My Life, My Legs': After a Woman's Wheelchair Was Damaged on a Delta Flight, 'Heartbreaking' Video Goes Viral." *USA Today,* June 22. https://www.usatoday.com/story/travel/airline-news/2021/06/04/delta-breaks-womans-wheelchair-viral-tiktok-shows-her-left-tears/7510470002.

[18] See U.S. DOT. 2020. *Air Travel Consumer Report,* February. https://www.transportation.gov/sites/dot.gov/files/2020-02/February%202020%20ATCR.pdf.

[19] Unfortunately, these data do not distinguish between wheelchairs and scooters, nor do they distinguish within the mishandled category among lost, damaged, delayed, or pilfered.

[20] U.S. DOT receives the greatest number of complaints in four areas: (1) wheelchair and guide assistance; (2) stowage, loss, delay, and damage of wheelchairs and other mobility assistive devices; (3) aircraft seating accommodations (under the ACAA, airlines are required to provide certain seating accommodations to passengers with disabilities who self-identify as needing to sit in a certain seat); and (4) travel with service animals.

wheelchairs with sufficient customer assistance.[21] This complaint category includes long waits for assistance to deplane, which can cause pain and discomfort for passengers, as well as missed connections or missed pre-arranged appointments with ground transportation providers. Indeed, instances have been reported in media accounts of passengers receiving no assistance with deplaning.[22]

Advocates for people with disabilities point to the stress that can be associated with air travel for people who use wheelchairs. Not only do they experience the many risks and hardships discussed above, but the whole process—from having to wait for assistance to being physically handled by strangers—can be undignified in a way that does not compare to the experience on other modes of transportation when wheelchair securement systems are available.

---

[21] The ACAA, 49 U.S.C. 41705, prohibits discriminatory treatment of persons with disabilities in air transportation. The Wendell H. Ford Aviation Investment and Reform Act for the 21st Century (AIR-21; Public Law 106-181) requires, among other things, that the Secretary of Transportation "regularly review all complaints received by air carriers alleging discrimination on the basis of disability" and "report annually to Congress on the results of such review." These annual reports to Congress cover disability-related complaints that U.S. and foreign passenger air carriers operating to, from, and within the United States received during the calendar year, as reported to U.S. DOT by those carriers. According to the 2019 Annual Report on Disability-Related Air Travel Complaints Received in Calendar Year 2018, failure to assist passengers in wheelchairs and damaged devices received the greatest number of complaints. See https://www.transportation.gov/sites/dot.gov/files/2020-03/Summary%20Report%20of%20CY2018%20Disability%20Complaints.pdf. The 31 U.S. carriers that submitted data for 2018 reported receiving 30,950 disability-related air travel complaints and 149 foreign air carriers reported receiving 5,980 complaints, for a total of 36,930 complaints. Of all of the complaints reported by domestic and foreign carriers operating to, from, and within the United States, 17,124 (46 percent) concerned the failure to provide adequate assistance to persons using wheelchairs, an increase of 1,917 complaints over the 15,207 complaints (44 percent of the total 34,351 complaints) received in 2017. The number of complaints probably underestimates the extent of problems; in a Muscular Dystrophy Association survey of 2,000 individuals with neuromuscular disabilities, only 4 percent of those who said they had experienced an access issue related to their disability had filed a complaint, and more than half of those surveyed did not know they could file a complaint; see https://strongly.mda.org/mda-community-weighs-accessible-air-travel-new-survey-results.

[22] For example, see Shaw, A. 2013. "Disabled Man Claims Delta Forced Him to Crawl On and Off Plane." *ABCNews,* July 29. https://abcnews.go.com/Travel/disabled-man-claims-delta-forced-crawl-off-plane/story?id=19801554; Holohan, M. 2019. "After Wheelchair Was Lost for 12 Hours, Couple Speaks Out About Traveling with a Disability." *Today,* July 24. https://www.today.com/health/couple-speaks-out-about-american-airlines-mistreatment-man-s-wheelchair-t159450; Gray, M., and S. Roth. 2015. "United Airlines Apologized After Disabled Man Crawls Off Flight." *CNN,* October 27. https://www.cnn.com/2015/10/25/us/united-airlines-disabled-man/index.html.

STUDY ORIGINS AND CHARGE

As noted previously, Congress mandated this study by calling on the U.S. Access Board to study "(1) the feasibility of in-cabin wheelchair restraint systems; and (2) if feasible, the ways in which individuals with significant disabilities using wheelchairs, including power wheelchairs, can be accommodated with in-cabin wheelchair restraint systems." Congress further directed the U.S. Access Board to consult with the Secretary of Transportation, airplane manufacturers, air carriers, and disability advocates during the conduct of the study.

In response to this mandate, the U.S. Access Board commissioned the National Academies of Sciences, Engineering, and Medicine to convene a committee of experts charged with determining whether it may be technically feasible to equip passenger airliners with wheelchair securement systems under reasonable circumstances.[23] "Reasonable circumstances," as understood by the committee, implies a feasibility assessment that takes into account the plausibility and practicality of a system, not just its theoretical technical possibility. To make this determination, the committee was tasked by the U.S. Access Board with assessing the design and engineering requirements for installation and use of wheelchair securement systems with both power (motorized) and manual wheelchairs.[24] In doing so, the committee is expected to consider the Federal Aviation Administration's (FAA's) requirements for safety assurance and to examine the technical issues associated with system implementations, including any associated with the airplane floor structure. The full study charge, or Statement of Task, is contained in Box 1-1.

Upon completion of this assessment, the Statement of Task calls on the committee to consider issues in accommodating passengers effectively with the systems, provided that there is sufficient reason to believe that they could be technically feasible.

[23] For precision and consistency with wheelchair industry standards, the committee uses the term "wheelchair securement system" in this report instead of "wheelchair restraint system" used in the FAA Reauthorization Act of 2018 and the committee's Statement of Task. The wheelchair securement system in this report consists of three main components: the personal wheelchair; the securement device used to "tie down" or otherwise attach the wheelchair to a vehicle; and occupant restraints, such as belts and straps, that secure the wheelchair user to the wheelchair. The Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) uses the term "wheelchair tiedown and occupant restraint systems" to refer to the combined securement device and occupant restraint that, as described in Chapter 2, must be tested together for safety as specified in the RESNA voluntary industry standards.

[24] For consistency with more widely used terms, the committee uses the term "power wheelchairs" to refer to motorized wheelchairs and the term "manual wheelchairs" to refer to non-motorized wheelchairs. In this report, the term "personal wheelchair" refers to either a power or a manual wheelchair owned by the user.

BOX 1-1
Statement of Task

The study will assess and evaluate the conditions under which it may be technically feasible to equip passenger aircraft with in-cabin wheelchair restraint systems, including assessments of the following:

a. design, engineering, and safety requirements for installation and use of the in-cabin restraint systems (e.g., any locking or tiedown mechanisms) for non-motorized and motorized wheelchairs used as seats in aircraft and the feasibility of strengthening or modifying the floor structure of the aircraft's passenger cabin to accommodate a restrained, occupied wheelchair in the cabin—taking into account, among other factors, the fact that different aircraft manufacturers and different aircraft types/models have varying specifications for cabin floors;
b. design, engineering, and safety requirements for non-motorized and motorized wheelchairs to be used as passenger seats in aircraft in all phases of air travel including enplaning, midair flight (including turbulence), deplaning, and emergency situations. Consideration should be given to the design, engineering, and construction specifications that both non-motorized and motorized wheelchairs (and their own internal occupant restraints) would have to conform to in order to meet injury criteria limits and otherwise achieve the level of safety equivalent to that established by the Federal Aviation Administration's (FAA's) existing requirements for passenger seating;
c. injury criteria limits for the users of in-cabin wheelchair restraint systems and the occupants of seats behind and adjacent to the users of in-cabin wheelchair restraint systems in crash situations (e.g., emergency and survivable crash environments); and
d. the implications of items (a), (b), and (c) on FAA regulations and policies for airworthiness, crashworthiness, and other safety requirements.

If it finds, based on these analyses, reasonable circumstances under which it may be technically feasible to equip passenger airplanes with in-cabin wheelchair restraint systems, the study committee will then consider in more depth how individuals can be effectively accommodated using those systems. Some of the discrete issues encapsulated by the "accommodation" aspect of the study are how airlines will be able to use the systems to provide an equal level of service to air travelers with significant disabilities; the implications of removing standard aircraft seats to create the space needed for a restrained, occupied wheelchair in the cabin; the implications on cabin interior designs and furnishings (e.g., aircraft doors, aisles, galleys, lavatories); the implications on boarding and deboarding procedures and staff training; the implications on reservation procedures; and the treatment and handling of the batteries of power wheelchairs prior to and during flight.

Where appropriate, the committee's report may advise on further actions warranted for making public policy choices with respect to these systems, including recommendations on further research, information, and technical analyses.

STUDY SCOPE

To fulfill its charge, the committee had to consider and reach agreement on the types of determinations and advice expected from the study; issues that should be considered within and outside the study scope; and the kinds of circumstances that could be deemed "reasonable" for judging concept feasibility. After careful readings of the Statement of Task and legislative mandate, multiple consultations with the study sponsor on the study's purpose and goals, and requests for information from airlines, airplane manufacturers, assistive technology companies, people with disabilities and their advocates, and other experts and interested parties, the committee made the following decisions.

Nature of Determinations and Advice

Wheelchair securement systems in airplane passenger cabins remain a concept, as no systems have been defined or designed specifically for general airline use. At this preliminary stage, therefore, the committee decided that the most important role for this study is to identify and assess the most significant technical issues that would need to be addressed for such systems to progress from concept to design and implementation, giving particular attention to any technical challenges that are so formidable that they could hinder or thwart this progress. Accordingly, the study's focus is on identifying any major technical challenges that could render the concept infeasible, rather than trying to identify, define, and assess the most technically optimal system or to consider whether and how a system could be designed and engineered for all or specific airplane conditions and use scenarios. Moreover, the committee recognized that it would need to make these judgments on a preliminary basis with sound and creative use of the information at hand, recognizing that in-cabin wheelchair securement systems have not been developed and subjected to extensive technical evaluation. The committee was not charged with conducting its own tests or developing its own detailed technical information on plausible securement systems.

In the committee's view, an in-cabin wheelchair securement system should have the potential to be implemented on enough airplanes that people who are nonambulatory and use wheelchairs would be able to access a reasonable number of flights to places they want to go using the system. In other words, the committee did not predicate its assessment on an overly demanding expectation that all or even most airplanes could be equipped with the systems. At the same time, the committee was not interested in gauging the feasibility of systems that could only have very limited or niche applications. Niche applications on a few airplanes serving a handful of markets would provide little real benefit to many people who use wheelchairs and currently have little, if any, opportunity to fly. Hence, the study's focus is on securement systems that could provide "meaningful" access to flying, which requires more than a few flight offerings in a few high-demand markets, but does not require complete, network-wide access.[25]

Likewise, the committee decided that a critical element of the concept is that it could enable people to fly seated in a wheelchair optimized to their own physical and medical needs and not require a wheelchair designed exclusively and specifically for airplane use, which could limit the utility of in-cabin wheelchair securements. An ability to fly seated in a personal wheelchair is particularly important for some people with significant disabilities who need their own wheelchairs when seated for long periods and for their mobility, medical, and physical needs at the destination.

Accordingly, the committee decided that the purpose of its assessment was to gauge the feasibility of an in-cabin wheelchair securement concept that can meet the following two conditions: (1) allow people to travel seated in their personal wheelchairs, and (2) have the capability to be installed on enough airplanes to afford ample flight offerings. These two conditions are the norm for the accommodation of people who use wheelchairs on other modes of transportation.

In examining a concept, rather than a well-defined system, with regard to these two conditions, the committee recognized early on that it would have limited ability to provide a detailed assessment of the implications of securement systems on airline operations and the means by which people who use them could be accommodated by airlines. The details of such operational impacts and accommodation requirements would depend on a system's design, requirements imposed by FAA for their design and use, and specific airplane applications and airline procedures. The implementation of any in-cabin wheelchair securement system, however, would present some general operational and accommodation issues that can be identified and discussed even when considering these systems at the conceptual level. It would be important, for instance, for a sufficient number of airplanes to be equipped with securement systems for people with significant disabilities to have dependable access to scheduled airline service. Travelers in connecting service, for instance, could be stranded en route if very few airplanes are equipped with securement systems and the equipped airplane originally scheduled for the service is not available because of mechanical or operational issues. For people with significant disabilities, such strandings could

[25] The committee's analysis therefore focuses mainly on assessing technical feasibility with regard to the two most ubiquitous families of airplanes, the Boeing 737 and the Airbus A320. This focus should not be interpreted as a determination that wheelchair securements would be infeasible for other airplanes, including regional.

be more serious than an inconvenience. Likewise, reliable and sufficient customer service assistance would need to be available to passengers who choose to use the systems. While these are examples of nontechnical issues, they would need to be given serious consideration as potential obstacles to in-cabin wheelchair securement systems irrespective of their technical feasibility. The committee therefore recognized that it would need to identify and discuss such potentially critical issues.

Although the Statement of Task does not call on the committee to advise whether in-cabin wheelchair systems *should be* installed on airplanes, it does ask the committee to offer recommendations, where appropriate, on further actions warranted for making public policy with respect to these systems, including research, information gathering, and technical analysis. During the course of its work, the committee therefore made a point of identifying where more information would be desirable for assessing in-cabin wheelchair securement systems to make more informed public policy choices.

Issues Outside the Study Scope

Several other decisions had to be made concerning the study scope to keep the work focused on the Statement of Task and legislative mandate. For instance, the committee did not examine issues associated with the user of a wheelchair being able to access the airport terminal or gates, nor did it consider certain user needs that could arise in flight such as accessing lavatories and being able to evacuate in the event of an emergency. While these are important issues, they currently exist for all passengers who are nonambulatory and fly by transferring to an airplane seat, and they would not change appreciably if the passenger were to fly seated in a wheelchair. For example, passengers who are nonambulatory and cannot make the movements on their own that are needed to transfer to and from an airplane seat would not be expected to be able to make the movements required to use the lavatory, irrespective of whether that person is seated in an airplane seat or a wheelchair.[26] Likewise, during an emergency situation, it is not currently possible to evacuate a passenger who is nonambulatory from an airplane cabin using an aisle chair and one should not expect that such an evacuation should be possible in a personal wheelchair. Consistent with

[26] Other efforts have focused on issues with airplane lavatory access by wheelchair users who currently fly, including U.S. Government Accountability Office. 2020. "Aviation Consumer Protection: Few U.S. Aircraft Have Lavatories Designed to Accommodate Passengers with Reduced Mobility." https://www.gao.gov/assets/gao-20-258.pdf#:~:text=Page%204-,GAO%2D20%2D258%20Aircraft%20Lavatories,order%20to%20use%20the%20facilities; and U.S. DOT ACCESS Advisory Committee. n.d. https://www.transportation.gov/access-advisory-committee.

its charge, however, the committee considered how FAA crashworthiness criteria should apply to wheelchairs, as with airplane seats, to ensure that secured wheelchairs do not become damaged in a crash and obstruct cabin evacuations.

Significantly, the committee did not consider whether a technically feasible in-cabin wheelchair securement system *should be* installed on airplanes. Choices about whether to install these systems would entail many considerations other than a system's technical feasibility and operational implications to include the economic impacts on the airline. The report estimates the direct expenses associated with installing a securement system on an airplane because such estimates can provide insight into the effort, complexity, and technical challenge associated with an airplane implementation. Once installed, however, the systems would have impacts on an airplane's revenue-generating potential and thus on airline economics. While these impacts would presumably be a major factor in decisions about whether to pursue such systems (and how to design them), they are outside of the study charge.

Focus on People with Significant Disabilities and Power Wheelchairs

As noted above, the legislation calling for this study asks for an assessment of the ways in which individuals with significant disabilities using wheelchairs, including power wheelchairs, can be accommodated with in-cabin wheelchair securement systems. Because power wheelchairs tend to be larger and heavier than manual wheelchairs, while also having more components and features including batteries and seating functions, power wheelchairs are the subject of most of the analyses in this report. Another important reason to focus on power wheelchairs is that they are used most often by people who have disabilities that make sitting in and transferring to and from an airplane seat particularly burdensome, if possible at all. Moreover, it can be especially troubling when power wheelchairs are lost or damaged when checked, for reasons discussed above. Accordingly, it is reasonable to assume that the people who use power wheelchairs have the most to gain from in-cabin wheelchair securement systems; therefore, any technically feasible system would need to be able to accommodate them and their wheelchairs.

Although the study focuses on power wheelchairs for these reasons, the committee presumes that any in-cabin securement system that could accommodate power wheelchairs is likely to be able to accommodate manual wheelchairs. Therefore, the study addresses both manual and power wheelchairs, as called for in the study charge. Whether efforts to accommodate both types of wheelchairs would in fact be desirable, however, is a matter that would need to be given serious attention if the concept is pursued beyond this preliminary feasibility review. For example, assuming the number of wheelchair securement places on an airplane is limited, their use by passengers who can otherwise transfer to and from an airplane seat could make availability scarcer for people who cannot transfer and who are more likely to use a power wheelchair. Additionally, for people who can transfer to an airline seat without much difficulty, the relative benefit-risk calculus of remaining seated in a wheelchair versus flying in an FAA-certified airplane seat could differ from that of people whose disabilities make transferring highly problematic or impossible.

It is reasonable to assume that users of power wheelchairs have a wide range of disabilities and degrees of impairment (e.g., some can fly independently and others may need the assistance of a traveling companion). The committee considered the potential importance of a companion seat as part of a wheelchair securement system but decided against making this a technical requirement or condition for feasibility. A companion seat adjacent to the passenger seated in a wheelchair may be preferable, but it is likely to increase the technical challenge due to the added space requirements. While the need for companion seating would be a valid concern for follow-on work, the committee wanted to avoid assuming too many demanding conditions for technical feasibility.

STUDY APPROACH AND REPORT ORGANIZATION

The organization of this report and the content of the chapters align with how the committee conducted its work. Chapter 2 provides background information needed for the analyses in subsequent chapters. The chapter contains information on the population of personal wheelchairs in common use and their size, seating position features, and maneuvering characteristics. It also discusses the basic structure of today's airline service, the airplanes used for this service, and the seating systems and other relevant features of airplane cabin interiors. Both wheelchairs and airplane passenger cabins are subject to safety and quality assurance standards that have an important influence on their design and engineering. Accordingly, the role of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) is discussed in this chapter, in advance of discussing FAA's safety standard-setting role in Chapter 3.

A wheelchair securement "system" must be viewed as consisting of the wheelchair tiedown and occupant restraint mechanisms and a compatible wheelchair. Because safe performance is critical for air transportation, the challenges associated with designing and implementing a wheelchair securement system that can satisfy FAA's safety assurance requirements are the subject of Chapter 3. FAA closely regulates airlines and airplanes for safety, and a large body of the regulations focuses on the ability of the airplane cabin and seating systems to protect passengers and crew in the event of impacts from a crash or emergency landing. Understanding how a secured wheelchair would perform during such an event, when considering the safety of the wheelchair occupant and other airplane passengers and crew, is imperative. FAA crashworthiness criteria for airplane seats and cabin interiors are described and then compared to criteria developed by RESNA for the crashworthiness of wheelchairs in motor vehicle transportation.

While crashworthiness considerations will dictate many aspects of the design and implementation of a wheelchair securement system, space availability in the airline cabin will have a significant effect as well. For safety and other practical reasons, the airplane must have the requisite space for commonly sized wheelchairs to board, deplane, and maneuver to and from a sufficiently sized and structurally supported securement location. These space considerations are examined in Chapter 4 by estimating the clearances and clear spaces required for a wheelchair and comparing them to the dimensions of airplane doors and cabin interiors. An illustration of a securement location implemented in one of the most common interior layouts of the most common airplane family in the U.S. fleet provides insight into whether space constraints could present significant technical challenges that could limit the potential for securement systems to be implemented on enough airplanes to ensure broad and reliable service coverage.

Chapter 5, which is the report's final chapter, draws on the findings from the analyses in Chapters 3 and 4 to offer a summary assessment of the technical feasibility of an in-cabin wheelchair securement system concept. Consideration is also given to important airline operational and passenger accommodation issues that could arise in implementing wheelchair securement systems. The chapter concludes with the committee's recommendations about the kinds of research and evaluations needed to inform future public policy choices about in-cabin wheelchair securement systems.

2

Background

This chapter provides terminology, context, and other background information that are essential for identifying and examining technical issues associated with the use of wheelchairs as seats on passenger airplanes. The first half of the chapter focuses on the types, features, and performance characteristics of wheelchairs commonly used in the United States as well as the kinds of systems currently available to secure wheelchairs and safely restrain their occupants when traveling by car, van, transit bus, and other surface modes. The organizations responsible for establishing safety and quality assurance standards for wheelchairs and their transportation securement systems are then discussed, including standards pertinent to the committee's technical assessments in subsequent chapters.

The second half of the chapter focuses on passenger airplanes, their interiors and seating systems, and how airlines currently provide transportation service to ambulatory and nonambulatory people. Information on the airline industry, including passenger traffic and fleet data, is from 2019, prior to the disruptions of the pandemic. It is not possible to know how the airline industry will rebound over the next several years and adapt to the post-pandemic environment; however, the committee assumes that 2019 is a better indicator of the future than 2020 and early 2021, when this report was developed.

WHEELCHAIR CHARACTERISTICS AND USE AS SEATS IN TRANSPORTATION

Wheelchairs are varied in their designs, features, and functionality because the people who use them have different mobility requirements and physical and medical needs. At the same time, wheelchairs share certain design and operational characteristics, partly as a result of standards to ensure their use in a range of facilities, general durability and safety, and safe performance when used specifically as a seat in transportation. This section begins with an overview of the different types of wheelchairs, including power and manual wheelchairs, and the mobility and medical functions that they provide to wheelchair users. Statistics are then presented on the sizes of wheelchairs, including physical dimensions, which are influenced by U.S. standards for clearance and clear space.

Maneuvering capabilities of manual and power wheelchairs are also described, including basic movements required for access and mobility as included in U.S. standards for clearance and clear space. Wheelchair industry standards that ensure the durability and safety of wheelchairs for everyday use are presented, followed by a description of the types of and standards for wheelchair securement systems used in motor vehicles to safely transport people seated in their wheelchairs.

Basic Types, Features, and Functions of Wheelchairs

This section reviews the different types of wheelchairs in use, including power and manual wheelchairs; their basic mobility and medical functions; and how those functions can differ by wheelchair type. While the focus is on wheelchairs used by adults, pediatric wheelchairs are commonly used as seats during transportation. They are smaller and lighter than wheelchairs for adults but they can be equipped with many of the same features discussed for adult devices. Specialized wheelchairs such as beach wheelchairs and all-terrain wheelchairs are not discussed because they are not commonly used as seats in transportation. Mobility scooters also are not discussed because they do not meet industry standards for use of wheelchairs in transportation vehicles, and the people who use scooters are able to walk short distances, such as to their airplane seats, and do not likely have medical conditions that make it impossible to transfer to or sit in an airplane seat.

Power Wheelchairs

Power wheelchairs are used by people with significant disabilities and limited mobility, people with conditions that cause muscle weakness, and people who experience fatigue using manual wheelchairs. While some users of power wheelchairs may be ambulatory for short distances (and thus can potentially walk to their assigned seat on an airplane with minimal or no assistance), many are nonambulatory and unable to walk any distance.

The main subsystems of power wheelchairs include (1) a power base with a drivetrain and suspension system, (2) seating and power positioning so that the occupant can change positions in the chair and perform tasks such as reaching for objects, and (3) a control system for the user to operate the power and seating positioning. As with a car, the different drivetrain arrangements determine the ways in which the wheelchair moves and maneuvers. Power wheelchairs may have center- (or mid-) wheel drive, rear-wheel drive, or front-wheel drive configurations.

Many power wheelchairs have position change features such as recline, tilt, leg elevation, and seat elevation. These features can support the user's physiological functions including respiration, digestion, and circulation. Position changes also provide pressure relief to prevent tissue trauma. The recline function moves the back of the wheelchair independent of the rest of the chair. The tilt function tips back the entire wheelchair seating system frame (without changing the seat to back angle) in order to shift body weight for posture control and for pressure relief on joints. The leg elevation function moves the leg support in increments between a bent and straight position. While tilt, recline, and leg elevation are the most commonly used wheelchair functions for medical reasons, some power wheelchairs have seat elevation functions that enable sitting at a higher level for temporary expanded reach and to improve sightlines. Some elevation functions can enable a person to move from a seated to a standing position to interact with other people at eye level and can promote blood circulation, kidney function, or muscle tone.

Figure 2-1 shows examples of a basic power wheelchair and a larger power wheelchair equipped with the aforementioned powered seating functions typically used by people who have significant disabilities. Figure 2-2 illustrates the various powered seating functions.

(a) (b)

FIGURE 2-1 Examples of (a) a basic power wheelchair, which generally has no seat functions and may be used by people who can sometimes stand and walk short distances; and (b) a power wheelchair equipped with powered seating functions for people with significant disabilities.
SOURCE: Sunrise Medical.

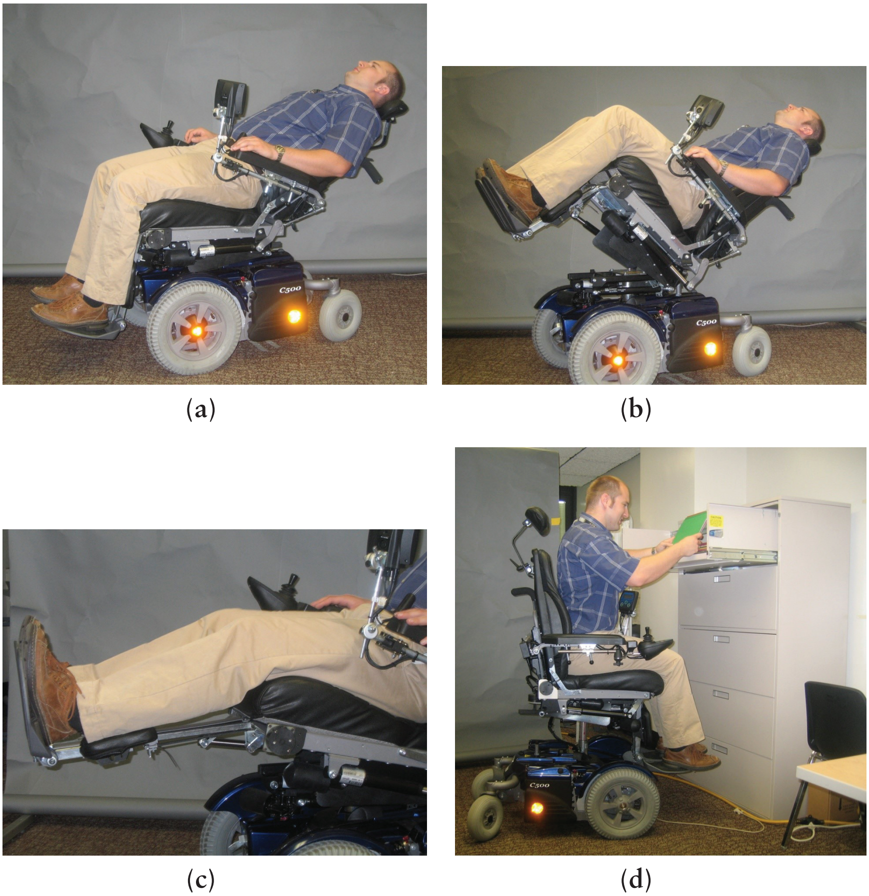

FIGURE 2-2 Illustrations of power wheelchair seating functions, including (a) back support recline, (b) tilt seating, (c) leg elevation, and (d) seat elevation.
SOURCE: Human Engineering Research Laboratories, University of Pittsburgh.

While some people with significant disabilities are not able to control the movement and positioning of their wheelchair, most users can maneuver independently or with limited assistance for some circumstances. A typical method of controlling the direction and speed of a power wheelchair is by a joystick usually mounted at the end of an armrest or on a bar that swings in front of the user. Some wheelchairs equipped for people with limited mobility have a tube for blowing out or taking in air to control the chair's movements.

Rechargeable batteries mounted under the wheelchair seat provide power to electric motors for propelling the wheelchair. Most power wheelchairs use sealed batteries.

Manual Wheelchairs

Many users of manual wheelchairs are nonambulatory and cannot walk any distance, while others are ambulatory at least for short distances.

As shown in Figure 2-3, manual wheelchairs may have either a folding frame or a rigid frame. Manual wheelchairs are moved by pushing down or pulling back the wheelchair's push rims. While some people are not physically able to propel the wheelchair, many people can maneuver with minimal assistance. Like power wheelchairs, manual wheelchairs may be equipped with seating systems that enable pressure relief and have tilt and recline mechanisms to accommodate the occupant's medical and physical needs.

(a) (b) (c)

FIGURE 2-3 Three main types of manual wheelchairs: (a) manual folding, (b) lightweight manual non-folding, and (c) manual with tilt seating.
SOURCE: Sunrise Medical.

Overview of Wheelchair Design Guidelines and Standards

Most personal wheelchairs are paid for by private insurers and the federal government through programs such as Medicare and Medicaid. The U.S. Department of Health and Human Services' Centers for Medicare & Medicaid Services (CMS) issues guidance for government reimbursement that is also followed by most private insurers.[1] The guidance, therefore, has a large influence on wheelchair dimensions, capabilities, and performance characteristics. CMS Pricing, Data Analysis and Coding (PDAC) guidelines assign wheelchairs to groups according to their type and dimension ranges. The guidelines are followed by wheelchair designers and manufacturers as well as by laboratories that test for compliance.

In addition, wheelchairs are designed and constructed according to voluntary industry standards issued by the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA). RESNA is a not-for-profit professional association dedicated to promoting the health and well-being of people with disabilities through access to technology.[2] Its standards consist of multiple volumes that cover methods for testing all wheelchairs (WC-1 and WC-2 [specific to power wheelchairs]) for capabilities such as stability, braking, strength, durability, and fire resistance. These standards also define methods for measuring the weight and dimensions of wheelchairs and the space required for maneuvering. The standards specific to power wheelchairs (WC-2) cover batteries and chargers. Significant for the purposes of this study, RESNA issues a series of standards (WC-4) for the safe securement and crash performance of wheelchairs when used as seats in transportation.

Also important to the design and performance of wheelchairs are the 2010 Americans with Disabilities Act (ADA) Standards for Accessible Design,[3] which include guidelines issued by the U.S. Access Board for the provision of clearance and clear space to accommodate a wide range of wheelchairs. These guidelines, contained in the U.S. Access Board's 2004 ADA Accessibility Guidelines (ADAAG), were developed based on

[1] Medicare Part B (Medical Insurance) provides coverage of power wheelchairs only when prescribed by a doctor as being medically necessary. Part B does not provide coverage for a second wheelchair, such as wheelchairs designed for specialized use (described earlier). Personal wheelchairs may be made specifically for indoor use, or they may be designed for use indoors and outdoors. To prevent damage to their indoor wheelchairs, owners must purchase added safety features to make the wheelchairs more transportable.

[2] RESNA is accredited by the American National Standards Institute (ANSI), which has an Assistive Technology Standards Board that oversees RESNA standards. ANSI is a member of the International Organization for Standardization (ISO); RESNA wheelchair standards aim to be as equivalent as possible to ISO wheelchair standards.

[3] See U.S. Department of Justice. 2010. *2010 ADA Standards for Accessible Design*. https://www.ada.gov/regs2010/2010ADAStandards/2010ADAStandards_prt.pdf.

assumptions about common wheelchair width and length dimensions. Two key assumptions are that the overall width of a wheelchair will not exceed 30 in. and the overall length will not exceed 48 in.[4] Wheelchair manufacturers will, in turn, design wheelchairs that do not exceed these ADAAG dimensions, given the importance of wheelchairs being able to maneuver through the clearances and clear spaces established in the guidelines and followed by building designers and architects to ensure ADA compliance. Moreover, the PDAC guidelines require that wheelchairs eligible for Medicare and Medicaid reimbursement can perform within the clearances and clear spaces established in ADAAG.

Common Wheelchair Sizes and Maneuvering Capabilities

As noted above, test methods for measuring wheelchair sizes and maneuvering capabilities are specified by RESNA in WC-1, specifically in Section 5: Determination of Dimensions, Mass and Maneuvering Space. The standard establishes tests for measuring a wheelchair's

- Overall length—distance between the most forward and most rearward points of the wheelchair;
- Overall width—distance between the most lateral points;
- Total mass—overall mass with all accessories;
- Pivot width—distance required to turn the wheelchair 180 degrees; and
- Angled corridor width—corridor width required to enter a right-angle turn traveling forward and then to exit in reverse.

The RESNA standards are used by testing laboratories to evaluate wheelchair models in the marketplace and provide data to insurers and the government in accordance with PDAC.

Information on the size, weight, and maneuvering capabilities of personal wheelchairs in the general population is important for the purposes of this study because of the need to assess airplane interior space and structural capacity to accommodate a range of personal wheelchairs in the cabin. Data from measurements of 193 models of power wheelchairs,[5] which were provided to the committee by testing laboratories and that are contained in

[4] While this report uses these ADAAG dimensions for reference, further analyses would consider the extent to which these dimensions account for the clearance needs of all people when using their wheelchairs with regard to issues such as toe positioning beyond foot support surface or postural positioning that a wheelchair user may require.

[5] Testing data were obtained from Beneficial Designs, Inc., and Ammer Consulting, LLC; these data did not include scooters for the reasons mentioned earlier.

the addendum to this chapter, reveal the following about power wheelchair weights and sizes:

- The maximum weight of a power wheelchair model is 470 lb and the median[6] is 300 lb. The maximum weight of an occupied power wheelchair is 895 lb, based on rated occupant weight. These values are based on records from 180 wheelchair models tested, as records for 13 models do not contain complete information on weight.
- The maximum width (at the widest point, normally at arm supports) of a power wheelchair model is 32.5 in. and the median is 25.5 in. Only 7 models of the 193 tested (<4 percent) exceeded the 30-in. width dimension used by ADAAG for clearance and clear space guidance.
- The maximum length of a power wheelchair model is 51.5 in. and the median is 44.9 in. Only 5 of the 193 tested models (<3 percent) exceeded the 48-in. length dimension used by ADAAG for clearance and clear space guidance.
- The maximum wheelbase width of a power wheelchair (below the armrests) is 28.5 in. and the median is 24.1 in. These measurements were available for 131 of the 193 models tested. Of those 131 models, only 5 (<4 percent) have a wheelbase width in excess of 26 in.[7,8]
- The testing data also reveal information about wheelchair maneuvering capabilities. Pivot width, as noted above, is the distance required to turn the wheelchair 180 degrees. One way to think about pivot distance is that it is the length of the side of a square in which a circle is inscribed, with the circle representing the wheelchair turning around while centered. The maximum pivot distance for 185 wheelchairs with test data is 62 in. and the median is 48.3 in. Only 1 percent of models exceed 60 in.
- Measurements of angle corridor distance—that is, the corridor width required for the wheelchair to make a right-angle turn—indicate that the maximum is 41 in. and the median is 32 in. Of the 185 models with test data, 83 percent require an angle corridor distance of 36 in. or less, and 95 percent require a distance of 38 in. or less.

---

[6] Information about the number of people who use each kind of chair is not available for reporting the weighted median.

[7] Other technical literature supports that the majority of wheelchair bases are 26 in. or less. See Steinfeld, E., V. Paquet, C. D'Souza, C. Joseph, and J. Maisel. 2010. *Anthropometry of Wheeled Mobility Project: Final Report*. Buffalo, NY: Center for Inclusive Design and Environmental Access.

[8] The testing that is required in RESNA standards includes the camber on a wheelchair, which is the angle that the wheel is placed on the chair for performance and stability.

Transportation Safety Standards for Wheelchairs and Securement Systems

Wheelchairs function as assistive devices to meet the everyday needs of people who are nonambulatory. In addition to providing mobility, the wheelchair benefits the user's physical health and quality of life by helping to reduce common problems such as pressure sores and improving respiration and digestion. Therefore, it can be important, indeed essential, for many people who are nonambulatory to remain seated in their personal wheelchairs when traveling by motor vehicle. Motor vehicle transportation, however, presents safety challenges for occupants of wheelchairs, and it has thus become the subject of increasing attention by standards organizations such as RESNA and by the manufacturers of wheelchairs and other assistive technologies.

Before the mid-1970s, the securement of wheelchairs in motor vehicles was accomplished through ad hoc means, mostly with the same methods used to secure cargo in transport.[9] Webbing-based cargo straps, ropes, and bungee cords were common, hooking to or threading through the wheelchair frame to secure it during travel when unoccupied in the cargo area or occupied in the vehicle passenger space. The orientation of the wheelchair relative to the vehicle was not specified, and thus securing the wheelchair in an unstable side-facing position was common. With the passage of legislation to promote the accommodation of people with disabilities in transportation, culminating later in the enactment of the ADA, more wheelchair users were traveling in motor vehicles, and more attention was being paid to securing wheelchairs and providing protection for occupants closer to that afforded passengers using conventional seats in motor vehicles.

The first marketed wheelchair securement systems were aimed primarily at limiting movement of the wheelchairs during typical driving maneuvers. These early systems took a variety of forms, including pin devices that threaded through the wheels, floor-mounted clamps that put downward pressure on the horizontal portions of the wheelchair frame, and various strapping designs to attach the wheelchair to the vehicle floor. In the late 1970s and early 1980s, research revealed that systems having four or more straps to attach the structural frame of the wheelchair to hard points in the vehicle floor were most likely to be effective in crash scenarios. Research also focused on the development of crashworthy seat belt restraints for people seated in wheelchairs when riding in motor vehicles. During the 1970s and 1980s, several commercial products were introduced with four-point strap designs, as shown in Figure 2-4, which evolved into the industry norm for use in motor vehicles that must accommodate many different types of wheelchairs. At about the same time, companies began

[9] In 1975, AMF-Bruns crash tested the first four-point, strap-type tiedown at Technische Universität Berlin. In 1977, Volkswagen tested a four-point, strap-type system to a high-*g* (20-*g*) crash pulse.

FIGURE 2-4 Four-point, strap-type wheelchair tiedown and three-point belt occupant restraint system.
SOURCE: University of Michigan Transportation Research Institute.

modifying personal vehicles, typically vans and minivans, for the transport of nonambulatory passengers and for people to drive while seated in their wheelchairs. Now common today, the modified vehicles are often equipped with docking securement systems that are installed and tuned to secure to a particular wheelchair, a floor that has been lowered by at least 10 in. to create more headspace for a person seated in the wheelchair, and other specialized technology to facilitate vehicle operation and ingress and egress.

By the 1980s, it was becoming clear that standards were needed to address the safe design and performance of wheelchair tiedown and occupant restraint systems (WTORS) and wheelchairs when used as seats in motor vehicles.[10] In the United States, these efforts began under the auspices of the Society of Automotive Engineers' (SAE's) Adaptive Devices Subcommittee, whose initial efforts conducted in conjunction with similar efforts of the International Organization for Standardization focused on developing standardized testing and evaluation criteria for WTORS that would offer a comparable level of occupant restraint and crash protection to that afforded occupants using the manufacturer-installed seat and belt restraint system in automobiles. In the United States, the work culminated in the 1999 publication of SAE Recommended Practice J2249, Wheelchair Tiedowns and Occupant Restraint Systems for Use in Motor Vehicles. As SAE J2249 was nearing completion in the mid-1990s, it was recognized that the vehicle seat is a critical part of an effective occupant restraint system, and that securing the wide variation in designs of manual and power wheelchairs presented

[10] The National Highway Traffic Safety Administration has chosen not to address wheelchair transportation safety in passenger motor vehicles, other than adding a reference to static pull testing of wheelchair tiedown straps in Federal Motor Vehicle Safety Standard 222, a standard that regulates school buses.

a safety assurance challenge.[11] As a result, work began in the mid-1990s to develop the first standards to address safety issues and features to make wheelchairs more securable and crashworthy when used as seats in motor vehicles. RESNA had already established a Standards Committee on Wheelchairs, and therefore it created a Subcommittee on Wheelchairs and Transportation. The result was the publication in 2000 of Section 19 of American National Standards Institute/RESNA Wheelchair Standards/Volume 1, Wheelchairs for Use as Seats in Motor Vehicles.

When it came time to upgrade the SAE J2249 standard for WTORS, RESNA assumed this responsibility so that all wheelchair transportation safety standards were developed by one standards body. Today, RESNA Volume 4 (WC-4), Wheelchairs and Transportation, which was last updated in 2017, contains four sections addressing aspects of wheelchair transportation safety:

- Section 10 (WC10) on wheelchair containment and occupant retention systems for use in large accessible transit vehicles,[12]
- Section 18 (WC18) on WTORS,
- Section 19 (WC19) on wheelchairs used as seats in motor vehicles, and
- Section 20 (WC20) on wheelchair seating systems for use in motor vehicles.[13]

The WC18 and WC19 standards and testing procedures are discussed in detail in Chapter 3 as part of the safety assessments conducted because the standards establish criteria for crash performance of WTORS and wheelchairs. Importantly, these standards were developed with recognition that assistive technologies will change. For instance, a critical design specification of the WC19 standard is for the wheelchair to have four specific securement points for attaching the end fittings of tiedown strap assemblies to enable easy and effective securement of the wheelchair, as shown in Figure 2-5. There are other means of securing wheelchairs in motor vehicles that are compliant with WC18, such as auto-docking securement systems

[11] See University of Michigan Transportation Research Institute. n.d. "Wheelchair Transportation Safety Standards." http://wc-transportation-safety.umtri.umich.edu/wts-standards.

[12] In recognition that the likelihood of a moderate-to-severe crash is low in a large accessible urban transit vehicle, the WC10 standard, which applies to wheelchair passenger spaces intended for use by rear-facing, wheelchair-seated occupants, is meant to provide a level of safety during travel for passengers seated in wheelchairs that is equivalent to passengers in transit vehicle seats or who are standing using handholds.

[13] Because wheelchair seating systems are often provided as aftermarket products, WC20 establishes design and performance requirements and related test methods to evaluate seating systems relative to their use as seats in motor vehicles independent of their installation on production wheelchair frames.

FIGURE 2-5 Power wheelchair with four securement points (red) required by WC19 for a four-point WTORS.
SOURCE: University of Michigan Transportation Research Institute.

that can be secured by the wheelchair user. However, the four-point securement brackets that WC19 requires are highly relevant for the purposes of this study because they are required for all wheelchairs to be compliant with WC19. In this regard, the four securement points on WC19-compliant wheelchairs could provide a commonly implemented interface for the development of securement systems for airplanes, thereby addressing one potential technical challenge for this concept. It is beyond the scope of this study, however, to define the appropriate securement method.[14]

Other Wheelchair Standards for Strength, Durability, and General Safety

For wheelchairs to comply with RESNA's WC19 transportation safety standards for crash performance, they must also comply with various other RESNA standards, including those noted above. For instance, to comply

[14] This report assumes the use of "brackets" installed by the wheelchair manufacturer for wheelchair securement. Post-production or aftermarket versions, commonly referred to as "loops," are typically not provided by a wheelchair manufacturer, although a manufacturer may weld or bolt these to the frame if requested by the wheelchair user when ordering the wheelchair. Loops are usually purchased by the wheelchair user after the wheelchair purchase for easier use of public transportation. Loops are often not crash tested and they can be attached improperly, such as to a weak element of the wheelchair.

with WC-1 Section 8 (WC8), the wheelchair model must demonstrate the strength to withstand static loads applied to various components such as foot supports, caster wheels, backrest, seat, armrest, and hand rims. The standards call for a rolling drum test, whereby loads are imparted in three directions during 200,000 revolutions of the wheelchair's primary drive wheels. The wheelchair model must also undergo a drop test loaded with a test dummy at maximum user weight.[15] In this test, the wheelchair is dropped repeatedly from a vertical distance of 2 in., applying approximately 2 *g* (acceleration of gravity) of vertical acceleration to the wheelchair for 6,667 cycles.[16] Static stability of wheelchairs when traversing surfaces with slopes and cross-slopes must also be demonstrated according to this set of standards as well as those specific to power wheelchairs (WC-2).

As will be addressed in more detail in Chapter 3, all WC19-compliant wheelchairs must meet the WC-1 Section 16 (WC16) standard for resistance to flammability by a wheelchair's upholstered surfaces. Additionally, WC-2 Section 25 (WC25) contains performance and test criteria for wheelchair batteries, including labeling standards.

OVERVIEW OF PASSENGER AIRPLANES, THEIR SEATS AND INTERIORS, AND THE AIRLINE INDUSTRY

Most air transportation service is on scheduled airlines, which serve thousands of city-pair markets in the United States alone. Airplanes in scheduled airline service are the focus of this report because a central aim of an in-cabin wheelchair securement system would be to provide people who are nonambulatory and have significant disabilities with access to regular air transportation service close to that afforded to people who are ambulatory. The types and number of airplanes in scheduled airline service are therefore reviewed, including their interior features and seating configurations. Airplane operations in scheduled service are then discussed, including airplane use for different types of flight offerings and in networks that serve a range of airports with different capabilities to accommodate people who use wheelchairs.

Passenger Airplanes in Airline Service

In 2019, U.S. airlines, consisting of mainline and regional carriers, operated approximately 6,400 airplanes (see Chapter 4). Mainline carriers (e.g.,

---

[15] The 220-lb dummy, which is approximately equal to the mass of a 90th percentile human male, is used most often.

[16] See VanSickle, D.P., R.A. Cooper, and M.L. Boninger. 2000. "Road Loads Acting on Manual Wheelchairs." *IEEE Transactions on Rehabilitation Engineering* 8, no. 2: 371–384. Vertical acceleration of approximately 2 *g* was derived from this article by dividing the mean of the sum of the forces on each wheel in Newtons by the mean of the mass of the wheelchair and test dummy.

United, Delta, Southwest, American) provide service primarily using airplanes with 90 or more seats, while regional carriers (e.g., Mesa, Republic, Skywest, and others often affiliated with mainline carriers) provide service in smaller airplanes. The vast majority of the airplanes in the U.S. airline fleet are jets. The three major classes of jet airplanes are narrow-body (single-aisle), wide-body (twin-aisle), and smaller regional jets (RJs) that carry less than 100 passengers. While small turboprop airplanes are still used in some small markets, they have become increasingly less common for airline service and are not considered any further in this report.

The narrow-body jet is by far the most common airplane in airline service. Narrow-body jets comprise more than two-thirds of the U.S. airline fleet, and their share is even higher among airplanes used in domestic service. Narrow-body jets, which have capacities in the range of 90 to 250 seats, are suited for service on medium-distance routes with moderate to high passenger traffic densities. Accordingly, they have become the workhorses of the airline fleet, accounting for most airline departures (about 60 percent) and a large majority of passenger enplanements (about 75 percent) (see Figures 2-6 and 2-7). Wide-body jets, which have capacities of 250 or more seats, are used mainly in international service and on a few high-traffic, long-distance, domestic routes, while smaller RJs serve mostly short-haul markets with low to moderate passenger traffic. Any implementation of a wheelchair securement system that does not have applicability on narrow-body airplanes (e.g., by focusing exclusively on the more spacious wide-body jets) would provide users of these systems with relatively few flight offerings for travel to and from the highest-demand cities within the continental United States.

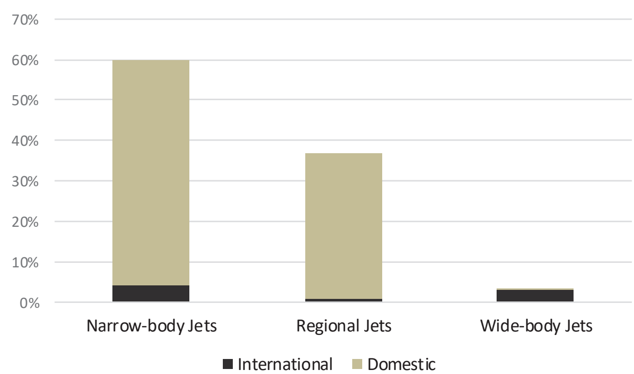

FIGURE 2-6 Mix of scheduled passenger aircraft departures by U.S. airlines, July–December 2019.
SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, T100 data, scheduled passenger service in U.S. airlines.

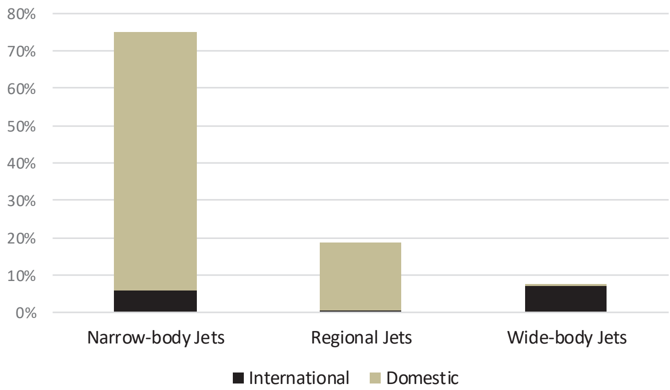

FIGURE 2-7 Mix of scheduled passenger enplanements by U.S. airlines, July–December 2019.
SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, T100 data, scheduled passenger service in U.S. airlines.

Table 2-1 shows the major airplane models that accounted for passenger enplanements and departures by U.S. airlines during the second half of 2019. It merits noting that just two narrow-body jet airplane families—the Boeing 737 and the Airbus A320 (including A381, A319, A320, and A321)—accounted for a majority of all passenger enplanements.

Airplane Seating Configurations and Interiors

Having a single aisle and a cabin interior width of 12 to 13 ft, the typical seating configuration for a narrow-body airplane is six-abreast, with each row containing two triple-place seat assemblies (one on each side of the aisle). First class areas of the cabin, usually located at the front of the cabin, will normally have four-abreast seating, with each row containing a twin-place seat assembly (one on each side of the aisle). In contrast, a wide-body airplane, which can have a cabin width greater than 16 ft, will usually have at least seven- or eight-abreast seating depending on the cabin class. RJs, which have cabin interior widths of about 8 to 10 ft, will usually be configured for four-abreast seating.

In the case of a narrow-body airplane with a 12- to 13-ft-wide cabin interior, each triple-place seat assembly will typically require about 60 in. of width, allowing for an aisle width of no more than 25 in. (see Figure 2-8). These seat assemblies are usually attached to two seat tracks that run lengthwise (fore-aft) along the cabin floor and are anchored to cross beams that run widthwise under the cabin floor. However, individual airplane seating configurations can differ widely even within the same airplane model.

TABLE 2-1 Share of Scheduled Passenger Enplanements and Departures by U.S. Airlines, July–December 2019 by Airplane Model

Airplane Model	Body Type	Percent Share of Enplanements	Percent Share of Departures
Boeing 737-800	NB	16.2	12.4
Boeing 737-700/700LR/Max 7	NB	13.7	12.8
Airbus A320-100/200	NB	10.2	8.1
Airbus A321	NB	9.7	6.3
Boeing 737-900ER	NB	7.4	5.1
Airbus A319	NB	6.1	5.8
Embraer ER-J-175	RJ	5.6	9.9
Canadair CRJ 900	RJ	3.4	5.9
Boeing 757-200	NB	3.2	2.1
Canadair RJ-200 ER/RJ-440	RJ	2.5	6.8
Canadair RJ-700	RJ	2.2	4.4
Boeing 717-200	NB	2.2	2.5
Embraer 145	RJ	2.2	5.8
Subtotal		84.6	87.9
All Other		15.4	12.1

NOTE: NB = narrow body; RJ = regional jet.
SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, T100 data.

For instance, some airlines only configure their airplanes for economy class seating, while others reserve areas for first class and business class seating, usually at the front of the cabin.

Wide-body airplanes operating in overseas markets have the greatest variability in seating types and configurations in order to provide space, comfort, and privacy, especially for passengers paying premium fares. They may include, for instance, reclining seat pods and seat ottomans in enclosed suites. When such installations do not align with existing floor seat tracks, airlines may use various devices for distributing the load across the floor structure, such as the aluminum pallet shown in Figure 2-9. These lightweight pallets overlay and attach to the seat tracks at multiple points and the seat assembly is then anchored to them. While the pallets create a slight rise from the aisle, on the order of 1 in., the sharpness of the rise is tempered by the overlay of carpeting and padding.

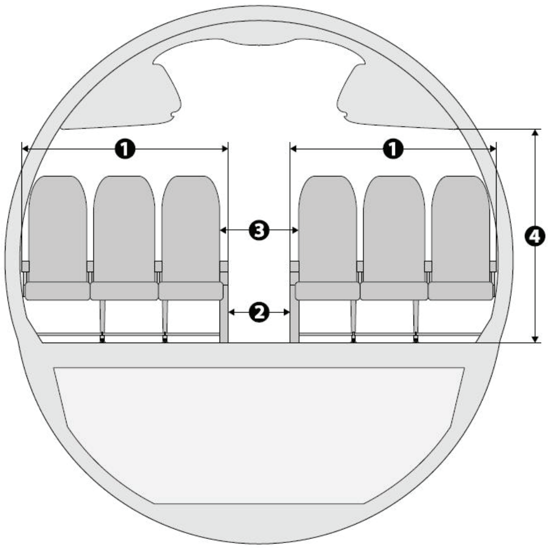

FIGURE 2-8 Cross-section of narrow-body cabin interior with six-abreast seating.
NOTES: Dimension ranges for numbered areas in the figure are illustrative and apply only to common economy cabin configurations for a narrow body:
1: Typical seat assembly width: 56.5 to 60 in.
2: Lower aisle width: 15 to 18 in. from the floor up to 25 in. above the floor
3: Upper aisle width: 20 to 25 in. from 25 in. above the floor
4: Height beneath overhead bin: 62.2 in. (Boeing) and 63.1 in. (Airbus) from the lower surface of the standard overhead bin to the floor
SOURCES: Notes 1 and 3: Boeing. 2005. *Boeing 737 Ground Handling Manual*, pp. 66–67. Notes 2 and 4: Federal Aviation Regulation 14 CFR 25.815.

While seats occupy most of the floor space in an airplane cabin, other major features that take up space are lavatories, galleys, bulkheads, and closets. They are referred to as "monuments" by cabin interior designers and furnishing manufacturers. The size and location of some monuments, especially lavatories and galleys, may be dictated by the availability of needed structure and systems (e.g., plumbing, electrical); hence, they are frequently located in certain installation zones, usually at the very front and rear of the passenger cabin. During the course of a typical airplane's service life, which is usually several decades, its seating and monuments may be removed, relocated, and reconfigured multiple times to align with changes in an airline's business model, to meet new safety requirements, and to refresh aging and worn equipment.

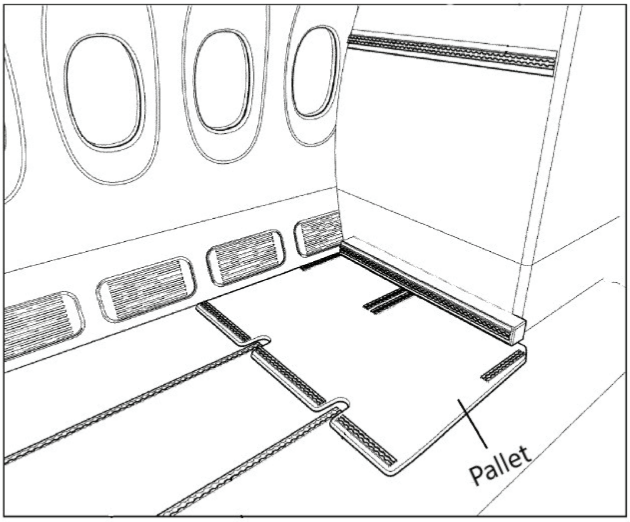

FIGURE 2-9 Aluminum pallet for distributing load across airplane floor structure.
SOURCE: European Patent Application.[17]

Airplane Operations in Airline Service

One reason that narrow-body jets are predominant in the airline fleet—and indeed dominant in markets having the most passenger traffic—is that most airlines operate their fleets in hub-and-spoke networks suited to the capacity and range of this airline class. Major airports in centrally located cities such as Atlanta, Chicago, Dallas/Fort Worth, and Denver account for a disproportionate share of airline departures and enplanements because they are operated as "hubs" for connecting service to and from scores of "spoke" airports. By operating hub-and-spoke networks, airlines are able to offer more frequent flights between city pairs than what is economically possible with direct service. Two passengers originating from the same airport but headed to different destinations can share the same flight to the hub and then transfer to flights going to their final destinations accompanied by passengers connecting from other origin cities.

Because of hub-and-spoke service, many airline trips require connections to complete the itinerary, particularly for travel between distant cities and smaller cities. Indeed, in states that lack a large hub airport, most airline trips require a hub transfer. As shown in Table 2-2, 29 percent of airline

[17] EP 3 608 227, Figure 9, p. 15. https://patentimages.storage.googleapis.com/db/e0/39/92ce801b96fef6/EP3608227A1.pdf.

TABLE 2-2 Percent Share of Passengers Using Nonstop and Connecting Service by State of Trip Origin, Showing States with Highest and Lowest Shares

	Percent Share of Nonstop Passengers	Percent Share of Connecting Passengers
All States	71	29
Illinois	87	13
New Jersey	86	14
Colorado	84	16
Georgia	83	17
Massachusetts	81	19
Arkansas	31	69
Kansas	29	71
Alabama	28	72
Mississippi	17	83
Wyoming	16	84

SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, Airline Origin and Destination Survey DB1BTicket.

passenger trips made during the second half of 2019 involved connections; however, for passengers originating from some states (that are mostly rural) without a major hub airport, connecting service was the norm, required for more than two-thirds of trips. The reality of how airline service is structured is important for considering the potential operational requirements of in-cabin wheelchair securement systems. Because connecting service is required for a large share of airline itineraries, this suggests that in-cabin wheelchair securement systems would need to be installed on a significant number of airplanes to ensure ample flight offerings.

Passenger Boarding and Deplaning at Airports

Scheduled airlines operate at more than 300 airports in the United States, but the busiest 60 of these airports account for more than 85 percent of passenger enplanements.[18] These 60 airports have a full complement of passenger infrastructure and services, including ground transportation and convenient access from the concourse to airplanes. Passengers are generally enplaned and deplaned at the gate using a boarding bridge, which is a

[18] FAA. "Commercial Service Airports (Rank Order) Based on Calendar Year 2019 (issued 9/26/2020)." https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger.

movable enclosure that is secure and environmentally controlled. Bridges usually interface with the airplane at the left-side door, usually forward of the wings.[19]

Yet, even in some of the country's largest airports, bridge boarding systems may not be available at all gates, particularly for smaller RJs. Many bridges are not able to reach a RJ or they cannot be safely used because the stairs or other equipment on the airplane's exterior can be damaged when the bridge is extended. In these cases, the airplane may be ground loaded, which entails passengers accessing the aircraft at tarmac level and using stairs built into the aircraft or a mobile stairway positioned at the boarding door. Aircraft-stair vehicles are also used to enplane and deplane passengers. These vehicles are equipped with stairs that can be raised or lowered to meet the sill of the airplane door.[20]

People who use wheelchairs and fly by transferring to airplane seats must be cognizant of the airplane boarding capabilities at the airports that they travel to and from. When a boarding bridge is not available to serve an airplane, airports use other devices such as switchback ramps or trucks with lifts. In some very limited circumstances, catering trucks or freight elevators may be used to provide level entry into the airplane for wheelchair users. While the scope of this study excludes assessments of boarding and deplaning methods for people flying seated in their wheelchairs, the implementation of in-cabin wheelchair securement systems may need to be accompanied by investments and innovations in such wheelchair accessible boarding methods.

[19] National Academies of Sciences, Engineering, and Medicine. 2013. *Apron Planning and Design Guidebook*. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/22460.

[20] National Academies of Sciences, Engineering, and Medicine. 2013. *Apron Planning and Design Guidebook*. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/22460.

ADDENDUM

Weight, Size, and Performance Measurements of Power Wheelchair Models Tested Since 2009 for Pricing, Data Analysis and Coding (PDAC) for Medicare Eligibility Following Procedures of Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) WC-1, Section 5

NOTES: Weight is reported in pounds; size and performance measurements are reported in inches. Each wheelchair is identified by its K-Code as assigned by PDAC for reimbursement through Medicare Part B. A full list of the PDAC K-Codes can be found at https://hcpcscodes.org/kcodes.
SOURCES: Beneficial Designs, Inc., and Ammer Consulting, LLC.

Definitions:

Angled Corridor—minimum width of a corridor with a right-angled turn in which the wheelchair can be driven in both forward and rearward directions (RESNA Section 5, Clause 8.15: Required width of angled corridor)

Max User Weight—the maximum user mass allowed or specified by the manufacturer (RESNA Section 22, Clause 6.2: Determine the maximum user mass for testing)

Overall Length—distance between the most forward and most rearward points of the wheelchair when it is ready for use, measured in a direction parallel to the forward direction of movement (RESNA Section 5, Clause 8.2: Full overall length)

Overall Width—distance between the outermost side-to-side points of the wheelchair when fully opened and ready for use, measured in a direction perpendicular to the forward direction of movement (RESNA Section 5, Clause 8.3: Overall width)

Pivot Width—minimum corridor width required for the occupied wheelchair to turn through 180 degrees where backward movements of the wheelchair may not be used (RESNA Section 5, Clause 8.11: Pivot width)

Product Weight—mass of the wheelchair when ready for use but unoccupied (RESNA Section 5, Clause 8.9: Total mass)

Wheelbase Width (outside tread width)—distance between outermost points of wheel treads

Model	PDAC K-Code	Max User Weight (lb)	Product Weight (lb)	Combined Weight (lb)
1	K0816	300	136.0	436.0
2	K0816	300	148.0	448.0
3	K0820	450	127.0	577.0
4	K0820	200	150.6	350.6
5	K0821	300	150.3	450.3
6	K0821	300	126.5	426.5
7	K0821	250	121.0	371.0
8	K0822	300	237.1	537.1
9	K0822	300	169.2	469.2
10	K0822	300	210.7	510.7
11	K0822	300	292.0	592.0
12	K0822	300		300.0
13	K0822	300	160.0	460.0
14	K0822	300	130.0	430.0
15	K0822	300	187.0	487.0
16	K0822	300	278.5	578.5
17	K0822	300	176.5	476.5
18	K0822	200	151.1	351.1
19	K0823	300	171.1	471.1
20	K0823	300	284.0	584.0
21	K0823	300	239.8	539.8
22	K0823	300	146.5	446.5
23	K0823	300	219.0	519.0
24	K0823	300	171.0	471.0
25	K0823	300	208.2	508.2
26	K0823	300	171.0	471.0
27	K0823	300	284.0	584.0
28	K0823	300	164.0	464.0
29	K0823	300	175.0	475.0
30	K0823	300	188.5	488.5

Overall Length (in.)	Overall Width (in.)	Pivot Width (in.)	Angled Corridor (in.)	Wheelbase Width (in.)
40.0	27.0	46.0	33.0	
40.0	24.0	52.0	33.0	24.0
33.0	25.0	52.0	30.0	23.0
28.5	23.5	48.0	29.0	23.0
40.0	24.8	50.0	32.0	24.0
35.5	24.5	57.0	30.0	22.0
38.4	24.0	40.0	30.0	
44.5	27.8	52.0	34.0	23.8
40.8	27.5	49.0	34.0	23.0
43.5	27.3	50.0	33.0	23.0
43.0	26.8	45.0	32.0	24.0
42.0	26.0	41.0	30.0	24.0
47.4	25.4	48.0	36.0	
48.0	25.3	50.0	36.0	
42.5	25.0	50.0	30.0	24.0
44.5	24.5	47.0	32.0	24.0
39.5	24.5	44.0	30.0	23.0
28.5	23.5	48.0	29.0	23.0
39.3	30.0	40.0	30.0	25.5
42.5	26.8	44.0	31.0	24.0
44.5	26.0	52.0	34.0	23.8
41.5	25.0	56.0	30.0	23.5
44.8	24.9	43.3	29.0	
39.8	24.8	40.9	29.1	
44.0	24.8	48.0	32.0	23.0
43.5	24.6	47.0	31.0	
44.5	24.5	47.0	32.0	24.0
40.8	24.5	50.0	31.0	23.0
49.6	24.5	51.2	31.9	
42.0	24.0	45.0	30.0	23.5

continued

Model	PDAC K-Code	Max User Weight (lb)	Product Weight (lb)	Combined Weight (lb)
31	K0823	250	121.0	371.0
32	K0823	300	159.0	459.0
33	K0823	300	172.0	472.0
34	K0824	450	243.1	693.1
35	K0824	430	175.5	605.5
36	K0824	450	251.0	701.0
37	K0824	400	217.5	617.5
38	K0825	450	224.0	674.0
39	K0825	350	141.0	491.0
40	K0825	450	247.5	697.5
41	K0825	450	233.5	683.5
42	K0827	470	216.9	686.9
43	K0835	300		300.0
44	K0835	300		300.0
45	K0835	300		300.0
46	K0835	300	384.5	684.5
47	K0835	300	338.0	638.0
48	K0835	300	300.2	600.2
49	K0837	450	272.5	722.5
50	K0837	450	297.0	747.0
51	K0841	300		300.0
52	K0841	300		300.0
53	K0848	300	368.0	668.0
54	K0848	300	352.0	652.0
55	K0848	300	310.5	610.5
56	K0848	300	318.0	618.0
57	K0848	300	309.5	609.5
58	K0848	300	432.0	732.0
59	K0848	300	433.0	733.0
60	K0848	300	272.0	572.0

Overall Length (in.)	Overall Width (in.)	Pivot Width (in.)	Angled Corridor (in.)	Wheelbase Width (in.)
38.4	24.0	40.0	30.0	
38.5	23.6	43.0	33.1	
40.0	23.0	42.0	30.0	
48.0	30.0	52.0	36.0	28.5
50.8	30.0	52.5	41.0	
46.3	27.3	57.0	33.0	27.3
44.5	26.5	45.0	32.0	
48.0	30.0	58.0	38.0	
41.0	25.5	62.0	32.0	23.5
43.7	24.6	45.0	32.0	
43.7	24.5	43.0	32.0	
47.0	27.3	46.0	34.0	26.0
47.2	28.3			
47.2	28.3			
47.2	27.0			
45.5	25.3	51.0	31.0	24.0
46.5	24.0	50.0	32.0	24.0
46.3	24.0	56.0	32.0	23.8
45.5	28.5	51.0	32.0	27.5
46.5	28.0	58.0	33.0	27.0
47.2	28.3			
47.2	28.3			
45.2	29.1	48.2	33.9	24.1
45.0	29.0	61.0	36.0	24.5
44.5	29.0	48.0	32.0	24.5
44.9	28.9	45.0	33.9	
43.8	28.8	46.0	32.9	24.0
45.3	28.3	55.0	38.5	25.2
47.2	27.3	54.5	37.0	25.4
46.0	27.0	50.0	32.0	25.0

continued

Model	PDAC K-Code	Max User Weight (lb)	Product Weight (lb)	Combined Weight (lb)
61	K0848	300	365.0	665.0
62	K0848	300	405.0	705.0
63	K0848	300	325.0	625.0
64	K0848	300	277.0	577.0
65	K0848	300	266.5	566.5
66	K0848	300	308.0	608.0
67	K0848	300	298.0	598.0
68	K0848	300	274.5	574.5
69	K0848	300	336.0	636.0
70	K0848	300	312.8	612.8
71	K0848	300	350.9	650.9
72	K0848	220	260.0	480.0
73	K0848	220	255.0	475.0
74	K0848	220	283.0	503.0
75	K0849	300	301.5	601.5
76	K0849	300	405.0	705.0
77	K0849	300	294.0	594.0
78	K0849	300	386.0	686.0
79	K0849	300	273.5	573.5
80	K0849	300	272.7	572.7
81	K0849	300	270.0	570.0
82	K0849	300	275.0	575.0
83	K0849	300	275.0	575.0
84	K0849	300	290.0	590.0
85	K0849	300	277.7	577.7
86	K0849	300	230.0	530.0
87	K0849	300	317.5	617.5
88	K0849	300	250.0	550.0
89	K0850	450	339.5	789.5
90	K0850	400	421.0	821.0

Overall Length (in.)	Overall Width (in.)	Pivot Width (in.)	Angled Corridor (in.)	Wheelbase Width (in.)
46.9	26.8	47.4	34.1	24.1
46.2	26.3	48.4	31.5	25.0
45.5	26.0	50.0	32.0	20.0
41.5	26.0	42.0	31.0	24.0
45.8	25.5	48.0	32.0	25.0
45.7	25.4	45.9	30.1	
41.7	25.0	43.9	30.1	22.5
45.0	24.8	48.0	31.0	24.0
42.5	24.5	48.0	30.0	24.0
46.5	24.5	54.0	32.0	24.0
45.0	24.3	48.0	31.0	24.0
41.6	23.7	45.1	31.4	21.8
44.3	23.7	45.7	36.3	21.8
40.3	23.4	41.7	32.2	21.8
44.5	29.0	48.0	32.0	24.5
45.5	27.6	48.1	31.3	25.0
41.0	27.5	43.0	32.0	20.0
44.3	26.4	54.5	35.5	25.4
41.5	26.0	42.0	31.0	24.0
43.0	25.5	44.0	30.0	24.5
45.5	25.5	48.0	32.0	25.0
44.5	25.3	49.0	32.0	24.0
44.3	25.3	46.0	31.0	24.0
41.7	25.0	41.0	31.0	22.5
43.5	25.0	44.0	32.0	24.0
46.7	24.8	44.7	30.5	
43.3	24.3	56.0	32.0	24.0
44.7	24.2	44.5	28.0	
47.8	31.8	56.0	36.0	26.0
45.3	28.3	55.5	39.0	25.2

continued

Model	PDAC K-Code	Max User Weight (lb)	Product Weight (lb)	Combined Weight (lb)
91	K0850	450	271.5	721.5
92	K0850	350	433.0	783.0
93	K0850	350	405.0	755.0
94	K0850	450	275.0	725.0
95	K0850	400	307.5	707.5
96	K0850	400		400.0
97	K0851	450	331.0	781.0
98	K0851	450	280.5	730.5
99	K0851	400	405.0	805.0
100	K0851	400		400.0
101	K0851	350	386.0	736.0
102	K0851	400	307.0	707.0
103	K0856	300	345.0	645.0
104	K0856	300	345.0	645.0
105	K0856	300	310.5	610.5
106	K0856	300	432.0	732.0
107	K0856	300	338.0	638.0
108	K0856	300	433.0	733.0
109	K0856	300	377.0	677.0
110	K0856	300	374.0	674.0
111	K0856	300	370.0	670.0
112	K0856	300	303.3	603.3
113	K0856	250	405.0	655.0
114	K0856	300	390.5	690.5
115	K0856	300	448.6	748.6
116	K0856	300	372.2	672.2
117	K0856	300	344.0	644.0
118	K0856	300	388.0	688.0
119	K0856	165	321.0	486.0
120	K0856	300	410.5	710.5

Overall Length (in.)	Overall Width (in.)	Pivot Width (in.)	Angled Corridor (in.)	Wheelbase Width (in.)
46.0	28.3	48.0	33.0	25.3
47.2	27.3	54.5	37.0	25.4
46.2	26.3	48.4	31.5	25.0
46.5	25.3	45.0	32.0	24.0
44.5	25.2	50.0	33.9	
44.5	25.2	50.0	33.9	
45.0	30.8	46.0	34.0	26.0
45.5	28.5	48.0	33.0	25.3
45.5	27.6	48.1	31.3	25.0
50.2	26.6			
44.3	26.4	54.5	35.5	25.4
42.4	26.0	46.1	29.3	
44.9	28.9	45.0	33.9	
44.9	28.9	45.0	33.9	
43.8	28.8	46.0	32.9	24.0
45.3	28.3	55.0	38.5	25.2
39.6	27.4	59.3	38.0	
47.2	27.3	54.5	37.0	25.4
41.7	27.1	44.7	33.7	24.1
46.9	26.8	47.4	34.1	24.1
42.5	26.8	43.0	30.0	20.0
47.0	26.5	52.0	32.0	25.0
46.2	26.3	48.4	31.5	25.0
45.5	26.3	54.0	33.0	24.0
47.0	25.3	51.0	30.0	24.3
44.5	25.0	45.0	30.0	24.0
41.7	25.0	43.9	30.1	22.5
42.3	24.7	45.1	31.5	24.7
43.0	24.7	46.7	29.7	
42.5	24.5	54.0	32.0	24.0

continued

Model	PDAC K-Code	Max User Weight (lb)	Product Weight (lb)	Combined Weight (lb)
121	K0856	300	291.0	591.0
122	K0856	300		300.0
123	K0856	300	338.5	638.5
124	K0857	300	382.3	682.3
125	K0857	300	405.0	705.0
126	K0857	300	386.0	686.0
127	K0857	300	296.0	596.0
128	K0857	300	282.5	582.5
129	K0857	300	361.0	661.0
130	K0858	450	428.0	878.0
131	K0858	400	409.0	809.0
132	K0858	400		400.0
133	K0858	400	421.0	821.0
134	K0858	350	433.0	783.0
135	K0858	450	313.0	763.0
136	K0858	350	405.0	755.0
137	K0859	400	405.0	805.0
138	K0859	350	386.0	736.0
139	K0861	300	394.6	694.6
140	K0861	300	460.0	760.0
141	K0861	300	408.0	708.0
142	K0861	300	384.0	684.0
143	K0861	300	345.0	645.0
144	K0861	300	345.0	645.0
145	K0861	300	345.0	645.0
146	K0861	300	318.5	618.5
147	K0861	300	395.0	695.0
148	K0861	300	432.0	732.0
149	K0861	300	338.0	638.0
150	K0861	300	386.0	686.0

Overall Length (in.)	Overall Width (in.)	Pivot Width (in.)	Angled Corridor (in.)	Wheelbase Width (in.)
44.9	24.3	44.5	28.0	
44.9	24.3	44.5	28.0	
46.3	24.0	50.0	31.0	23.8
46.0	29.0	51.0	34.0	27.0
45.5	27.6	48.1	31.3	25.0
44.3	26.4	54.5	35.5	25.4
42.8	26.0	48.0	32.0	24.0
47.0	25.3	54.0	34.0	23.8
40.0	24.0	41.0	28.0	21.0
47.3	31.4	54.5	36.5	
44.6	29.4	48.3	37.0	
44.6	29.4	48.3	37.0	
45.3	28.3	55.5	39.0	25.2
47.2	27.3	54.5	37.0	25.4
47.8	26.8	54.0	34.0	25.5
46.2	26.3	48.4	31.5	25.0
45.5	27.6	48.1	31.3	25.0
44.3	26.4	54.5	35.5	25.4
47.0	32.5	56.0	38.0	25.5
47.9	30.0	51.8	34.5	25.0
41.0	29.1	43.0	31.1	
47.2	29.1	50.2	34.9	24.1
44.9	28.9	45.0	33.9	
44.9	28.9	45.0	33.9	
44.9	28.9	45.0	33.9	
43.8	28.8	46.0	32.9	24.0
42.3	28.5	45.1	31.5	24.7
45.3	28.3	55.0	38.5	25.2
39.6	27.4	59.3	38.0	
46.9	26.8	47.4	34.1	24.1

continued

Model	PDAC K-Code	Max User Weight (lb)	Product Weight (lb)	Combined Weight (lb)
151	K0861	300	370.0	670.0
152	K0861	300	390.5	690.5
153	K0861	300	345.0	645.0
154	K0861	300	449.0	749.0
155	K0861	300	414.0	714.0
156	K0861	300	448.6	748.6
157	K0861	300	428.2	728.2
158	K0861	300	351.5	651.5
159	K0861	300	410.5	710.5
160	K0861	300	346.5	646.5
161	K0862	450	445.0	895.0
162	K0862	450	445.0	895.0
163	K0862	450	445.0	895.0
164	K0862	350	460.0	810.0
165	K0862	400	409.0	809.0
166	K0862	400		400.0
167	K0862	400	421.0	821.0
168	K0862	450	313.0	763.0
169	K0862	350	449.0	799.0
170	K0868	300	405.0	705.0
171	K0868	400	307.5	707.5
172	K0868	400	307.5	707.5
173	K0868	400	307.5	707.5
174	K0869	300	405.0	705.0
175	K0869	300	307.5	607.5
176	K0877	300	409.0	709.0
177	K0877	300	409.0	709.0
178	K0877	300	425.0	725.0
179	K0877	300	415.0	715.0
180	K0877	300	403.0	703.0

Overall Length (in.)	Overall Width (in.)	Pivot Width (in.)	Angled Corridor (in.)	Wheelbase Width (in.)
42.5	26.8	43.0	30.0	20.0
45.5	26.3	54.0	33.0	24.0
47.5	26.2	50.8	32.0	
45.7	26.0	52.8	34.9	25.4
45.2	25.7	54.8	37.5	25.7
47.0	25.3	51.0	30.0	24.3
41.5	25.0	42.5	25.0	24.0
41.7	25.0	43.9	30.1	22.5
42.5	24.5	54.0	32.0	24.0
46.5	24.5	50.0	32.0	23.8
47.3	31.4	54.5	36.5	
47.3	31.4	54.5	36.5	
47.3	31.4	54.5	36.5	
47.9	30.0	51.8	34.5	25.0
44.6	29.4	48.3	37.0	
44.6	29.4	48.3	37.0	
45.3	28.3	55.5	39.0	25.2
47.8	26.8	54.0	34.0	24.8
45.7	26.0	52.8	34.9	25.4
46.2	26.3	48.4	31.5	25.0
44.5	25.2	50.0	33.9	
44.5	25.2	50.0	33.9	
44.5	25.2	50.0	33.9	
45.5	27.6	48.1	31.3	25.0
42.4	26.0	46.1	29.3	
44.6	29.4	48.3	37.0	
44.6	29.4	48.3	37.0	
45.3	28.3	55.5	39.0	25.2
47.2	27.0	52.2	36.0	25.1
46.9	26.8	47.4	34.1	25.1

continued

Model	PDAC K-Code	Max User Weight (lb)	Product Weight (lb)	Combined Weight (lb)
181	K0877	300	405.0	705.0
182	K0878	300	405.0	705.0
183	K0884	300	460.0	760.0
184	K0884	300	409.0	709.0
185	K0884	300	409.0	709.0
186	K0884	300		300.0
187	K0884	300		300.0
188	K0884	300	369.0	669.0
189	K0884	300	369.0	669.0
190	K0884	300	369.0	669.0
191	K0884	300	425.0	725.0
192	K0884	300	427.0	727.0
193	K0884	300	403.0	703.0

Overall Length (in.)	Overall Width (in.)	Pivot Width (in.)	Angled Corridor (in.)	Wheelbase Width (in.)
46.2	26.3	48.4	30.1	25.0
45.5	27.6	48.1	31.3	25.0
47.9	30.0	51.8	34.5	25.0
44.6	29.4	48.3	37.0	
44.6	29.4	48.3	37.0	
51.5	29.0			
51.5	29.0			
45.3	28.9	44.0	31.0	
45.3	28.9	44.0	31.0	
45.3	28.9	44.0	31.0	
45.3	28.3	55.5	39.0	25.2
47.2	27.0	52.2	36.0	25.1
46.9	26.8	47.4	34.1	25.1

3

Crashworthiness and Other Safety Considerations

With the exception of regulations governing school bus passenger transportation and crash protection,[1] the federal government has not established safety standards that apply to wheelchair securement systems or wheelchairs used as seats in surface transportation vehicles or airplanes.[2] Nevertheless, wheelchairs and securement systems that are designed and constructed according to voluntary industry standards intended to ensure safer transportation for people who must use their personal wheelchairs as seats in motor vehicles are currently in use. As explained in Chapter 2, the standards are issued by the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA), a not-for-profit professional association dedicated to promoting the health and well-being of people with disabilities through access to technology. The RESNA standards cover design requirements, performance criteria, test methods, and product labeling for wheelchair tiedown and occupant restraint

[1] An exception are regulations governing school bus passenger transportation and crash protection (Federal Motor Vehicle Safety Standards [FMVSS] 222).

[2] Title 14 CFR Part 382, administered by the U.S. Department of Transportation, does contain requirements for manual wheelchair cabin stowage and the provision of aisle wheelchairs, but these are not safety-related standards and do not pertain to the securement and use of wheelchairs when used as seats in airplanes.

systems (WTORS) and for wheelchairs that may be used as seats in motor vehicles.[3]

Although it was created in 1979 and has been issuing wheelchair transportation safety standards since the 1990s, RESNA has not established standards for the safe securement and use of wheelchairs in passenger airplanes. All U.S. safety regulations governing aircraft design certification are administered by the Federal Aviation Administration (FAA). The main body of FAA regulations that applies to the cabin interiors of airplanes is in Title 14 Part 25 of the Code of Federal Regulations (14 CFR 25). These regulations are intended to ensure cabin interior "crashworthiness," a term used by FAA in reference to a "survivable crash" when the cabin occupants are subjected to crash forces within human tolerances and the structural integrity of the passenger space remains intact such that the occupants can rapidly evacuate.[4] While the Part 25 regulations do not refer to WTORS or wheelchairs used as passenger seats, they govern most aspects of the performance, design, and testing of airplane seats, including their occupant restraint systems and supporting structures and attachment to the floor and primary airplane structure. Of particular relevance to seats are the Part 25 sections intended to protect airplane occupants during crash conditions in an emergency landing, prevent items of mass from shifting or becoming loose and creating a hazard to occupants, and minimize the potential for and severity of a post-crash fire. A review of these applicable Part 25 requirements is therefore important inasmuch as FAA may require satisfactory demonstration that secured wheelchairs can meet the same crashworthiness performance criteria as airplane seats.

The remainder of the chapter begins with a review of the relevant FAA Part 25 requirements and the RESNA standards for WTORS and wheelchairs when used as seats for motor vehicle transportation. The FAA and RESNA requirements are then compared, with an emphasis on both alignments between the two and differences and gaps, particularly with respect to whether and how compliance with RESNA standards could satisfy the crashworthiness criteria of the Part 25 requirements. The findings from these comparisons inform the assessment of the space within an airplane cabin that would

[3] RESNA's Assistive Technology Standards are approved for publication as American National Standards by the American National Standards Institute (ANSI), ensuring that the standards development process meets ANSI's essential requirements for openness, balance, consensus, and due process. The standards are grouped under the general title ANSI/RESNA WC-4. See ANSI/RESNA. 2017. "WC-4:2017 American National Standard for Wheelchairs—Volume 4: Wheelchairs and Transportation." https://www.resna.org/Portals/0/Documents/AT_WC4_SellSheet_8.13.19.pdf.

[4] FAA. 2009. *Advisory Circular 25-17A—Transport Airplane Cabin Interiors Crashworthiness Handbook*. https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentid/74596.

be needed for a wheelchair to be positioned and secured in Chapter 4 and the summary assessment of the technical issues, challenges, and uncertainties associated with a wheelchair securement system concept in Chapter 5.

FAA CABIN INTERIOR CRASHWORTHINESS REQUIREMENTS

FAA's aviation safety regulations in 14 CFR are organized into more than 40 parts, each addressing a specific activity, such as the flight rules governing aircraft operation and the certification of pilots, aircraft, and aircraft technicians. Part 25 is titled "Airworthiness Standards: Transport Category Airplanes." Transport category airplanes are defined as jet airplanes with 10 or more seats and turboprop and other propeller-driven airplanes with 20 or more seats, which essentially covers all passenger airplanes in scheduled service. Historically, the emphasis of federal safety regulations was on ensuring aircraft airworthiness;[5] however, by the 1960s additional emphasis was placed on ensuring crashworthiness as technical knowledge was gained from research and service experience and as crash investigations permitted the development of interior design parameters to aid in crash survival.[6] The major regulatory sections of Part 25 that pertain to crashworthiness requirements for cabin interiors are shown in Box 3-1.

FAA's approach to cabin crashworthiness has principally involved three areas of concern: (1) protecting cabin occupants from crash impact, (2) minimizing the potential for and severity of a post-crash fire in the cabin, and (3) rapidly evacuating the cabin in the event of an emergency. Some of the Part 25 sections intended for these purposes pertain directly to the design and configuration of passenger seats and are thus most pertinent to a review of the technical issues associated with in-cabin securement of wheelchairs and their use as seats in an airplane. Of particular interest are the requirements governing the performance of cabin interior components during emergency landing conditions (§ 25.561 and § 25.562), seats and safety belts (§ 25.785), retention of items of mass (§ 25.789), and flammability of seat cushions and coverings (§ 25.853). An important point regarding these four sets of requirements, which are described next, is that each is intended to serve two purposes: (1) to protect the seat's occupant by reducing the potential for serious or fatal injuries and (2) to protect occupants of the airplane generally by reducing the potential for fires, obstructions to rapid evacuation, and loose objects becoming hazards.

---

[5] According to 14 CFR Part 25 § 3.5(a) airworthy means an aircraft conforms to its type design and is in a condition for safe operation.

[6] FAA. 2009. *Advisory Circular 25-17A—Transport Airplane Cabin Interiors Crashworthiness Handbook,* p. ii. https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentid/74596.

BOX 3-1
Crashworthiness Requirements for Cabin Inferiors of Transport Category Airplanes:

Major Sections. Title 14 Part 25 of the Code of Federal Regulations (14 CFR 25)

Section 25.561	Emergency Landing Conditions General
Section 25.562	Emergency Landing Dynamic Conditions
Section 25.772	Pilot Compartment Doors
Section 25.783	Doors
Section 25.785	Seats, Berths, Safety Belts, and Harnesses
Section 25.787	Stowage Compartments
Section 25.789	Retention of Items of Mass
Section 25.791	Passenger Information Signs
Section 25.793	Floor Surfaces
Section 25.795	Security Considerations
Section 25.801	Ditching
Section 25.803	Emergency Evacuation
Section 25.805	Flight Crew Emergency Exits
Section 25.807	Passenger Emergency Exits
Section 25.809	Emergency Exit Arrangement
Section 25.810	Emergency Egress Assist Means and Escape Routes
Section 25.811	Emergency Exit Marking
Section 25.812	Emergency Lighting
Section 25.813	Emergency Exit Access
Section 25.815	Width of Main Aisle
Section 25.817	Maximum Number of Seats Abreast
Section 25.819	Lower Deck Service Compartments (Including Galleys)
Section 25.851	Fire Extinguishers
Section 25.853	Compartment Interiors
Section 25.854	Lavatory Fire Protection
Section 25.855	Cargo and Baggage Compartments
Section 25.856	Thermal/Acoustic Insulation Materials
Section 25.857	Cargo Compartment Classification
Section 25.869	Fire Protection: Systems
Section 25.1307	Miscellaneous Equipment
Section 25.1359	Electrical System Fire and Smoke Protection
Section 25.1411	Safety Equipment – General
Section 25.1413	Safety Belts
Section 25.1415	Ditching Equipment
Section 25.1421	Megaphones
Section 25.1423	Public Address Systems
Section 25.1439 (a)	Protective Breathing Equipment
Section 25.1447	Equipment Standards for Oxygen Dispensing Units
Section 25.1451	Fire Protection for Oxygen Equipment
Section 25.1541	Markings and Placards – General
Section 25.1557 (a), (c), and (d)	Miscellaneous Markings and Placards
Section 25.1561	Safety Equipment

Note that several of the other Part 25 requirements for cabin crashworthiness that are listed in Box 3-1 do not pertain directly to passenger seats, but the airplane's seating can nevertheless play an important role in enabling compliance. For instance, Part 25 contains performance requirements for an emergency evacuation (§ 25.803), which must be possible within 90 seconds, and therefore seats are generally designed and configured to help achieve this performance mandate.[7] In addition, Part 25 contains other cabin safety requirements that are often satisfied with the help of cabin seats, such as by housing flotation devices (§ 25.1415) and by providing handgrips (as part of § 25.785) and emergency lighting (§ 25.1415). In all of these cases, however, the regulations do not mandate a specific role for seats, and the performance-based nature of FAA requirements means that airplane manufacturers and interior designers have latitude for deciding how they will meet them. Because of this opportunity for innovation by interior designers, it is not possible to know exactly *how* they would try to satisfy FAA performance-based requirements where a wheelchair is used as a seat. However, in having this latitude, it is also reasonable to assume that designers would indeed be able to come up with solutions through the application of creative design and engineering approaches. Accordingly, these and other similar Part 25 requirements that can reasonably be met through an ordinary level of design and engineering creativity and effort are not considered further in this chapter, which focuses on identifying potentially significant technical challenges.

Emergency Landing Conditions (§ 25.561 and § 25.562)

When the Part 25 crashworthiness requirements were introduced, they contained a single section (§ 25.561) on emergency landing conditions, which stipulated certain resting, or static, load forces that the airplane, including seating systems and their supporting structure and items of mass, must be able to withstand without deforming to a degree that would impede rapid evacuation of the airplane. The forces were given as static strength requirements for different loading directions and expressed in multiples of the acceleration of gravity, or *g*. The static load factors, as stipulated today, are (1) upward 3 *g*, (2) forward 9 *g*, (3) sideward 3 *g* (airframe) and 4 *g* (seats), (4) downward 6 *g*, and (5) rearward 1.5 *g*. The static load testing procedure is typically accomplished by applying a force to the seat through the safety belt by means of a hydraulic or cable and winch system. For instance, in testing the forward direction, the minimum force that the seat

[7] Currently, passengers who are nonambulatory and seated in airplane seats will need assistance in the event of an evacuation, and that same assistance would presumably be needed by nonambulatory passengers seated in wheelchairs.

must be capable of withstanding without structural failure is nine times the combined weight of the seat and a 170-lb occupant.

In 1988, a new section, § 25.562, was added that includes dynamic force performance standards for seating systems intended to provide increased occupant protection in survivable crashes. Two separate dynamic tests are conducted to simulate two different crash scenarios. In the first test, the impact vector is predominantly vertical (in combination with a forward force component) from an airplane descending to impact, such as during an emergency landing with a high descent rate. The vertical test demonstrates the seat structure's ability to avoid severe deformation, retain items of mass, and protect the occupant from spinal injury under vertical loadings. In the second test, the impact vector is predominantly horizontal from an airplane moving forward and slightly sideways to impact, such as on the runway or ground where the main impact force is along the airplane's longitudinal axis but with a lateral impact component, as might occur during a hard landing. The test procedures require rapidly decelerating the seat. In the vertical test, each seat must be able to withstand a change in downward vertical velocity from 35 to 0 ft per second (i.e., from 24 to 0 mph) in not more than 0.08 seconds, with the airplane's longitudinal axis canted downward 30 degrees with respect to the horizontal plane and with the wings level. A peak floor deceleration of at least 14 *g* must occur after impact. In the longitudinal test, deceleration must go from 44 to 0 ft per second (30 to 0 mph) in not more than 0.09 seconds and with the airplane's longitudinal axis horizontal and yawed 10 degrees either right or left with the wings level. A peak floor deceleration of at least 16 *g* must occur after impact.[8]

Passenger seats are also tested with a 170-lb anthropomorphic test dummy (ATD), or its equivalent, sitting in the normal upright position and instrumented to measure forces and accelerations.[9] The testing requires that the lap belt remain on the ATD's pelvis during the impact. Protection from impact forces must be provided in situations where the testing indicates that the occupant's head could strike seats or other surfaces such that a

---

[8] Because § 25.562 did not take effect in new aircraft until the mid-1990s and was applied to only newly type certificated aircraft, seat strength requirements can vary among airplanes in the existing fleet depending on the type of aircraft and when that aircraft model was first certified. A Boeing 767-300, for instance, only requires passenger seating to meet static strength requirements, whereas a newer Boeing 787 requires testing for both static and dynamic loading. However, with the passage of § 121.311(j) all transport passenger aircraft manufactured on or after October 27, 2009, must meet the requirements of § 25.562. This requirement has led to very few 9 *g* seats being installed on aircraft where their installation is still permitted.

[9] 49 CFR Part 572, Subpart B.

head injury criterion (HIC) of 1,000 units is not exceeded.[10] The maximum compressive load measured between the pelvis and the lumbar column of the ATD must not exceed 1,500 lb, as protection against a spinal column injury, and axial compressive loads on the femur must not exceed 2,250 lb, as protection against a debilitating leg injury such as through knee contact with seats or other structures in front of the passenger.[11] Photos depicting sequences during both types of dynamic tests are shown in Figure 3-1.[12]

The dynamic testing process is significantly more complicated than the static testing process because the head and leg injury criteria can only be completely evaluated when the seat is considered in relationship to where it is installed in the airplane.[13] For example, the testing will cause the upper torso and head to swing forward in an arcing motion because the ATD is constrained only at the pelvis by the safety belt. A record of the motion of the head through the arc is used during the installation approval process to ensure there is enough clearance from hard surfaces and objects, such as unpadded bulkheads, to reduce the possibility of injurious head impact. The striking radius of the head is considered to be an arc of 35 in. from the cushion reference point, the point where the back cushion and bottom cushion intersect at the center of the passenger seat.[14]

If all seats were uniformly installed at the same distance from one row to the next in every airplane, only a few head-path reviews would be required. However, this is not the case because cabin configurations vary from one airplane to the next and from one airline to the next. Some airlines will have different seat configurations within the same airplane model in their fleets. Because cabin interior arrangements differ, the head-path must be evaluated for each unique installation.

---

[10] HIC is a quantitative measure of head injury risk in crash situations. The HIC 1,000 value was consistent with acceptable head injury protection levels for a mid-size adult when an airbag is activated in a motor vehicle crash, as defined in FMVSS at the time FAA adopted the dynamic testing requirements for airplane seats.

[11] The leg injury criteria also have their origins in FMVSS.

[12] The weight of the ATDs used in motor vehicle testing, wheelchair testing, and airplane seat testing is less than the average weight of an adult age 20 or over in the United States. See Centers for Disease Control and Prevention National Center for Health Statistics. 2021. "Body Measurements." https://www.cdc.gov/nchs/fastats/body-measurements.htm.

[13] The discussion of the dynamic testing process that follows derives from the original text and descriptions in FAA. 2005. "Improved Seats in Air Carrier Transport Category Airplanes: Final Rule." *Federal Register* 70, no. 186: 56541–56559.

[14] More specifically, the striking radius of the head is considered to be an arc of 35 in. whose center is at the intersection of the plane of the uncompressed top of the seat cushion with the plane of the uncompressed front of the back cushion; this is commonly referred to as the cushion reference point.

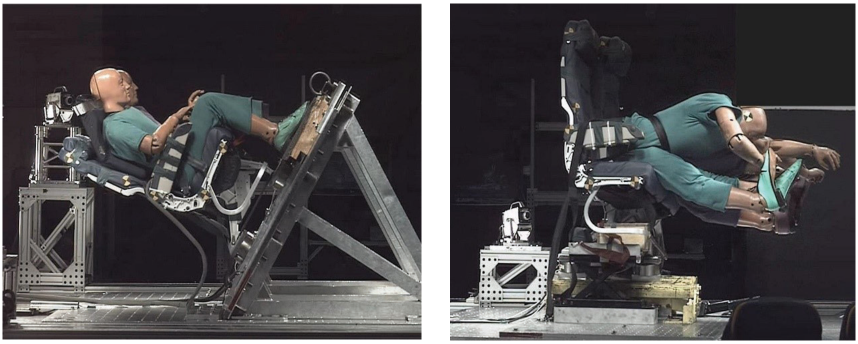

FIGURE 3-1 Dynamic tests (vertical [14 *g*] and longitudinal [16 *g*]) to demonstrate compliance with § 25.562.
NOTES: The images are from a sled running on a horizontal track, which is the typical test facility. Accordingly, for the vertical test setup using a horizontal track, the seat is rotated backward 60 degrees to meet the regulatory criteria for this test condition (i.e., canted downward 30 degrees). The images show the ATDs at near peak movement. In the vertical test, the typical sequence is that the ATD initially slumps down in the seat, which compresses the spine to create the maximum lumbar load. In the longitudinal test, the typical sequence is that the ATD slides forward until the lap belt reaches maximum stretch, at which point the upper torso and head rotate forward and legs flail.

Seating systems are also dynamically tested with regard to the integrity and strength of their attachment to the seat tracks and floor beams. When they are being tested in the longitudinal direction, seat tracks and seat attachments that hold the seats to the test fixture must be misaligned with respect to the adjacent set of tracks by at least 10 degrees vertically with one rolled 10 degrees. During the testing, the seats must remain attached at all points and not yield to an extent that they could impede rapid evacuation of the airplane. Additional requirements pertaining to seating system attachments are prescribed in the section on Seats, Berths, Safety Belts, and Harnesses (§ 25.785), as noted below. For reference, a drawing of a typical economy class seat assembly and attachments to seat tracks is shown in Figure 3-2a. An illustration of floor and seat deformation is provided in Figure 3-2b.

Seats, Berths, Safety Belts, and Harnesses (§ 25.785)

§ 25.785 stipulates that each airplane seating system, including the occupant restraint system, must be designed so that an occupant making proper use of it will not sustain serious injury in an emergency landing as a result of the static and dynamic forces specified in § 25.561 and § 25.562. The

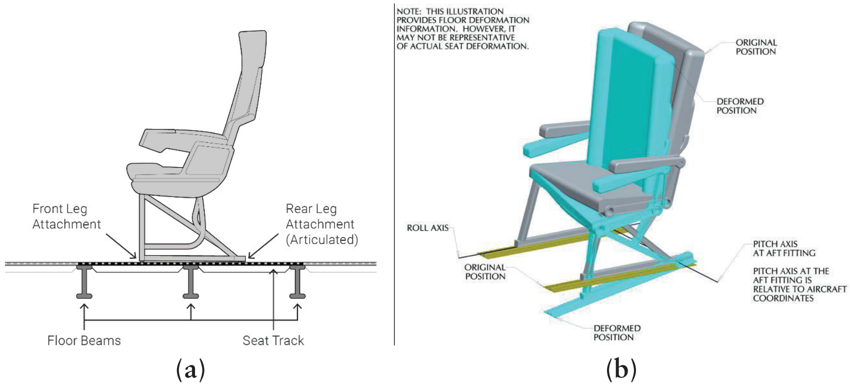

FIGURE 3-2 Illustrations of (a) a typical economy class passenger seat assembly and attachment to seat track, and (b) the floor and seat deformation position.
SOURCE: (b) SAE International.

section further states that each occupant of a seat must be protected from head injury by a safety belt (equipped with a metal-to-metal latch) and, as appropriate to the seat's type, location, and facing angle, by one or more of the following: (1) a shoulder harness that will prevent the head from contacting any injurious object; (2) the elimination of any injurious object within striking radius of the head; and (3) energy absorbing rest that will support the arms, shoulders, head, and spine. Furthermore, any projecting objects that could injure people seated or moving about the airplane in normal flight must be padded.

§ 25.785 states that each seat, supporting structure, belt, and belt anchorage must be designed for an occupant weighing 170 lb. The regulation requires that the seating system be designed to withstand all flight and ground load conditions, including those specified in § 25.561 and § 25.562. The static forces specified in § 25.561 must be multiplied by a factor of 1.33 in determining the strength of the attachment fittings of each seat to the structure and each belt to the seat and structure.

Retention of Items of Mass in the Passenger Compartment (§ 25.789)

§ 25.789 prescribes that each item of mass in the passenger compartment that is part of the airplane type design, including parts of seating systems, be prevented from becoming a hazard by shifting or becoming a projectile in the cabin due to application of the maximum loading conditions corresponding to the specified flight and ground load conditions and to emergency landing conditions specified in § 25.561. Compliance is demonstrated through the static testing conducted for § 25.561. Although retention of items of mass is not explicitly mentioned in the § 25.562 requirement for dynamic testing, it is typically demonstrated for seating systems during these tests.

Compartment Interiors Flammability (§ 25.853)

§ 25.853 prescribes that all materials in the passenger cabin successfully complete flammability performance criteria to demonstrate that they are self-extinguishing. The test must be performed using a small-flame Bunsen burner. The seat cushions, seat covers, and all other materials used in the seating system, including finishes or decorative surfaces applied to the materials, must meet the criteria. In addition, all seat cushions and covers must successfully complete flammability testing that prescribes use of a large-flame oil burner to ensure that a fire will not propagate throughout the cabin due to cushions burning.

WHEELCHAIR TRANSPORTATION SAFETY STANDARDS

There are two common approaches used for providing adequate safety and crash protection of passengers who remain seated in wheelchairs while riding in motor vehicles: (1) securement and (2) containment. Securement involves connecting the wheelchair frame to the vehicle by using some form of attachment points. Containment involves creating a defined space for the occupant and the wheelchair that is separate from the space of other passengers, such as by employing a barrier to prevent ingress of the wheelchair into the space of other passengers. For vehicles subject to high levels of acceleration, such as passenger cars and light buses, the emphasis is usually placed on good securement. For large, slower-moving vehicles, such as public transit buses, ensuring effective containment is usually emphasized. The former crash environment is frequently referred to as "high *g*" and the latter environment as "low *g*."

When a person remains in the wheelchair during transportation in a passenger car or light bus (i.e., high-*g* environment), the wheelchair must take on the role of a vehicle seat according to the securement approach. Just as a conventional seat is rigidly anchored to the vehicle chassis, the wheelchair must be secured in the vehicle so that it does not move substantially during a crash or emergency maneuver.[15] When anchored, the wheelchair should not become a projectile that endangers vehicle occupants in a collision. Securement should reduce the chance that the wheelchair mass loads the occupant, adding to a seat belt's ability to limit occupant movement within the vehicle. The wheelchair should support the occupant

[15] In the frontal impact test, there is a 200-mm horizontal excursion limit.

throughout the crash event so that a properly positioned seat belt engages with the strong parts of the occupant's skeletal structure. Accordingly, the seat design should not interfere with proper placement of seat belts or cause failure of belt components during dynamic loading.

As described in Chapter 2, RESNA standards contain four sections that address aspects of wheelchair user transportation safety: Section 10 (WC10) on wheelchair containment and occupant retention systems for use in large accessible transit vehicles,[16] Section 18 (WC18) on WTORS, Section 19 (WC19) on wheelchairs used as seats in motor vehicles, and Section 20 (WC20) on wheelchair seating systems for use in motor vehicles.[17] The focus of the discussion that follows is on WC18 and WC19, which are the main RESNA standards governing the safety of wheelchairs when used in motor vehicle transportation.

The goal of WC18 is to promote the design and use of WTORS that provide protection for forward-facing occupants in wheelchairs that is comparable to the protection afforded occupants of conventional vehicle seating. The key performance objective of the standard is to reduce the likelihood of serious and fatal injuries to occupants who are involved in frontal vehicle crashes; however, use of WTORS equipment that complies with WC18 was also expected to result in increased safety and security for occupants seated in wheelchairs during normal travel, emergency vehicle maneuvers, and other types of crashes such as vehicle rollovers and side impacts.

WC18 was created on the premise that WTORS manufacturers are not able to control the end use of their products, including the types of wheelchairs they secure and the motor vehicles in which they are installed. Accordingly, WC18 emphasizes WTORS design requirements, test procedures, and performance criteria for crashworthiness when used for all types of wheelchairs (manual and power) and for all types and sizes of motor vehicles. The standard calls for dynamically testing the securement and restraint system based on the assumption of a nominally worst-case frontal crash, creating a change in velocity from 30 to 0 mph with an average deceleration pulse of 20 *g*. The frontal impact test procedure, which is pictured in Figure 3-3, requires the use of a 185-lb rigid mass surrogate

[16] In recognition that the likelihood of a moderate-to-severe crash is low in a large accessible urban transit vehicle, the WC10 standard, which applies to wheelchair passenger spaces intended for use by rear-facing, wheelchair-seated occupants, is intended to provide a level of safety during travel for passengers seated in wheelchairs that is equivalent to passengers in transit vehicle seats or who are standing using handholds.

[17] Because wheelchair seating systems are often provided as aftermarket products, WC20 establishes design and performance requirements and related test methods to evaluate seating systems relative to their use as seats in motor vehicles independent of their installation on production wheelchair frames.

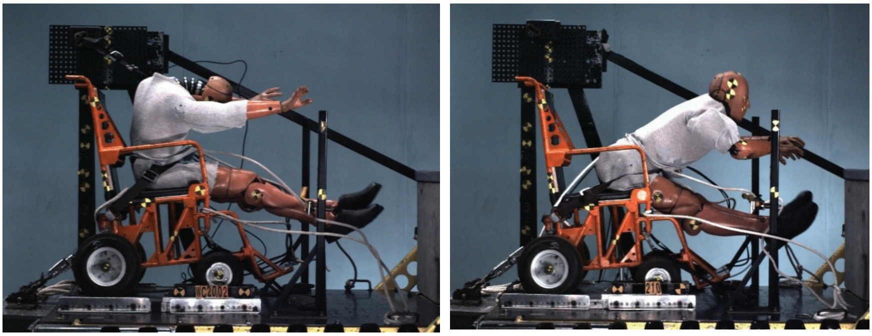

FIGURE 3-3 Peak-of-action photos for a 30-mph, 20-*g* frontal impact test of WTORS (WC18) using a 185-lb rigid surrogate wheelchair and a mid-size male ATD.
NOTE: Images show two different restraint configurations: lap/shoulder belt (left) and wheelchair-anchored lap belt (right).
SOURCE: University of Michigan Transportation Research Institute.

wheelchair occupied by a mid-size adult male ATD (approximately 170 lb) to dynamically load the wheelchair and WTORS, respectively.

Wheelchairs that have been tested for crashworthiness using WC19 test methods must include readily identifiable (by a hook symbol) tiedown strap securement points with specified slot-type geometry located near the four corners of the wheelchair. In a typical tiedown arrangement (illustrated in Chapter 2), steel securement points with slot openings are used as wheelchair attachment points and the tiedown straps terminate with steel hooks to engage with the securement points.

In recognition that transportation safety assurance is a system problem, WC19 establishes the design and performance requirements for wheelchairs that may be secured by a WC18-compliant WTORS and used as a seat during motor vehicle transportation. The standard, which applies to both manual and power wheelchairs, was established under the premise that a seat must be effectively secured so that its mass does not add to crash-generated restraint forces on the occupant and so that seat belts will effectively limit occupant movement within the vehicle during a 30-mph, 20-*g* frontal impact. It further establishes that the seating system must be designed so that it is not the source of occupant injuries, does not interfere with proper placement of belt restraints on the occupant, does not cause failures of belt restraint components during dynamic loading, and supports the occupant throughout the crash event so that belt restraints remain properly positioned on the bony regions of the body such as the pelvis and shoulder. RESNA requirements for wheelchairs used for transportation are summarized in Box 3-2.

BOX 3-2
RESNA Transportation Requirements for Wheelchairs

A wheelchair that complies with the RESNA transportation standard has the following features:

- Four permanently labeled, easily accessible securement-point brackets with specific geometry that allows for one-hand attachment of one or two tiedown hooks from tiedown-strap assemblies by a driver or caregiver reaching from one side of the wheelchair;
- A base frame and seating system that, along with the four securement points, have been successfully crash tested in a 30-mph, 20-*g* frontal impact when loaded by an appropriate-size crash test dummy with the wheelchair secured facing forward by a surrogate four-point, strap-type tiedown;
- Tiedown strap–clear paths between the securement points on the wheelchair and typical anchor points on the vehicle floor, such that tiedown straps will not be in close proximity to sharp edges (on the wheelchair) that could cause failure of webbing material when loaded in a frontal crash;
- Anchor points that enable the wheelchair occupant to use a wheelchair-anchored crashworthy pelvic/lap belt to which the lower end of a vehicle-anchored shoulder belt can be readily connected near the occupant's hip;
- A manufacturer-disclosed rating of poor, acceptable, good, or excellent for the wheelchair's accommodation of properly using and positioning a vehicle-anchored belt restraint;
- A measure of wheelchair lateral stability (determined with a lateral tip test) when secured facing forward by a four-point, strap-type tiedown;
- Reduction of sharp points and edges that could damage belt restraints or injure passengers; and
- Provision for crashworthy retention of wheelchair batteries and motors, and use of gel-cell or sealed batteries to eliminate the potential for acid spills.

While most wheelchairs occupied by passengers are secured using strap-type securement systems, WC18 and WC19 also include design and performance criteria for docking systems. In addition, the standards include the requirements for the Universal Docking Interface Geometry, which is intended to allow wheelchair stations of public vehicles to secure many different types of wheelchairs in high-severity crashes while allowing for independent use.

Using the same 30-mph, 20-*g* frontal impact dynamic force test conditions specified in WC18, WC19 requires that a wheelchair perform effectively in a moderate-to-severe frontal crash. The performance criteria are intended to ensure that the structural components of the wheelchair securement points do not fail, the points do not deform in a manner that prevents manual disengagement of the tiedown hook, the wheelchair remains in an upright position, and the occupant remains in a seated posture in the wheelchair seat. The dynamic loading reveals the strength of the wheelchair frame, belts, and securement points, as well as retention of wheelchair components, including the battery.

Another aim of WC19 is to improve the accessibility and ease of attaching the end fittings of straps and to remove deterrents to the proper and effective use and positioning of belt restraints. Consequently, WC19 addresses the problem of wheelchair occupants not being restrained properly due to wheelchair interference with the positioning of the WTORS belts or the wheelchair occupant wanting to avoid intrusion into personal space by drivers and caregivers assisting with restraint positioning. WC19's solution is that wheelchair manufacturers offer the option of a dynamically tested wheelchair-anchored pelvic belt that can be fastened by the occupant or another person such as a caregiver. While WC19-compliant wheelchairs do not necessarily come equipped with the pelvic belt, the belts must be offered as an option to purchasers or consumers, and the wheelchairs are crash tested with the prescribed belt. RESNA has developed a label that can be applied to wheelchairs that comply with WC19, as shown in Figure 3-4.[18]

In addition to developing standards applicable for wheelchairs when used as seats in motor vehicles, RESNA develops standards for wheelchairs that apply to everyday usage. WC16, for instance, provides the requirements and test methods for the ignition of upholstered parts for wheelchairs and seating systems. This standard, as noted below, can have relevance when

FIGURE 3-4 RESNA WC19-compliant label and its application on a power wheelchair.
SOURCES: RESNA and the University of Michigan Transportation Research Institute.

[18] WC19 also allows an integrated seat and lap belt, with anchored shoulder strap.

considering FAA's concern about passenger seat cabin interior flammability. Because all wheelchairs must meet WC16 and other standards for everyday usage, wheelchairs labeled as compliant with WC19 will also comply with WC16, and WC19 includes this flammability testing requirement.

Before turning to a review of FAA's safety requirements, differences in the crash environments of airline and motor vehicle transportation are presented in Box 3-3. These differences are important because they underlie key variations in the crash performance test criteria of FAA, with respect to

BOX 3-3
Differences Between Motor Vehicle and Airplane Crashes

Passenger car crashes and survivable commercial passenger jet airplane crashes can differ in several ways. In the United States in 2018, there were nearly 2 million passenger car crashes in which one or more persons died or was injured (including pedestrians in some cases).[a] More than 80 percent of these crashes involved vehicles colliding with one another, about 8 percent involved a vehicle striking a fixed object (e.g., guardrail, pole), about 7 percent involved collisions with nonfixed objects (e.g., parked vehicles), and the remainder did not involve collisions, such as rollovers. Crashes in which the front of the vehicle was the initial point of contact accounted for about half of crashes involving injuries but nearly two-thirds of fatal crashes.[b] Ensuring the safety of vehicle occupants in frontal collisions is therefore a critical goal of efforts to improve vehicle crashworthiness.

Compared with motor vehicle crashes, injuries and fatalities from crashes or other emergencies involving commercial passenger airplanes are exceedingly rare. The main concern for the safety of passenger seating in airplanes is with survivable incidents. Most of these survivable incidents occur during attempted landings or takeoffs. Landing crashes can occur when the airplane lands short of the runway, overruns the runway, leaves the runway to the side, or lands someplace other than the runway.[c] Takeoff crashes, which are not as frequent as landing crashes, can occur when the airplane leaves the runway, perhaps to the side in strong wind conditions.[d] Accordingly, crash protection of airplane occupants must take into account vertical forces.

Another notable difference between motor vehicle and passenger jet airplane crashes is that the speed of the airplane on takeoff or landing is typically in the range of 150 to 200 mph, much faster than the speed of a passenger motor vehicle. In addition, in an airplane crash, a large number of passengers may need to be evacuated while the occupants of a motor vehicle are far fewer.

---

[a] See NHTSA (National Highway Traffic Safety Administration). n.d. "Traffic Safety Facts Annual Report Tables: Table 42." https://cdan.dot.gov/tsftables/tsfar.htm#.

[b] See NHTSA. n.d. "Traffic Safety Facts Annual Report Tables: Table 43." https://cdan.dot.gov/tsftables/tsfar.htm.

[c] See, for example, the following National Transportation Safety Board (NTSB) Aircraft Accident Reports (AAR): AAR-16-02, AAR-12-01, AAR-07-06, AAR-01-02, AAR-97-03, AAR-97-01, and AAR-96-05. https://huntlibrary.erau.edu/collections/aerospace-and-aviation-reports/ntsb/aircraft-accident-reports.

[d] See, for example, NTSB AAR-10-04. https://libraryonline.erau.edu/online-full-text/ntsb/aircraft-accident-reports/AAR10-04.pdf.

airplane seats and cabins, and of RESNA, with respect to wheelchairs used as seats in motor vehicles.

COMPARISON OF FAA AND RESNA CRASHWORTHINESS CRITERIA

As is clear from the discussion above, most FAA Part 25 regulations are performance based; for instance, § 25.561 and § 25.562 specify the forces or accelerations that a seating system must be capable of withstanding without excessive deformation (i.e., to the point where the seat could impede evacuation), but they contain limited direction on how the seat or its structure should be designed. To facilitate compliance with these performance specifications, FAA provides guidance in Advisory Circulars (ACs) on acceptable testing methods. The primary guidance for the Part 25 crashworthiness requirements is AC 25-17A, *Transport Aircraft Cabin Interiors Handbook*. The AC guidelines on test methods are not mandatory but they are generally followed by airplane manufacturers, modifiers, and type certification engineers because the cost, time, and complexity of demonstrating compliance through other testing methods can be prohibitive. In this regard, none of the performance and testing criteria specified by the RESNA WC18 and WC19 standards for demonstrating the crashworthiness of WTORS and wheelchairs when used as seats in a motor vehicle can be said to align completely with the FAA Part 25 testing and performance criteria. The differences, of course, are to be expected because the conditions of, and concerns associated with, the airplane and motor vehicle crash environments differ as discussed in Box 3-3.

With respect to the static testing prescribed by FAA § 25.561, neither WC18 nor WC19 specify that the wheelchair and WTORS complete such static load testing in six directions. Likewise, the RESNA standards do not call for testing under both a vertical dynamic loading condition (14 *g*) and a longitudinal dynamic loading condition (16 *g*) as specified by FAA § 25.562 and its criteria for the protection of the seat occupant from head, spinal column, and leg injuries. However, the WC18 and WC19 standards require that a wheelchair and WTORS perform effectively in a frontal crash event creating an average deceleration pulse of 20 *g*, which bears resemblance to FAA's longitudinal testing condition inasmuch as both tests are for impacts on a horizontal vector. The RESNA dynamic test is intended to demonstrate that the structural components of the wheelchair do not completely fail, the securement points do not deform in a manner that prevents manual disengagement, and the wheelchair remains in an upright position with the occupant remaining in a seated posture. In this regard, the RESNA standards test for the limits of total excursion to minimize the occupant's impact with stationary objects within a motor vehicle during a crash, but they do not specify occupant injury criteria in the same manner as § 25.562.[19] The WC18 and WC19 standards assume that sufficient clear space will be provided in front of the wheelchair so there is less risk of secondary head and leg injuries to a properly belted occupant. Thus, whereas head, torso, and leg injury measures are often collected from the ATD during WTORS and wheelchair testing, they are not used specifically for assessing compliance with WC18 and WC19.

How well a WC19-compliant wheelchair and its securement system would perform if tested according to FAA's two dynamic loading conditions is unclear in the absence of comprehensive testing data for a range of wheelchairs and securement system designs suited to airplanes.[20] Because WC18 and WC19 do not require a dynamic loading test with a predominantly vertical direction, it is not known how WC19-compliant wheelchairs would perform under this 24-mph, 14-*g* crash condition, and whether the occupant would be afforded satisfactory protection from spinal injury, as defined by FAA injury criteria. One could surmise, however, that a wheelchair that performs effectively in the 30-mph, 20-*g* WC19 frontal crash test could meet FAA's 16-*g* longitudinal impact test, perhaps with modest design changes. Both tests follow the horizontal axis but FAA's test requires the seat to be yawed 10 degrees either right or left (with the wings level), whereas WC19 testing follows the vehicle floor's horizontal axis. The effect that this yaw condition would have on wheelchair performance, as well as § 25.562's requirement for testing with misaligned seat tracks, would need to be assessed. However, valid testing of wheelchair crashworthiness according to FAA criteria would also require the use of a securement system design that could reasonably be expected to be installed in an airplane cabin. WTORS designed for motor vehicle use might suffice, but one would expect systems to be developed that are optimized to perform well under FAA test conditions. Significantly, however, FAA's criteria for HIC and leg injuries may not be relevant to a wheelchair securement evaluation, under the premise that the wheelchair will be secured in a location with sufficient front and rear clearance so that the occupant of the wheelchair and passengers behind it do not come into contact with hard structures during a high-*g* event. The size of such a clear space footprint is estimated below and considered further in Chapter 4.

As with the dynamic testing criteria, the extent to which RESNA's WC16 standard for resistance to flammability by a wheelchair's upholstered surfaces would satisfy FAA's requirements (in § 25.853) that govern the self-extinguishing capability and flammability of airplane seating systems is difficult to gauge based on side-by-side comparisons of the two sets of

[19] And, as noted earlier, for § 25.785's HIC for safety belt performance.

[20] In Chapter 5, some recent, limited testing of aspects of this capability is discussed.

requirements but without testing or other evaluation data. All WC19-compliant wheelchairs must meet WC16, which specifies performance tests for demonstrating the resistance of the wheelchair seating and upholstery materials to ignition by a cigarette and match. While the WC16 testing criteria may provide an indication of the ignition resistance behavior of the wheelchair as a whole, the criteria do not apply to all of the materials that may be used on a fully outfitted, finished wheelchair, including any added or modified cushions for occupant posture, stability, and pressure relief. If such cushions are viewed as an extension of the passenger's clothing (as they are in WC16), the § 25.853 testing criteria might not apply, but that would be a determination for FAA.

With regard to FAA § 25.785's requirement for seats having energy absorbing arm, shoulder, back, and head rests, WC19 does not contain comparable standards for wheelchairs. There is likewise no WC19 equivalent to FAA § 25.785's requirement for the padding of protruding objects, the benefits of which would presumably be limited to the occupant of the wheelchair if it is properly isolated in the designated securement zone. With regard to FAA § 25.789's requirement for the retention of items of mass, the WC19 standard requires that rigid components, equipment, and accessories in excess of 150 *g* do not become detached from the wheelchair during the 20-*g* frontal impact test. Additionally, the standard requires that wheelchair components that may contact the wheelchair occupant or other nearby occupants do not fragment or separate in a manner that produces sharp edges with a radius of less than 2 mm and that wheelchair batteries stay within the wheelchair footprint, remain attached or tethered to the battery compartment, and do not enter the wheelchair user's space during the impact event. Nevertheless, because the WC19 dynamic testing criteria, including setup and durations, differ from the dynamic testing criteria in the FAA requirements, it is not possible to make definitive determinations about the likelihood of wheelchair compliance with the latter.

As noted above, one would expect that any testing of a wheelchair according to FAA requirements would use a securement system designed to interface effectively with a wide range of wheelchairs but that is also optimized for the airplane operating and crash environments. The fact that WTORS used in motor vehicles are designed to meet WC18's 20-*g* dynamic frontal crash test suggests that an effective airplane-specific securement system could be designed, assuming there is sufficient airplane structural strength for its attachments. Like WTORS used in motor vehicles, an airplane-specific securement system would need to be capable of securing a wide range of personal wheelchairs, and thus WC19's requirement for wheelchairs to have four-point securement brackets would likely remain essential to the design of any initial airplane securement system. Such a system could conceivably be designed with a cabin-anchored occupant restraint system that includes both pelvic and upper torso safety belts; however, if such an installation is not possible, WC19 also prescribes a pelvic belt that can be anchored to the wheelchair. As described earlier, WC19-compliant chairs have been crash tested with a wheelchair-anchored pelvic belt, and pelvic belts without shoulder belts are the norm for conventional airplane passenger seats.

Although developed for WTORS used in a motor vehicle securement space, WC18 nevertheless contains helpful guidance for estimating the front and rear clear zones required for an occupied forward-facing wheelchair if secured in an airplane cabin. The desired length of this zone is specified in WC18 to be 950 mm (~36 in.) forward (measured from the front of the occupant's head when restrained with a pelvic belt) and 500 mm (~20 in.) rearward (measured from the rear of the occupant's head). This length is established to provide ample clear space to protect the occupant from head and leg injury, while also serving the purpose of providing sufficient room for maneuvering into the securement space, providing footrest and toe space, and enabling wheelchair functionality such as tilting and reclining for occupant posture support and pressure relief. The total distance between the outer limits of the front and rear of the clear-space zone would measure about 60 in., which for a 30-in. wheelchair would create a 30- × 60-in. footprint for the securement space.[21] Presumably, an airplane-specific securement system could be designed to fit fully within this footprint with sufficient room to secure and release the wheelchair.

The analyses and testing that would be required to develop an airplane-specific securement system and any associated standards is outside the scope of this study. Nevertheless, an important question is whether the airplane structure in the securement area would need to be strengthened and otherwise modified to distribute wheelchair static and dynamic loads to primary structure, particularly for occupied power wheelchairs, which are heavier than manual wheelchairs. Because WC18 is intended for WTORS installed in a range of motor vehicles, the relevance of its requirements for anchorage and tiedown point locations may be limited for defining the needs of an in-cabin system. However, in the case of conventional airplane seat assemblies, they are usually attached to seat tracks running fore-aft that are connected to cross beams extending widthwise under the floor. For a narrow-body, mid-size airplane with double-place or triple-place standard seat assemblies, the provision of sufficient clear space for a 30- × 60-in. wheelchair securement area could be provided by removing two assemblies, given that the distance between seats (seat pitch) tends to range from about 28 to 42 in.

[21] As will be discussed in Chapter 4, this wheelchair securement footprint is consistent with guidelines developed for the Americans with Disabilities Act. The 30- × 60-in. space should allow enough room for maneuvering into the space and securing four-point straps.

The removal of these assemblies would also free up floor seat track attachment points, which would be needed to provide structural load bearing capacity for a secured wheelchair and securement system.

The occupied weight of the wheelchair relevant to the occupied weight of the displaced seat assemblies is therefore an important consideration for assessing whether the removal of two seat assemblies for a securement zone would provide sufficient seat track connections for load bearing capacity. As established in Chapter 2, an occupied power wheelchair could weigh as much as 850 lb, including a 450-lb wheelchair (with battery) and an occupant weighing up to 400 lb.[22] When fully occupied with passengers, two triple-place seat assemblies are estimated to weigh about 1,200 lb (see Box 3-4); thus, presumably an airplane's seats tracks and support structures would be designed to distribute and otherwise safely accommodate the loads imparted by at least that much weight, which is about 40 percent more than the estimated maximum weight of an occupied power wheelchair. Also, as discussed in Chapter 2, there are systems in common use by airlines, including high-strength and lightweight aluminum pallets, to distribute seat assembly loads across the seat tracks, and presumably similar systems could be engineered and used to distribute the weight of an occupied wheelchair across the seat tracks freed up by two displaced seat assemblies. While it is conceivable that this needed space and structural support could be obtained by removing fewer seats, the assumption that two rows of seats will be displaced is maintained in this chapter.[23]

Because the location and configuration of seats, galleys, closets, and other floor-mounted components that impart loads can differ across airplane types and interior layouts, it is not possible in this study to make definitive determinations about whether modifications to a given airplane's floor and primary structure would be required to accommodate a wheelchair securement system for any given securement location in a cabin. However, in light of the weight calculations above, and knowing that load distribution systems such as pallets are available and in common use for passenger seating, the ability to distribute wheelchair static and dynamic loads would appear to be possible within the norms of interior design and engineering. Indeed, when questioned during briefings to the committee, representatives of airlines and interior component manufacturers expressed confidence that the weight of an occupied wheelchair could be appropriately distributed through commonly used load distribution means such as seat pallets. Of course, this is a

[22] A wheelchair manufacturer briefing the committee indicated that the heaviest fully configured power wheelchairs with batteries can weigh as much as 450 lb and accommodate a 400-lb occupant (Mark Greig, vice president, R&D, Sunrise Medical, August 11, 2020).

[23] Typical row seating layouts for airplane models in the U.S. commercial transport fleet (as of December 2019) are included in the Chapter 4 addendum.

BOX 3-4
Estimating Passenger Airplane Seat Weights and Imparted Loads

While specific information about airplane seating and other cabin interior products is usually proprietary, estimates of passenger airplane seat assembly weights can be made based on public information provided by seat manufacturers and confirmed by committee members with expertise in airplane interior design. For instance, in an August 2020 *Aviation Week* article, Mark Hiller, chief executive officer of Recaro Aircraft Seating, one of the three largest commercial aircraft passenger seat suppliers, reported that an economy seat typically weighs 18 to 33 lb.[a] If one assumes that this range represents a reasonable approximation of typical seat assembly weights, then a triple-seat assembly would weigh between 54 and 99 lb. As noted in this chapter, seats are loaded for FAA testing with a 170-lb dummy in each seat. If 170 lb is considered to be representative of average passenger weight, a fully occupied three-seat assembly would weigh between 564 and 609 lb, and two rows of seats would equate to between 1,128 and 1,218 lb. This range is comparable to the figures used by FAA in the 2005 rulemaking to extend requirements for dynamically tested (16 ***g***) seats to more airplanes. In that rulemaking, FAA estimated that a triple-seat assembly weighs 100 lb and that each occupant weighs 170 lb, resulting in a total assembly weight of 610 lb (or two assemblies weighing 1,220 lb).[b]

[a] See Dubois, T. 2020. "Aircraft Passenger Seat Design Gets Smarter." *Aviation Week*, August 14. https://aviationweek.com/mro/interiors-connectivity/aircraft-passenger-seat-design-gets-smarter.

[b] FAA. 2005. "Improved Seats in Air Carrier Transport Category Airplanes: Final Rule." *Federal Register* 70, no. 186: 56543.

technical matter that would require more thorough engineering analysis to reach definitive conclusions about floor structural capacity and the viability of using typical systems for load distribution.[24]

[24] In public information-gathering sessions, the committee heard from engineering and other experts from individual airlines, an airplane manufacturer, and airplane seat and cabin interior designers. Hans-Gerhard Giesa and Ralf Schliwa of Airbus stated that there would likely be "no need for changes in aircraft structure" to accommodate dynamic loads. Raki Islam of SAFRAN Seats and SAFRAN stated, "It should not be difficult to assign an area of the aircraft that is safe … considering track design, floor strength." Glenn Johnson of Collins Aerospace stated that it may be "difficult but not impossible" to design concepts to handle floor loading. Giesa, Islam, and Johnson referred to the installation of a pallet in the wheelchair securement area as a way to effectively distribute wheelchair loads to the aircraft; Gregg Fesenmyer of American Airlines also stated that structural loading is a solvable problem. Bryan Parker of Southwest Airlines said that restraining a wheelchair would require adding a plate or pallet to the securement area to transfer dynamic loads, and dynamic testing likely would be needed to certify the wheelchair securement and pallet system together with the wheelchair.

Finally, the issue of power wheelchair batteries and any hazards that they may create in the cabin will warrant attention, both with regard to a fire hazard and retention of items of mass during an emergency landing or crash. With regard to a fire hazard, most power wheelchairs use lead-acid sealed batteries but other battery types are in use, including nickel metal hydride and lithium ion batteries. The stowage of wheelchairs with these batteries is already allowed by FAA,[25] which advises that non-spillable and sealed batteries remain installed on the wheelchair if it is securely attached and its housing and terminals are protected from damage and short circuit.[26,27] RESNA WC25 contains performance and test criteria and product labeling for wheelchair batteries, as shown in Figure 3-5. The label can be used as a means of permitting an airline to verify compliance with FAA requirements applicable to battery-powered wheelchairs, whether stowed in baggage holds or secured in the cabin.

With regard to batteries being sufficiently secured and retained during an airplane crash or emergency landing, WC19 testing verifies that the

FIGURE 3-5 Label indicating compatibility of battery with RESNA WC25 standards.
SOURCE: RESNA.

[25] 45 CFR 175.10.

[26] Lithium polymer batteries are growing in popularity, but suitable sizes for power wheelchair applications can conflict with FAA requirements forbidding lithium batteries with more than 100 watt hours.

[27] Industry standards developed by the International Air Transport Association (IATA, in partnership with airlines and the battery industry) address the issues of battery engagement, power activation, and seating function availability when wheelchairs are in the cabin. See IATA. 2021. *Battery Powered Wheelchair and Mobility Aid Guidance Document*. https://www.iata.org/contentassets/6fea26dd84d24b26a7a1fd5788561d6e/mobility-aid-guidance-document.pdf.

wheelchair's battery does not become dislodged in a frontal motor vehicle crash. As noted above, WC19's 20-*g* frontal crash test bears a resemblance to FAA's 16-*g* longitudinal test for airplane seats. Given the higher *g* loading in the WC19 test, this suggests that battery securement might not be an issue at least with respect to crash impacts along the horizontal vector, or potentially one that is minor and could be solved with some modest engineering attention.

SUMMARY OF KEY POINTS

FAA, which establishes safety and certification standards for passenger airplanes, has not established safety standards that apply to wheelchair securement systems or wheelchairs used as seats in airplanes. The main body of FAA regulations that applies to the passenger compartments of airplanes is Title 14 Part 25 of the Code of Federal Regulations (14 CFR 25). These regulations govern airplane seat and cabin interior crashworthiness in a survivable crash or emergency event when the cabin occupants are subjected to forces within human tolerances and the structural integrity of the passenger space remains intact such that the occupants can rapidly evacuate.

Voluntary industry standards have been established for the safety of people seated in wheelchairs during motor vehicle transportation. **RESNA standards WC18 and WC19 contain performance criteria, test methods, and product labeling for WTORS and wheelchairs used in motor vehicles as seats, respectively. The WC19 standard assures that all compliant wheelchairs will have the four designated securement points with specified opening geometry for connecting tiedown straps.** The standards require wheelchairs to be tested under dynamic loading that can occur in a frontal motor vehicle crash, specifying that the secured wheelchair be subjected to a 30-mph, 20-*g* frontal impact test. The tests demonstrate that the structural components of the wheelchair do not fail, the securement points do not deform in a manner that prevents manual disengagement, and the wheelchair remains in an upright position with the occupant in an upright seated posture at the end of the crash event.

There has been no systematic evaluation of wheelchairs and their securement systems regarding their ability to demonstrate satisfactory performance with respect to FAA's crashworthiness criteria for airplane seats, including criteria intended to protect airplane occupants from injury during survivable crash impacts and emergency landings, resist post-crash fire, and prevent items of mass from becoming loose to create a hazard in the cabin or impede evacuations. The FAA crashworthiness regulations require that airplane seating systems and their occupant restraints perform effectively when subjected to testing with multi-directional static and dynamic loadings. The requirements seek to ensure that the seating systems remain attached to the airplane structure, do not deform to impede evacuation, and protect the occupant from serious injuries. They contain specific criteria for head, spinal, and leg injuries when tested according to the dynamic loading conditions intended to simulate airplane crash scenarios. The dynamic tests also demonstrate that items of mass in the seating system will not break loose to become a hazard in the cabin. Additional FAA requirements for seats and their coverings are intended to reduce the potential for fire by specifying performance criteria for self-extinguishment and fire resistance.

Crash protection criteria specified by WC19 are not fully aligned with FAA's crashworthiness criteria for airplane seating systems and cabin interiors, as would be expected because the conditions of, and concerns associated with, the airplane and motor vehicle crash environments differ. **Significantly, there are no requirements in WC19 that are comparable to FAA's multi-directional dynamic force testing of a passenger seat intended to simulate airplane crash conditions and to measure satisfactory protection of the seat's occupant from injury. WC19's lack of a vertical direction crash test with associated spinal injury criteria is notable because with the information available it is not possible to know how WC19-compliant wheelchairs would perform when subject to this test intended to simulate a crash in airplane descent. However, when compared to FAA's longitudinal crash test on a horizontal axis and requiring a peak 16-*g* loading, WC19's average 20-*g* frontal crash test loading may be more exacting than FAA's peak 16-*g* longitudinal test, while the lack of head and leg injury criteria in the WC19 test may not be pertinent when the wheelchair is secured in a cabin area and has sufficient clearance from structure and objects to prevent such injuries.** All WC19-compliant wheelchairs must meet RESNA standard WC16 for fire resistance; however, **FAA fire resistance criteria for passenger seats and cabins are substantially different such that comparative assessments are not possible without testing and evaluation data.**

An important advantage of the RESNA standards is that they establish a baseline minimum level of crash and safety performance that many commonly used wheelchairs comply with today and that more wheelchairs can be designed to comply with in the future. If the RESNA standards did not exist to provide this common baseline level of safety performance that can be evaluated according to the FAA testing criteria, blanket testing might be required for all individual models of wheelchairs, each having an unknown and potentially wide range of crash performance capabilities. **While WC19 compliance does not indicate that a secured wheelchair would satisfy all crashworthiness criteria as required by FAA, it does provide assurance that secured wheelchairs would possess a common set of safety performance characteristics as well as standardized features for securement and occupant restraint. The WC19 standard would also provide a defined platform for conducting safety evaluations of wheelchairs used as seats in airplanes,**

including evaluations conducted for the purpose of strengthening their safety performance in an airplane environment and for supporting decisions by FAA about needed crashworthiness demonstration.

Guidance in the WC18 standard for forward-facing wheelchair securements in a motor vehicle suggests that a 30- × 60-in. securement zone would be needed for a wheelchair used as a seat in an airplane to provide sufficient clear space to protect the occupant from crash injuries sustained from striking objects; maneuver into and from the securement space; and enable tilting, reclining, and other necessary wheelchair adjustments.

The wheelchair securement area would require sufficient airplane structural support to distribute the load imparted by an occupied power wheelchair. **The removal of two successive rows of airplane seats would accommodate a 30- × 60-in. securement zone and free up seat tracks for attachments to structural support sufficient for the secured wheelchair when occupied without necessarily requiring any modifications to airplane structure and by using common methods for seat load distribution.**

4

Airplane Space Considerations

Airplane door openings and cabin spaces will need to be able to accommodate a range of wheelchair sizes and dimensions if reasonably large numbers of people are going to be able to fly while seated in their personal wheelchairs. Airplanes will need to have sufficient doorway and aisle clearances and clear spaces for wheelchair ingress and egress and maneuvering to and from the designated securement location. Cabins will also need sufficient room in the securement location for essential wheelchair functionality and protective space for the occupant and surrounding passengers to avoid injury in the event of a survivable crash impact, emergency landing, or severe turbulence. These spaces will need to exist on many airplanes in scheduled service—but particularly in high-demand markets—for people who are nonambulatory with significant disabilities to access flights to and from places they want to go. This chapter estimates these space requirements and considers them in relation to the doorways, aisles, and other features of the cabin interiors of existing airplanes in the U.S. airline fleet.

As a reference for many of the estimates, the 2010 Americans with Disabilities Act (ADA) Standards for Accessible Design[1] and the ADA Accessibility Guidelines (ADAAG) on the standards are consulted along with wheelchair size testing and sampling data and other relevant technical literature discussed in Chapter 2. Although the ADA does not apply to airline service, ADAAG's clearance and clear space requirements were developed to ensure that buildings and other facilities can accommodate the dimensions

[1] See U.S. Department of Justice. 2010. *2010 ADA Standards for Accessible Design*. https://www.ada.gov/regs2010/2010ADAStandards/2010ADAStandards_prt.pdf.

and operating capabilities of a wide range of personal wheelchairs.[2] The total space required for an in-cabin securement area will depend on the dimensions of the wheelchair plus any additional room needed for the design and operation of the securement system, essential wheelchair seat functionality, and protection of the occupant and nearby passengers from objects and structure that can cause injury. To have sufficient clear space for injury protection, the dimensions of a cabin securement area were estimated in Chapter 3 to be 30 × 60 in. Also in Chapter 3, it was estimated that if two successive rows of seats are removed from a typical narrow-body airplane, then enough securement space would be provided along with sufficient floor structural support to distribute the load impact by an occupied power wheelchair. While it is possible that this needed space and structural support could be obtained by removing fewer seats—which would be desirable—the assumption that two rows will be displaced is maintained in this chapter given the study's aforementioned interest in determining system feasibility and not optimality.

After estimating the space requirements for maneuvering and securing a wheelchair inside the cabin, these estimations are considered in relation to the door, aisle, and seating area dimensions of airplanes in the existing fleet, taking into account interior features such as closets, galleys, and lavatories. Because data on the dimensions of boarding doors are available for a wide range of airplane models, they can be compared to the minimum clearances that ADAAG, other relevant technical literature, and wheelchair test data indicate would be needed for most wheelchairs to enter and exit the cabin. In the case of aisle dimensions, the minimum width required by the Federal Aviation Administration (FAA) for evacuation is used as the reference because it is the norm for many cabin aisles. Together, these door and aisle dimensions are likely to have a major influence on where a wheelchair securement area could be located in the cabin. Indeed, they suggest that a prospective location would be in the cabin seating area adjacent to the left forward door, which is the largest and most commonly used door for passenger boarding and deplaning on most airplanes at most U.S. airports. This location would enable access to sufficient space for securement with minimal changes to aisle widths.[3] While other cabin locations may be preferable

[2] Some portion of the wheelchair user population likely will not be accommodated with the dimensions in ADAAG's standards used for this preliminary analysis. See Steinfeld, E., V. Paquet, C. D'Souza, C. Joseph, and J. Maisel. 2010. *Anthropometry of Wheeled Mobility Project: Final Report.* Buffalo, NY: Center for Inclusive Design and Environmental Access. As noted in Chapter 2, further analyses would consider the extent to which these dimensions account for the clearance needs of all people when using their wheelchairs for air travel.

[3] In briefing the study committee, a representative of Southwest Airlines observed that a typical Boeing 737 configuration can best accommodate an occupied wheelchair in the forward portion of the aircraft (Bryan Parker, manager of interior engineering, Southwest Airlines, August 20, 2020).

or even optimal under some circumstances, depending on specific airplane interior layouts and other considerations, a front cabin location is assumed for this chapter's limited purpose of assessing space-related technical issues and implications related to system feasibility.

To help illustrate and reach some conclusions about how a front cabin securement location could be accommodated space-wise, the chapter takes a closer look at the interior of a common airplane in the airline fleet. The ADAAG-estimated clearance and clear space requirements are superimposed on the layout of a commonly configured interior of a Boeing 737 (737) that usually boards and deplanes through the left forward door. A rationale for using a 737 for this purpose is that its cabin width is comparable to that of the Airbus A320 (A320), which likewise usually boards and deplanes through the left forward door. Significantly, these two airplane families are by far the most common in the U.S. airline fleet and the most heavily used for passenger travel in hundreds of high- and moderate-demand domestic markets.

Depictions of the interior changes that would be needed to make room for a wheelchair securement system in the front cabin of this illustrative 737 are followed by a description of the scope of installation work entailed, including approximations of the cost incurred for the modifications when mainly considering material and labor expenses. Estimates of installation costs are given because they provide an indication of the technical complexity or technical effort required, which is helpful for understanding technical feasibility. Of course, a full accounting of costs from an airline economic standpoint would include the revenue implications of airplanes operating with securement systems installed, which is beyond the scope of this study.

The chapter ends with a summary of key points to provide a basis for the summary assessment of the relevant technical issues, challenges, and uncertainties associated with an in-cabin wheelchair securement system concept in Chapter 5.

SPACE FOR BOARDING, MANEUVERING, AND SECUREMENT

There are four main space considerations for enabling a person to use a wheelchair as a seat in an airplane: (1) doorway space for entry to and egress from the airplane, (2) aisle space to turn the wheelchair between the entryway and cabin aisle, (3) aisle space for the wheelchair to be maneuvered into and out of the securement location, and (4) room in the cabin seating area for an appropriately sized securement area.

For reasons explained above, this chapter assumes that a securement location will be designated in the front cabin near the left forward boarding door. Figure 4-1a depicts a passenger backing through this door for entry to the airplane and exiting through the same door in a forward direction. A power wheelchair is shown because its size and operation would generally require more space than a manual wheelchair. Nevertheless, both types of wheelchairs are accounted for in the ADAAG-referenced specifications for clearance and clear space. Backing through a doorway will be a complex maneuver for many users of power wheelchairs, and therefore assistance may be required. However, by backing through the forward door, the wheelchair may be more easily maneuvered into the securement area for securement in a front-facing direction, which is consistent with the direction of seating in the vast majority of airline cabins. As will be discussed below, however, an ample-sized securement location that is made possible by the removal of two successive rows of seats may enable the occupant of the wheelchair to enter the airplane facing forward and then have sufficient pivot space to reorient the wheelchair for a forward-facing securement.

Once through the door, the passenger is shown in Figure 4-1b maneuvering the wheelchair through a 90-degree turn between the entryway and main cabin aisle. Figure 4-1c depicts the passenger moving the wheelchair laterally between the aisle and securement zone, and Figure 4-ld shows the wheelchair secured for flight.

Having identified these occupied wheelchair movements, it is possible to estimate the room required in the cabin to enable them by referencing specifications for clearances and clear spaces. The ADAAG specifications assume that a wheelchair's maximum width is no more than 30 in. (including armrests), and maximum length is no more than 48 in.[4] As discussed in Chapter 2, testing data and other technical literature indicate that a large majority of wheelchairs have wheelbases of 26 in. or less. Measurements of 193 power wheelchair models, as cited in Chapter 2, show that 96 percent have a maximum width of 30 in. or less[5] and 97 percent have a maximum length of 48 in. or less.[6] The same measurement data indicate that in the vast majority of cases, wheelchair models with a maximum width of 30 in. have a wheelbase width of 26 in. or less.[7]

[4] ADAAG specifications are based in part on wheelchair manufacturer tests; the *2010 ADA Standards for Accessible Design*—which includes ADAAG—combined with the testing results for wheelchair models per Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) WC-1:2019 Section 5 provide clear and harmonized guidance on spatial requirements for wheelchair use.

[5] Ninety-nine percent of all tested models were found to be less than 32 in. wide. The wheelchairs that exceed 30 in. in width represent wheelchairs primarily designed for occupants weighing more than 300 lb.

[6] One hundred percent of all tested models of power wheelchairs were found to be less than 51.5 in. long.

[7] These measurements were available for 131 of the 193 models tested. Of those 131 models, only 5 (<4 percent) have a wheelbase width in excess of 26 in. Additional technical literature supports that the majority of wheelchair bases are 26 in. or less. See Steinfeld, E., V. Paquet, C. D'Souza, C. Joseph, and J. Maisel. 2010. *Anthropometry of Wheeled Mobility Project: Final Report*. Buffalo, NY: Center for Inclusive Design and Environmental Access.

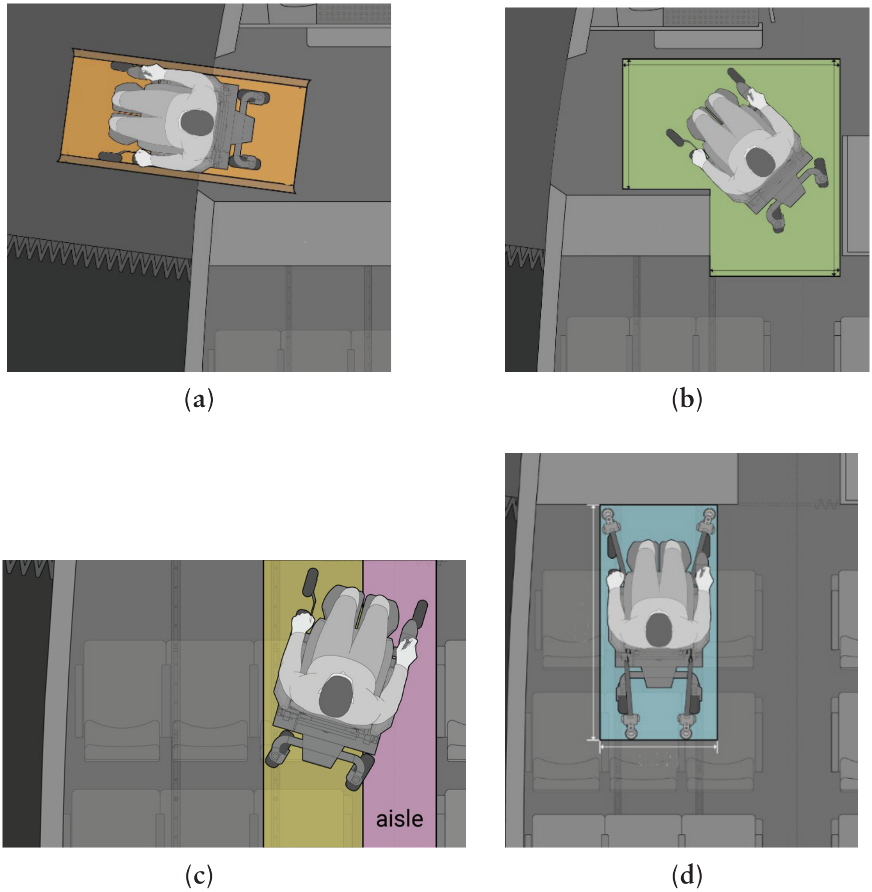

FIGURE 4-1 Wheelchair maneuvers required to access a securement location at the front of the cabin near the forward boarding door: (a) maneuvering through the left forward boarding doorway (gold area indicates the space required for the wheelchair to maneuver); (b) turning between the doorway and main aisle of the passenger compartment (green indicates the space required to perform this maneuver); (c) maneuvering between the main aisle and securement area (yellow indicates the additional space required for this maneuver beyond the aisle); and (d) positioned in a securement location (blue indicates the securement space).

In the sections that follow, these wheelchair dimensions and clear space specifications required for the maneuvers shown in Figure 4-1 are compared to the dimensions of doorways, aisles, and other cabin interior spaces of passenger airplanes. The comparisons can be complicated because different airplane families (e.g., B737, A320), airplane models within families (e.g., B737-600, -700, -800), and individual airplanes differ in their interior layouts, dimensions, and features. However, cabin doorway dimensions, as well as overall cabin interior dimensions such as interior cabin width and height, tend to be consistent across all models in an airplane family. Likewise, because FAA requires a minimum aisle width for evacuations, this width tends to be common across many airplanes, especially in the main (economy) cabin of the narrow-body (single-aisle) airplanes that account for the vast majority of domestic airline service. There is much more heterogeneity, however, in other cabin interior dimensions, layouts, and features, both across models in a family and within a model, because airlines establish their own interior specifications. Even within an individual airline's sub-fleet of a given airplane model, the interiors of the airplanes may differ. For example, an airline may operate A320s purchased or leased from multiple sources and thus have airplanes of the same model with many interior configurations.

Doorway Clearances

The number, size, shape, and location of doorways to the cabin of an airplane will vary by airplane family and be influenced by factors such as the size of the airplane, certified maximum passenger capacity, and regulations governing evacuation. In general, the forward left door, usually referred to as the primary boarding door, is the largest on the airplane. Its shape, like that of other cabin doors, includes rounded corners to alleviate structural stress concentrations. The doorway opening will also have intrusions from hinges, latches, and other hardware and design features. This variability means that doorway clearances need to be measured at multiple places.

Figure 4-2 shows the following two doorway clearances of interest for passage of a personal wheelchair: (A) the minimum opening width partway up the doorway when accounting for doorway intrusions, and (B) the opening width measured 1.5 in. above the sill (bottom) of the doorway, accounting for the radii of the door's two lower corners. Dimension A is relevant for determining the clearance available for the maximum overall width of a wheelchair, which is usually at the arm supports. Dimension B is relevant for determining the narrower clearance required for the wheelchair's wheelbase as it passes through the bottom of the door opening. If the surface of the boarding bridge floor and door sill are flush, the placement of a ramp over the sill would allow the wheelbase to pass at a higher, and thus slightly wider, point in the curved bottom portion of the opening. Because ADAAG specifications call for any such rise not to exceed 1.5 in., this height is used and shown as Dimension B in Figure 4-2.[8]

[8] The 1.5-in. lip height was chosen based on ADAAG Sub Part D Section 1192.73 as it relates to light rail vehicles and the difference in height between train station and rail cars. Note, however, that the ADAAG guidance requires newly designed rail cars and train stations to have a 0.625-in. max height difference.

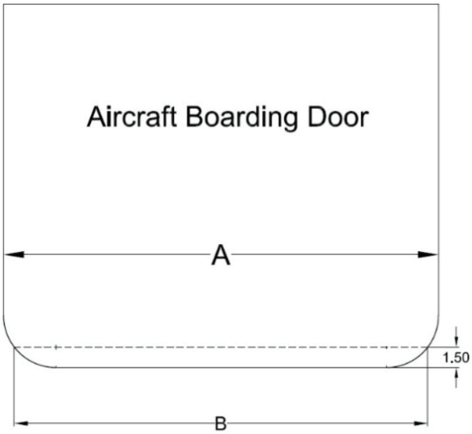

FIGURE 4-2 Boarding doorway width dimensions relevant for determining clearance for a personal wheelchair.

As discussed above, a large majority of wheelchairs have a maximum overall width (Dimension A) of 30 in. or less, including armrests; most of these wheelchairs will have a wheelbase width (Dimension B) of 26 in. or less. The minimum clearance requirement for passing through the airplane door will therefore be determined by these dimensions, as shown in Figure 4-3. While ADAAG permits a 32-in. doorway clearance,[9] a 30-in. opening could suffice for users of most wheelchairs with a maximum width of 30 in. or less when given guidance assistance.[10]

Because airplane cabin doors are standard for each airplane model and data on their dimensions are available, it is possible to compare these two wheelchair dimensions with the doorway dimensions of all airplane models in the U.S. fleet. The results of such a fleet-wide comparison, focusing on the largest cabin door, are provided in the addendum to this chapter and summarized in Table 4-1.[11] For the purposes of this comparison, Dimension A is measured as described above, while Dimension B is measured 1.5

[9] Section 403.5.1 of ADAAG specifies that except as provided in 403.5.2 and 403.5.3, the clear width of walking surfaces shall be 36 in. minimum, except clear width shall be permitted to be reduced to 32 in. minimum for a length of 24 in. maximum, provided that reduced width segments are separated by segments that are 48 in. long minimum and 36 in. wide minimum.

[10] A secondary operator is sometimes needed when maneuvering in a tight space. For example, in wheelchair laboratory testing, guidance assistance, which may be verbal, visual, or physical, is provided to the wheelchair occupant to help maneuver a wheelchair through tight turns for the purpose of determining the minimum size turn corridor.

[11] The addendum also presents typical row seating layouts for airplane models in the U.S. commercial transport fleet.

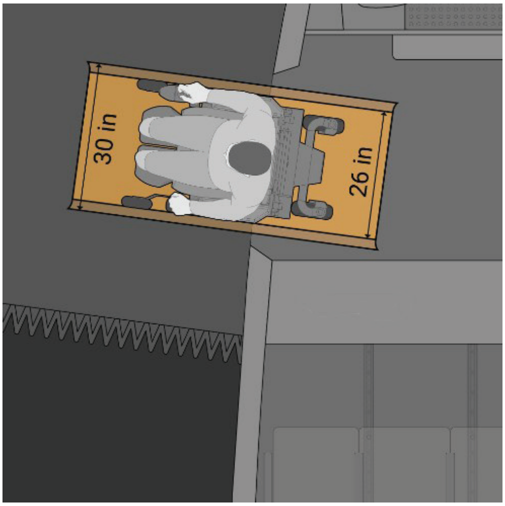

FIGURE 4-3 Minimum clearances required for a wheelchair to maneuver through a cabin boarding door (30-in. clearance partway up the door for clearance of maximum wheelchair width at arm support and 26-in. clearance 1.5 in. above door sill for clearance of wheelbase).

in. above the sill and assumes the presence of a ramp over the sill for the wheelchair to traverse.

The doorway measurements, which are for an airplane's largest boarding door, indicate that more than 83 percent of airplanes have a doorway opening (at Dimension A) that is at least 32 in. wide and 93 percent have a doorway opening that is at least 30 in. wide. All of these airplanes are therefore potentially capable of accommodating wheelchairs with a maximum width of 30 in. or less. However, when smaller regional jets (RJs) are excluded from the fleet data, 100 percent of the remaining airplanes, which account for most passenger enplanements (as documented in Chapter 2), have a passenger doorway opening that is at least 30 in. wide.[12] Additionally, the data indicate that all airplane main boarding doorways have clearance widths when measured 1.5 in. above the sill (Dimension B) that exceed 26 in., and therefore this doorway dimension should not present

[12] The Embraer family of small RJs, the EMB-134, -140, and -145, present the greatest challenges for Dimension A, having a maximum door width of 28.6 in. Embraer's larger EJ family's maximum door width (A) is also on the lower side, at 30 in. All other RJs in the U.S. fleet have door opening widths of at least 32 in. This analysis does not include turboprop category aircraft because they comprised less than 2 percent of the U.S. commercial transport fleet by the end of 2019.

TABLE 4-1 Percent of U.S. Passenger Airplane Fleet (on December 1, 2019) with Sufficient Boarding Door Clearances to Accommodate an ADAAG-Aligned Wheelchair, with Clearances Measured at Points (A and B) Defined in Figure 4-2

Doorway Opening Clearance Width	Percent of Total Jet Fleet	Percent of Jet Fleet Excluding EMB-135, -140, -145[a]
≥32 in. at A	83.2	88.9
≥30 in. at A	93.6	100.0
≥28 in. at B	93.6	100.0
≥26 in. at B	100.0	100.0

NOTE: The measurements are for an airplane's largest door that could be used for boarding.
[a] EMBs comprised only about 6.4 percent of the U.S. fleet in 2019.

an impediment for the large majority of wheelchairs that have a wheelbase width of 26 in. or less.

In summary, measurement data for the U.S. airplane fleet suggest that main boarding doorways should not present a physical constraint for a wheelchair securement system, except potentially for the smallest RJs.[13]

Space for Turning Between the Doorway and Main Aisle

Because the cabin main aisle runs perpendicular to the entryway, the passenger using a wheelchair must navigate a 90-degree turn when proceeding between the entryway and passenger seating area. ADAAG does not provide space specifications for a circular turn but provides them for angle-shaped turning space with room for knee and toe clearance.[14] According to the guidelines, the turn would require two perpendicular 36- × 60-in. clear spaces, configured to enable a 36-in. turning radius, as shown in Figure 4-4. Results from wheelchair testing discussed in Chapter 2 indicate that more

[13] With a few exceptions, RJs have doors wide enough to accommodate power wheelchairs, but provision of RJ service with wheelchair securements would require addressing additional considerations described in Chapter 2 that include smaller cabin interiors and lack of passenger boarding bridges at airports to enable passengers to wheel on and off the airplane.

[14] Section 304.3.2 of ADAAG specifies minimum space requirements that comply with section 306 Knee and Toe Clearance. The requirements do not assume use of the wheelchair's extended footrest. Use of the extended footrest while turning from the doorway into the aisle may present a difficulty for some passengers. See Steinfeld, E., V. Paquet, C. D'Souza, C. Joseph, and J. Maisel. 2010. *Anthropometry of Wheeled Mobility Project: Final Report*. Buffalo, NY: Center for Inclusive Design and Environmental Access. However, the 30- × 60-in. minimum space for the wheelchair securement area is sufficient for use of the extended footrest when maneuvering into the wheelchair space and while the wheelchair is secured.

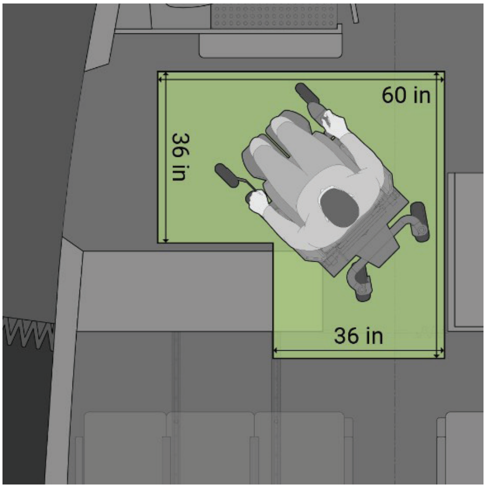

FIGURE 4-4 Space required to turn between the entryway and main aisle.

than 83 percent of wheelchairs (of 185 power wheelchair models tested) can execute a right-angle turn if provided this amount of space. When the tested dimension was increased from 36 to 38 in., 95 percent could execute the maneuver; however, ADAAG's 36- × 60-in. space is referenced here.

The availability of a clear space for turning between the entryway and cabin seating area will differ by airplane and interior layout. Many airplanes will have a closet adjacent to the main boarding door, but some will have other features such as a windscreen, galley, or passenger seating that will affect the decision about where to locate the securement area and the best door to be used for wheelchair boarding and deplaning. Regardless of where the wheelchair enters and exits the airplane, it is likely that one or more of these stationary features would impede the turn and need to be resized or removed from the area, as discussed more below. However, as noted earlier, a cabin interior dimension that can be characterized with more confidence is the width of the aisle between the seats in the main passenger cabin. To facilitate evacuation, FAA regulations (14 CFR § 25.815) require the passenger aisle to be at least 15 in. wide from floor level up to a distance of 25 in., above which the aisle must be at least 20 in. wide. As a result, many narrow-body airplanes will have aisle widths of 15 in. at floor level in order to maximize the space available for passenger seats. This aisle width would be a physical constraint for an airline considering a wheelchair securement area located far from the boarding door because nearly all personal wheelchairs will have a wider wheelbase (outer tread width) that would require widening the aisle by removing revenue-producing seats.

A wheelchair securement area located near the turn from the boarding door is likely to require fewer changes to the interior, including aisle widths. Partly for this reason, Figure 4-4 depicts a turn between the commonly used left forward boarding doorway and a securement location at the head of the main aisle in the passenger cabin. Assuming that two successive rows of seats will be displaced for the creation of a securement location with sufficient structural capacity (see Chapter 3), the liberated space would mean that no additional aisle widening would be required for a wheelchair to maneuver to a securement area located close to the turn. While Figure 4-4 shows two rows of economy seating (i.e., three-place seat assemblies) being displaced, the same number of rows would need to be displaced within first class seating (i.e., two-place seat assemblies).

Space for Maneuvering into Position and Securement

Once in the aisle and adjacent to the securement location, the wheelchair will need to move forward and backward in small increments to maneuver laterally into position. A 30- × 48-in. occupied wheelchair would need at least that much rectangular area plus some additional length to execute the back-and-forth movements. However, it was established in Chapter 3[15] that the securement location would require a 30- × 60-in. space and the removal of two successive rows of seats for distributing the wheelchair load to the floor and primary airplane structure. The available aisle width and the space afforded by the removal of two seat assemblies should provide sufficient room for lateral movement into the securement space, as shown in Figure 4-5. This 30- × 60-in. area would provide space for the occupant of the wheelchair to make seat adjustments for medical pressure relief (e.g., tilt, recline, and leg elevate), without encroaching on surrounding passenger space.[16]

The 30- × 60-in. securement area footprint is shown in Figure 4-6. Because the distance available for seats between the window and aisle varies, it is not clear where the wheelchair would be positioned within the larger space (approximately 60 × 60 in.) afforded by the removal of two seat assemblies, but it would probably be centered between the two seat tracks (for even load distribution) and thus far enough from the aisle not to encroach on the 15-in. minimum aisle width.

Assuming the 30- × 60-in. securement space is situated in a 60- × 60-in. square, this space plus the 15-in. wide aisle should provide sufficient room, as determined from ADAAG, for an occupied power wheelchair to enter

[15] Per Section 305 of ADAAG.

[16] See Steinfeld, E., V. Paquet, C. D'Souza, C. Joseph, and J. Maisel. 2010. *Anthropometry of Wheeled Mobility Project: Final Report*. Buffalo, NY: Center for Inclusive Design and Environmental Access.

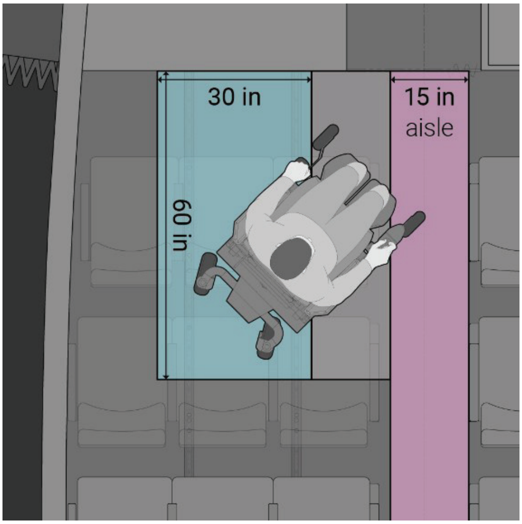

FIGURE 4-5 Space required to maneuver between the aisle and securement location (15-in. aisle width depicted at floor level).

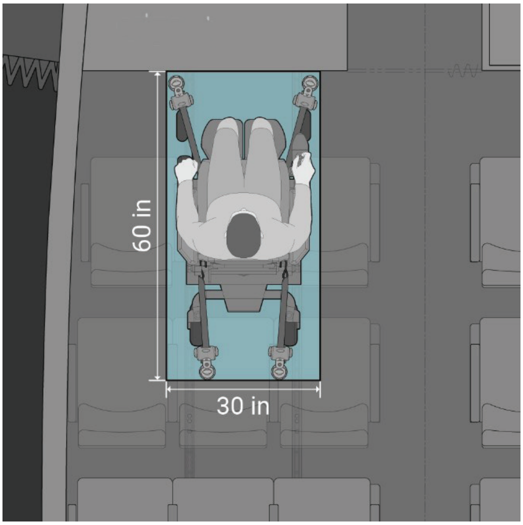

FIGURE 4-6 Space required for the securement area.

the airplane moving forward and to execute a 180-degree turnaround to place the wheelchair in a front-facing position in the securement zone, as shown in Figure 4-7. As discussed in Chapter 2, only 1 percent of tested wheelchairs require a pivot width that exceeds 60 in.[17]

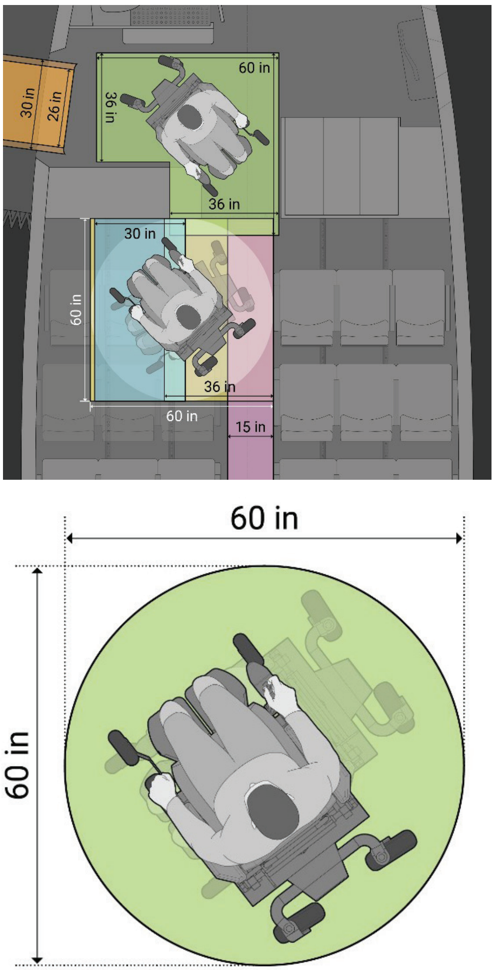

FIGURE 4-7 Minimum space required in the securement area and adjacent aisle to turn the wheelchair around to a front-facing securement position after entering facing forward.

[17] Note that Figures 4-1 through 4-7 show a person with knees flexed at 90 degrees; as noted in Chapter 2, further analyses would consider the extent to which the dimensions shown account for the clearance needs of all people, including those who may not be able to flex their knees when using their wheelchairs.

Importantly, it is reasonable to expect that for some people who use wheelchairs, the execution of some or all of the maneuvers depicted above may require direction and guidance from a traveling companion or customer service agent.

SPACE REQUIREMENTS IN RELATION TO AN EXISTING AIRPLANE INTERIOR

The following sections illustrate the types of changes to an existing airplane interior that may be needed to meet the clearance and clear space minimums estimated above using a commonly configured 737 interior. A 737 airplane was selected because its family, along with the A320 family, dominate the U.S. airline industry. A strong case can be made that for any wheelchair securement concept to succeed, it would need to be applicable to these two airplane families, which together account for about two-thirds of scheduled airline enplanements, nearly half of all departures, and more than half of all airplanes in the airline fleet (see Table 4-2). Because the width of the 737's cabin interior (139 in.) is narrower than that of the A320 (146 in.), the interior dimensions that are depicted for the 737 would not be identical to those of the slightly larger A320 but still highly comparable. A left forward boarding door scenario is assumed for most of the illustrations but an alternative securement location situated close to a left rear boarding door is also shown to convey some of the interior space challenges that this scenario would present.

Some important caveats are required before illustrating with a 737 interior. While the illustrations show how the removal of passenger seats and changes in the locations and dimensions of monuments (e.g., closets, galleys, lavatories) may be required in those cabin areas where the wheelchair will need to maneuver and be secured, they cannot show the potential ramifications of these changes and relocations for the cabin as a whole.

TABLE 4-2 Share of Total U.S. Passenger Enplanements and Scheduled Departures in the Boeing 737 and the Airbus A320 Airplane Families and Their Share of the Airline Fleet, July–December 2019

Airplane Family	Percent of Enplanements	Percent of Departures	Percent of Airplanes in Airline Fleet
Boeing 737	37.8	30.7	29.1
Airbus A320	28	21.6	22.3
All Other	34.2	47.7	48.6

NOTES: Boeing 737 models include 737-800, 737-700/700LR/Max7, and 737-900. Airbus A320 models include A319, A320-100/200, A320/200n, A321, and A321-200n.
SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics, including T100 data.

These impacts would depend on the specific interior features requiring modification and/or relocation. If major monuments such as lavatories and galleys need to be relocated, some can only be moved to specific installment zones in the cabin due to constraints such as the airplane's structural capacity, electrical and plumbing system designs, weight and balance considerations, the location of flight and environmental control systems, and requirements for emergency exit. In most cases it would not be possible to move a galley or lavatory without making major changes to the cabin interior. Furthermore, even seemingly modest changes to an interior can have implications on a host of other passenger safety and comfort features, such as lighted signage, access to oxygen dispensing units, overhead lighting and passenger service units (PSUs), and emergency lighting. While potential impacts on such features are noted later, their locations are not shown in the illustrations.

The 737 illustrations assume that a storage closet is located near the forward boarding door where the wheelchair would enter and exit the airplane. Closets are commonly located near this boarding door for cabin service items and to allow passengers to stow garment bags and certain other carry-on items; hence, the assumption that a closet would be located at the entryway can be considered reasonble, albeit not universally applicable. If required, the resizing or removal of a closet is likely to be less problematic than the redesign, removal, or relocation of a major monument. The depictions show economy class seating in the front of the cabin; however, as noted earlier, two rows of seats would need to be removed regardless of whether the seating is economy, business, or first class. Finally, a depiction of boarding through the rear door is provided as a supplemental illustration. Because the rear of the airplane invariably houses lavatories and a galley, the presence of these stationary features will affect this scenario's suitability for a securement area. Use of the rear door for general boarding and deplaning could also present logistical challenges, as will be noted.

A full interior of a 737 with first class seating is shown in Figure 4-8. The major monument locations are depicted, including a storage closet just aft of the forward boarding door and galleys and lavatories near both the forward and rear doors.

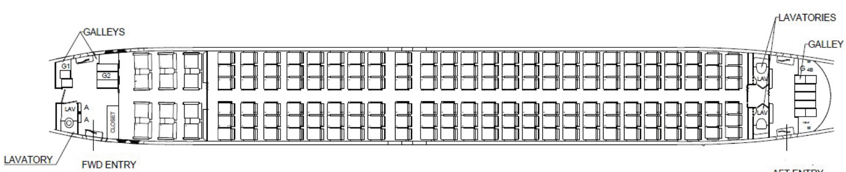

FIGURE 4-8 Boeing 737 interior layout with first class seating.

Clearing the Doorway

Figure 4-9 shows the clearance widths of the forward left boarding door of a 737. As established above, all airplanes in the U.S. airline fleet, except some RJs,[18] have main boarding doorway clearances capable of accommodating a wheelchair with the following dimensions: 30 in. wide with a 26-in.-wide wheelbase. The width of the 737 left forward boarding doorway measures 34 in. at its maximum (partway up the door frame) and 27.3 in. at 1.5 in. above the door sill. One would not expect that any changes to this doorway would be required for a personal wheelchair to pass through it, but a ramp may be required to clear the doorway's bottom corners.

Turning Between the Entryway and Aisle

ADAAG specifies two perpendicular 36- × 60-in. clear spaces after the entryway to allow for a 36-in. turning radius for maneuvering a wheelchair through the 90-degree turn.[19] The aft-side closet adjacent to the doorway of the 737's interior shown in Figure 4-10 would need to be reduced in size or removed to make room for this turning corridor.

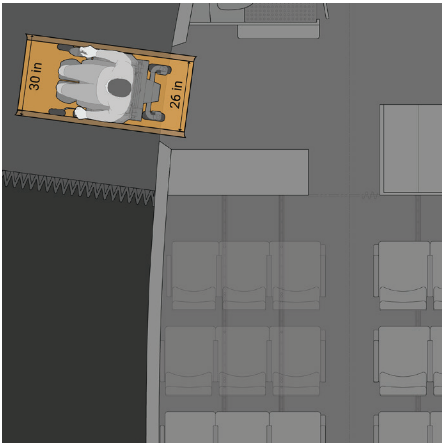

FIGURE 4-9 Forward boarding door clearances, Boeing 737.

[18] These include EMB-135, -140, and -145; turboprops were not evaluated due to the small percentage currently in use in the United States.

[19] As mentioned in Chapter 2, while this report uses the ADAAG dimensions for reference, further analyses would consider the extent to which these dimensions account for the clearance needs of all people when using their wheelchairs with regard to issues such as toe positioning beyond foot support surface.

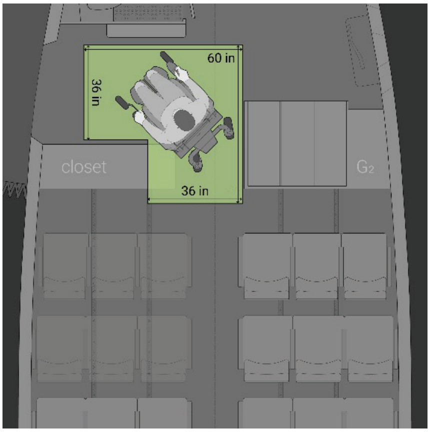

FIGURE 4-10 Turning corridor clearance between the entryway and aisle, Boeing 737.

Maneuvering Laterally Between the Aisle and Securement Area

Figure 4-11 shows the space requirements for a wheelchair maneuvering between the securement area and aisle. Because the requisite 30- × 60-in. corridor would already require the removal of two successive rows of seats, no additional modifications would be required apart from adding the securement system and its load distribution mechanism. The wheelchair securement location is assumed to be centered between the two seat tracks about 30 in. from the left edge of the aisle, ensuring that the wheelchair will not encroach into this protected space (see Figure 4-12).

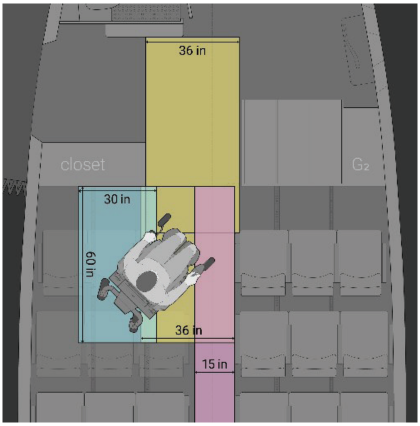

FIGURE 4-11 Space for a wheelchair maneuvering laterally between the aisle and securement area, Boeing 737.

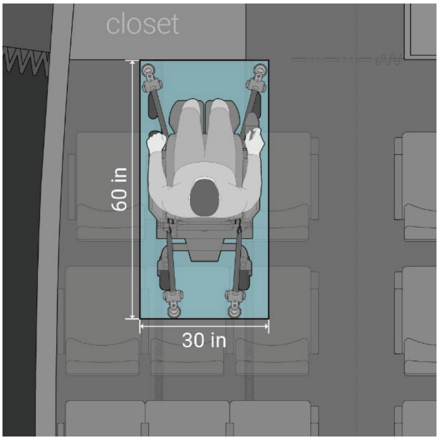

FIGURE 4-12 Space requirements for a wheelchair securement area near the forward loading door, Boeing 737.

The vertical space by the window in this depicted wheelchair securement area, which is the space with the lowest headroom clearance on the 737, is 62.2 in. from the lower surface of the standard overhead bin to the floor.[20] This vertical space should provide sufficient headroom for a person seated in a wheelchair considering that the sitting height for the 99th percentile male is 40.3 in.[21] Likewise, the A320 family has 63.1 in. of vertical space under the overhead bin.[22]

Rear Entry and Securement

A rear, or aft, entry and securement in the 737 is illustrated in Figure 4-13 based on the same space requirements depicted in the figures above. The same data on airplane doors as referenced above (although not shown) indicate that the rear door of a 737 would be wide enough (30 in.) for most wheelchairs to pass but with less clearance than when passing through the forward door. The passenger in the wheelchair could enter facing forward but may need to back out for egress (unless there is sufficient room to turn around in the securement zone), which would be particularly challenging due to the tighter doorway clearance. In this example, a lavatory

[20] Boeing. 2005. *Boeing 737 Ground Handling Manual,* pp. 66–67.

[21] This measurement was provided to the committee by Beneficial Design, Inc., from wheelchair testing described in Chapter 2.

[22] This information was provided to the committee via correspondence with Pierre-Antoine Senes, Airbus, March 2021.

would need to be removed or reduced in size, if even possible. Removal of the lavatory would also require relocating two flight attendant seats to a nearby structure other than the lavatory's outer wall. Figure 4-13 conveys some of the potential disadvantages of a securement location in this area of the cabin, which is a common location for lavatories that are space constrained and not good candidates for relocation or size reduction. Removal of one lavatory from a narrow-body airplane, whether at the rear or elsewhere in the airplane, could make the passenger-to-lavatory ratio too high. The aft of the airplane is also a common location for galleys. Removal of a galley or loss of galley space could affect in-flight meal service and storage space for carts and emergency equipment. In addition, boarding and deplaning through a rear door could also present logistical challenges at airports that have mostly fixed or stationary boarding bridges that are designed to access the forward doors of a narrow-body airplane.[23] If there is a need or preference to board all passengers (including passengers using wheelchairs) through the same door, general boarding and deplaning through a rear door would also keep high-fare, first class passengers who are usually seated at the front of the cabin from being able to deplane quickly ahead of other passengers, which may be undesirable from an airline's perspective.

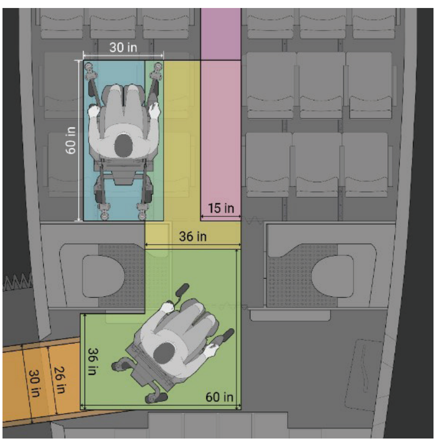

FIGURE 4-13 Space requirements for a wheelchair securement area near the rear door, Boeing 737.

[23] National Academies of Sciences, Engineering, and Medicine. 2013. *Apron Planning and Design Guidebook*. Washington, DC: The National Academies Press, p. 26. https://www.nap.edu/catalog/22460.

CHANGES REQUIRED TO AIRPLANE INTERIORS

The illustrations above indicate that modifications to an airplane cabin interior would be needed to accommodate the space required for wheelchair securement systems. All of the interior changes that would be needed, however, are not depicted in the illustrations because even modest revisions to an interior will require changes to systems and equipment other than monuments and seats. Implementing these changes will require investments in design and engineering to ensure that the renovated interior will operate seamlessly and reliably, while also meeting FAA certification criteria, integrating products from multiple manufacturers, and satisfying the airline's business model requirements. As a result, modifying or upgrading systems in a cabin interior, or introducing new equipment and systems, can be a complex optimization challenge.

As noted earlier, the fixed physical constraints of an interior modification can include the fuselage-limited cabin width, structural load limits, location of doors, availability of electric power and plumbing, and location of vital flight control systems. In addition, compliance with safety requirements is essential, including those associated with the following:

- Emergency oxygen,
- Escape path lighting,
- Signage visibility (fasten seat belt/no smoking),
- Life vest accessibility,
- Cabin crew visibility of the entire aisle and at least 50 percent of seating,
- Delethalization of interior objects (no sharp edges or loose parts that could injure passengers during an incident or evacuation),
- Smoke and toxicity (burn) certification of interior components,
- Emergency decompression flow (to prevent floor structural collapse in the event of a rapid decompression),
- Electrical load analysis, and
- Electro-magnetic interference for electrical systems and components.

All changes to the interior that will affect any of the items in this list, which is not exhaustive, must be evaluated against regulatory criteria.

Due to the need to balance these many different and often competing requirements and interests, the design of an airplane interior tends to be an iterative process that requires many tradeoffs. For example, an airline may consider more than 100 different regulatory-compliant interior layouts for a single desired seating configuration intended to maximize the revenue potential for a given route structure and customer base. Any change, even modest, to an airplane interior (e.g., seat count, seat positions, seat model or manufacturer, movement of a galley or lavatory) can alter the balance and require the airline to obtain a Supplemental Type Certificate from FAA to show airworthiness.

Changing the interior of an existing airplane, of course, will also require investments in the specific modifications that could be accompanied by revenue losses when the plane is out of service, thereby motivating interior modifications for wheelchair securement installations during periods of scheduled maintenance or other alternations. To illustrate some of the potential cost implications, a listing is provided of the kinds of interior systems and features likely to be impacted if a 737 interior were to be renovated to meet the space requirements depicted in Figures 4-9 through 4-12.

The list of systems and features that would need to be removed during the modification includes the following:

- Forward closet aft of the boarding door,
- Bulkhead mounted in-flight entertainment (IFE) screens and literature pockets from the aft wall of the closet,
- First two rows of seating on one side,
- IFE cabling between the first two rows of seating and the rest of the seat column,
- Overhead seat row placarding,
- Overhead PSU from above the area where the first two rows of seats were removed, and
- Carpet from under the area of the first two rows of removed seats.

The removal of these systems and features would need to be followed by the addition and reconfiguration of the following systems and features. Note that the next list assumes that a load-distributing pallet will be used to attach the wheelchair securement installation to the seat tracks, as described in Chapter 3. The securement system itself is not listed.

- Downsized closet;
- Rewiring of closet lighting as required;
- IFE screens and literature pocket on the aft wall of the new closet (this is the video screen for the occupant of the wheelchair);
- New entryway aisle flooring to compensate for reduced-size closet;
- New standard width front row economy class seat (at first seat row location behind the securement system) with in-arm tray tables and in-arm IFE screens;
- Sidewall mounted literature pocket for new front row passenger seats on side (for this new front row economy class seat);
- Modified emergency escape path lighting system to accommodate removal of first two rows of seats;

- Reconfigured overhead PSU for comfort and service functions to relocate PSU and drop-down oxygen location commensurate with wheelchair tiedown location (PSU filler panels as required);[24]
- PSU for wheelchair passenger to accommodate remote control of the panel functions and installation of remote control for reading light and attendant call functionality;
- Seat row placarding kit;
- Modified and reprogrammed cabin management system for seat reconfigurations (required due to changing the number of rows of seats in the airplane, as it affects the flight attendant call button);
- IFE seat to seat wiring;
- IFE software, as the number of IFE screens on the airplane has changed with the removal of the six passenger places (two rows of passenger seats); and
- Wheelchair securement pallet (including stowage for emergency life vest, and remote controls for PSU functionality), carpet kit for pallet installation, and installation of the securement system.

The total cost of these interior changes can be approximated for the purpose of providing insight into the potential technical complexity and scale of a renovation project. Individual airplane modifications also will entail many non-recurring engineering (NRE), design, and certification costs that are not shown because they can vary widely from airplane to airplane and thus cannot be generalized. It may or may not be possible to amortize these NRE and certification costs across multiple airplanes, depending on the heterogeneity of the airline fleet and whether multiple similar interiors will be modified. Changes to an airplane's interior that pertain to its type of certificate will require new investments in NRE that could substantially increase the cost of the modification, perhaps by multiples of the actual cost of kit materials and installation labor.

Table 4-3 shows the price ranges for kit materials that would be needed to make the modifications listed above for cabins with economy and first class seating configurations. The ranges represent approximations based on committee members' subject matter expertise and knowledge of interior renovation projects of comparable scale and complexity. Assuming the renovations could be made in 1 to 3 days during an airplane's scheduled maintenance, installation labor would be on the order of \$5,000 to \$15,000. It merits emphasizing again that this range for a single airplane does not include NRE and FAA certification costs, which will vary by airplane and depend on whether the costs can be amortized over multiple airplanes.

---

[24] On the 737 family, the reading light and attendant call buttons are located in the overhead PSU and normally require a passenger reaching up to the PSU to activate them. There are modifications that can be made for the 737 family that will allow a passenger to activate them with a remote control.

TABLE 4-3 Approximations of Price Ranges for Products (Kit Materials) Needed to Make Referenced Modifications for Cabins with First Class and Economy Class Seating

Economy Class	Price Range	
Reduced-size closet	$30,000	$36,000
Securement pallet	$5,000	$10,000
Standard front row triple-seat assembly with in-seat IFE	$20,000	$30,000
Escape path lighting modification kit	$2,000	$3,000
Flooring modification kit	$1,000	$2,000
PSU filler panels	$800	$1,200
Seat row placard kit	$50	$250
Remote control kit for wheelchair passenger PSU	$1,200	$1,800
Cabin management system software reprogramming	$500	$1,200
IFE modification kit	$2,300	$3,500
Sidewall mounted lit pockets	$1,600	$2,400
Sidewall mounted life vest for wheelchair passenger	$1,200	$1,800
Total	**$65,650**	**$93,150**
First/Business Class	**Price Range**	
Reduced-size closet	$30,000	$36,000
Securement pallet	$5,000	$10,000
Business class seat with in-arm video	$28,000	$40,000
Escape path lighting modification kit	$2,000	$3,000
Flooring modification kit	$1,000	$2,000
PSU filler panels	$800	$1,200
Seat row placard kit	$50	$250
Remote control kit for wheelchair passenger PSU	$1,200	$1,800
Cabin management system software reprogramming	$500	$1,200
IFE modification kit	$2,300	$3,500
Sidewall mounted lit pockets	$1,600	$2,400
Sidewall mounted life vest for wheelchair passenger	$1,200	$1,800
Total	**$73,650**	**$103,150**

SUMMARY OF KEY POINTS

Airplane cabin interiors will need sufficient room for the clearances and clear spaces required for a majority of personal wheelchairs of common types and sizes to (1) enter and egress through the boarding doorway, (2) move within the cabin to and from the securement location, (3) maneuver into and out of the securement location, and (4) be positioned for securement. ADAAG, other technical specifications, and wheelchair measurement data provide reference wheelchair dimensions of 30 × 48 in. with a maximum 26-in. wheelbase. These guidelines and reference dimensions can be used for estimating the clearance and clear space minimums needed for wheelchairs to maneuver through an airplane doorway and in the cabin.

Airplanes usually have multiple doors that can be used for passenger boarding, but the left forward door is used most often and is typically the largest door to the cabin. Based on the reference wheelchair dimensions, airplane doorway clearances will need to be at least 30 in. wide partway up the door opening and 26 in. wide at 1.5 in. above the sill to accommodate a range of personal wheelchairs. Measurements of all jet airplane models in the U.S. airline fleet indicate that more than 93 percent have doorway openings that will accommodate wheelchairs, including 100 percent when excluding some smaller RJs. **Door measurements for the U.S. passenger airline fleet suggest that airplane boarding doorways should not be a physical constraint to in-cabin wheelchair securement systems being installed widely.**

The variability in cabin interior layouts and dimensions precludes definitive determinations about where a wheelchair securement place would best be located in any given airplane's cabin. Nevertheless, **a securement area for a forward-facing wheelchair located near the forward boarding door is likely to require fewer changes to the interior than a placement in other locations, where lavatories and galleys are more likely to be impacted.** By backing into the doorway and through the turn to the main aisle, the wheelchair can be positioned for securement in a forward-facing direction, which is consistent with the orientation of most airline passenger seating. Alternatively, the space provided by the removal of two rows of seats in the securement zone, plus available aisle width, should provide sufficient room for a wheelchair entering facing forward to turn around for a forward-facing securement.

Maneuvering the wheelchair between the entryway and the main aisle of the airplane will require a 90-degree turn within two perpendicular 36- × 60-in. clear spaces to allow for a minimum 36-in. turning radius. A wheelchair securement at the front of the passenger cabin should not require further widening of the aisle, assuming that at least two successive rows of seats are removed to provide space for the securement. The securement space will provide part of the clear space required for maneuvering the wheelchair laterally between the aisle and securement position. A rectangular securement area of 30 × 60 in. would provide the clear space required for these lateral movements, the front and rear clearance needed for passenger safety, access to two seat tracks for distributing the load imparted by the occupied wheelchair, and room for essential wheelchair position adjustments (e.g., tilt, recline, and leg elevate) during flight.

The ability of the more than 6,000 U.S. passenger airplanes to provide the cabin space required for wheelchair securement systems, and the interior changes that would be required for each, is difficult to assess due to variability in interiors across and within airplane families, models, and fleets. Nevertheless, **because the airplanes in the 737 family and the comparably-sized A320 family are by far the most prevalent airplanes in the U.S. airline fleet, the ability of sufficient numbers of these ubiquitous airplanes to accommodate wheelchair securement would be critical for assuring adequate service availability and coverage. Comparisons of clearance and clear space minimums for a wheelchair securement system with the dimensions of a commonly configured 737 interior illustrate how the cabin space required for wheelchair securement can be created with interior changes that would likely be of moderate technical complexity.**

ADDENDUM

Doorway Dimensions and Typical Row Layouts for Airplane Models in the U.S. Commercial Transport Fleet

Airplane Type	Airplane Count	Percent of U.S. Fleet	Maximum Width of Largest Door (in.)	Door Width at 1.5 in. Lip (in.)	Floor Width Inside Corner Radii (in.)	Typical Y Class Seat Layout	Airplane Types with at Least One Column of Triple Seats
EMB-135	27	0.42	28.6	26.4	20.5	1 × 2	
EMB-140	58	0.90	28.6	26.4	20.5	1 × 2	
EMB-145	328	5.09	28.6	26.4	20.5	1 × 2	
E175	43	0.67	30	28.3	22.1	2 × 2	
ERJ170-100	62	0.96	30	28.3	22.1	2 × 2	
ERJ175	483	7.50	30	28.3	22.1	2 × 2	
ERJ190	80	1.24	30	28.3	22.1	2 × 2	
A319-100	355	5.51	32	30.4	24.3	3 × 3	X
A320-200	537	8.34	32	30.4	24.3	3 × 3	X
A320neo	116	1.80	32	30.4	24.3	3 × 3	X
A321-200	429	6.66	32	30.4	24.3	3 × 3	X
A220	28	0.43	32	32	32	2 × 3	X
MD-90-30	65	1.01	34	30	22	2 × 3	X
MD-88	90	1.40	34	30	22	2 × 3	X
757-200	204	3.17	33	26.3	17	3 × 3	X
757-300	37	0.57	33	26.3	17	3 × 3	X
767-200	9	0.14	33	36.7	28	2 × 3 × 2	X
717-200	111	1.72	34	30	22	2 × 3	X
737 MAX	72	1.12	34	27.3	18	3 × 3	X
737-200	2	0.03	34	27.3	18	3 × 3	X
737CL	26	0.40	34	27.3	18	3 × 3	X
737NG	1,774	27.55	34	27.3	18	3 × 3	X
747-400	9	0.14	34			3 × 4 × 3	X
CRJ100	8	0.12	38.2	35.3	27	2 × 2	
CRJ200	384	5.96	38.2	35.3	27	2 × 2	
CRJ700	265	4.12	38.2	35.3	27	2 × 2	
CRJ900	291	4.52	38.2	35.3	27	2 × 2	

767-300	131	2.03	42	36.7	28	2 × 3 × 2	X
767-400	37	0.57	42	36.7	28	2 × 3 × 2	X
777-200	141	2.19	35	32.3	28	3 × 3 × 3	X
777-300	40	0.62	35	32.3	28	3 × 3 × 3	X
787-10	11	0.17	35	32.3	28	3 × 3 × 3	X
A330-200	50	0.78	42	40.3	34.1	2 × 4 × 2	X
A330-300	40	0.62	42	40.3	34.1	2 × 4 × 2	X
A330neo	4	0.06	42	40.3	34.1	2 × 4 × 2	X
787-8	32	0.50	35	32.3	28	3 × 3 × 3	X
787-9	47	0.73	35	32.3	28	3 × 3 × 3	X
A350-900	13	0.20	42.3	37.9	29.8	3 × 3 × 3	X

SOURCES: Committee analysis and data obtained from personal communications with Andre Cavalca, Embraer; Stephen Kalhok, MHIRJ Aviation Group; Andrew Keleher, Boeing; and Pierre-Antoine Senes, Airbus.

5

Assessment of Findings and Recommended Next Steps

This chapter draws on the findings from the analyses in the previous chapters to offer a summary assessment, albeit preliminary, of the technical feasibility of an in-cabin wheelchair securement system concept. After reviewing the available information, the preceding chapters did not identify any technical issues that seem likely to present design and engineering challenges so formidable that they call into question the technical feasibility of an in-cabin wheelchair securement system and the value of exploring the concept further. While the chapter analyses and findings suggest that equipping enough airplanes with securement systems to provide meaningful levels of airline service would require substantial effort, the types of cabin modifications required to provide the needed space and structural support would likely be of moderate technical complexity for many individual airplanes. Further evaluation and assessments, including efforts to fill the information gaps identified in this report, would appear to be warranted, particularly to understand how personal wheelchairs secured in an airplane cabin are likely to perform relative to the Federal Aviation Administration's (FAA's) safety criteria in restraining and protecting occupants during a survivable crash or emergency landing.

Such follow-on assessments are warranted because the many technical issues that could be assessed using the information at hand appear to be manageable from an engineering perspective. Concerted efforts to understand and address the remaining technical uncertainties through more focused analysis and testing would enable more informed public policy considerations about the systems and their potential to expand air travel opportunities for people with significant disabilities. Indeed, the Statement of Task for this study calls on the committee to make recommendations on the additional research, information gathering, and technical analyses needed to inform public policy choices about in-cabin wheelchair securement systems.

Before summarizing the study's key findings and presenting the committee's conclusions and recommendations, the next section provides a recap of the objectives, reasoning, and analyses undertaken in each of the previous four chapters in accordance with the task items in the study committee's charge. In this regard, it is important to restate that the committee was not asked to define the optimal securement implementation for any given airplane and operational condition or to demonstrate how an in-cabin wheelchair securement system implementation could be designed and engineered to satisfy all constraints. The study was intended to be a preliminary feasibility assessment, as in-cabin wheelchair securement systems at this time are conceptual only. A central aim of this report, therefore, is to frame the technical challenge and its magnitude and check for technical issues and uncertainties that could impede the concept's realization, thus highlighting areas for follow-on information gathering and assessment.

Consideration is also given to some of the airline operational and passenger accommodation issues that could arise in implementing wheelchair securement systems. Central to these considerations is the presumption that the systems should allow people to remain seated in their personal wheelchairs for access to ample flight offerings to and from places they want to go, as opposed to being available sporadically or on only a handful of scheduled flights. Numerous operational issues arise from this presumption, such as ensuring that (1) a sufficient number of airplanes (although not necessarily all or even most) is equipped with securement systems, (2) requisite service assistance is available to passengers who choose to use the systems, and (3) efficient and standardized means are instituted to verify that a personal wheelchair meets all applicable eligibility requirements before ticketing and boarding. While these and several other operational and accommodation issues are noted, a more thorough treatment of them would be premature at this early stage when an in-cabin wheelchair securement system remains a concept and there is limited information available for assessing important factors such as system demand and use characteristics.

The chapter concludes with recommendations for next steps. They are focused on developing the information needed to fill identified gaps in understanding of certain technical issues and the potential for user demand.

RECAP OF CHAPTER TOPICS AND OBJECTIVES

The committee has framed the question of "technical feasibility" in keeping with the key interest that motivated the request for this study. The committee presumes that the interest, as noted above and for reasons explained more fully in Chapter 1, is for people who are nonambulatory and have significant disabilities to have access to ample flight offerings that will enable them to fly to and from places they want to go while seated in their personal wheelchairs. An emphasis on being seated in a personal wheelchair during flight is fundamental to the study's charge because it stems from a concern that people who have significant disabilities and use wheelchairs are not always able to board an airplane, transfer to and from a conventional passenger seat, and remain in that seat for the duration of a flight without significant discomfort, pain, and risk of injury. The idea is that by having the ability to fly while seated in a personal wheelchair that is customized to their medical and physical needs, travelers can avoid these hardships and also use their personal wheelchair (as opposed to a wheelchair optimized for air travel) at the destination. A securement system concept that has the potential to be used on many airplanes, and thus in many travel markets, is also fundamental to the study charge, because—as noted above—niche implementation would provide limited utility even if technically feasible. Indeed, an emphasis on meeting these two conditions—providing transportation service to people when seated in their *personal* wheelchairs and ensuring that travelers are afforded *ample service options* (i.e., flight offerings)—is the norm for the accommodation of people who use wheelchairs on most other modes of transportation.

With these two conditions in mind, Chapter 2 provides background on the population of personal wheelchairs in common use, the means by which wheelchairs are secured when used as seats in transportation, the structure of airline service, and the airplanes used for this service, including their seating and other relevant features of cabin interiors. The chapter also provides background on the role of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) in developing standards for wheelchair safety in transportation.

Because safe performance is critical for all modes of transportation including air travel, Chapter 3 explores the challenges associated with designing and implementing a wheelchair securement system that can satisfy FAA's aviation safety requirements. FAA closely regulates airlines and airplanes for safety assurance, and a large body of the regulations focuses on the ability of the airplane cabin and seating systems to protect passengers and crew in the event of a survivable crash or emergency landing. Understanding how a secured wheelchair would perform during such an event, when considering the safety of the wheelchair occupant and other airplane passengers and crew, is imperative. FAA crashworthiness criteria for airplane seats and cabin interiors are thus described and compared to criteria developed by RESNA for the crashworthiness of wheelchairs in motor vehicle transportation. Side-by-side comparisons of the two sets of crash performance criteria are complicated because each was established for different operating and crash environments. An important point, however, is that the RESNA standards establish a baseline minimum level of crash and safety performance that many commonly used wheelchairs comply with today and that more wheelchairs could be designed to comply with in the future, potentially facilitating future conformance to FAA safety criteria.

While safety considerations will dictate many aspects of the design and implementation of a wheelchair securement system, physical space in the airplane cabin will have a significant effect as well. The airplane must have the requisite space for commonly sized wheelchairs to board, deplane, and maneuver to and from a sufficiently sized and structurally supported securement location. These considerations are examined in Chapter 4 by estimating the clearances and clear spaces required and then comparing them to the dimensions of airplane doors and cabin interiors. The comparisons suggest that a wheelchair securement place that provides sufficient clearance and clear space could be created in the front of the cabin of many airplanes; however, due to variability in cabin sizes, features, and interior layouts, it is not possible to conclude that this would be the preferred or most feasible installation location for all airplanes. An illustration of a securement location implemented in one of the most common interior layouts of the most common airplane family in the U.S. airline fleet provides insight into whether space availability could present significant technical challenges to the implementation of securement systems on enough airplanes to provide travelers with ample flight options.

In the sections that follow, the key findings from these chapters are highlighted and assessed to identify any technical issues that have the potential to present major design and engineering challenges to the feasibility of an in-cabin wheelchair securement system concept. Where more information is needed to gauge this potential, those gaps are identified.

Of course, choices about whether and how to implement an in-cabin wheelchair securement system will depend on factors beyond technical feasibility. The economic implications for airlines from systems that may reduce the number of passenger seats in an airplane in total or by fare class will almost certainly create real challenges to implementation and acceptance. The displacement of seats could be particularly problematic for smaller airplanes that already have limited seating capacity. Such economic issues were not addressed in this study under the premise, as explained in Chapter 1, that the addition of any in-cabin wheelchair securement system would likely lead to a net reduction in passenger seats given the constrained interior space of an airplane and the existing norm of tightly spaced seating configurations. However, it is reasonable to assume that Congress would have recognized this likelihood when it asked for this feasibility study and that adding any constraint to the contrary (i.e., to predicate technical feasibility on an airplane without displaced seats) would have set a very high bar for a preliminary assessment of technical feasibility.

ASSESSMENT OF FINDINGS ON TECHNICAL FEASIBILITY ISSUES

It bears repeating that the purpose of this report is to provide a preliminary assessment of the technical feasibility of in-cabin wheelchair securement systems. The focus, therefore, has been on identifying any technical challenges that could be significant obstacles to the development and implementation of a system able to provide ample flight offerings to people who are nonambulatory. To do so, the committee considered technical challenges with respect to the following three areas: (1) whether airplanes common to airline service have enough physical space to enable a power or manual wheelchair to enter and exit the cabin and maneuver to and from a securement location that is sufficiently sized for the functioning of the securement system and essential wheelchair seat position adjustments; (2) whether an airplane floor structure can accommodate the loadings imparted by an occupied power wheelchair; and (3) whether a secured personal wheelchair could meet the crashworthiness, occupant injury protection, and other safety assurance requirements of FAA.

The analyses in this report, and specific findings cited next, indicate that airplane interior space and structure should not present major technical challenges to an in-cabin securement system that could be implemented on a wide enough basis to afford users meaningful levels of flight service. The safety assurance challenge, however, is more difficult to characterize in the absence of specific technical evaluations of how secured wheelchairs would perform in accordance with all of FAA's crashworthiness requirements.

Findings on Airplane Physical Space and Structure

Sufficient numbers of airplanes would need to have cabin interiors with the requisite clearances and clear spaces for occupied personal wheelchairs of common types and sizes to (1) enter and exit through the boarding doorway, (2) move within the cabin to and from the securement location, (3) maneuver into and out of the securement location, and (4) be positioned for securement. Airplane floor and structural support in the airplane would need to be able to accommodate the load imparted by the heaviest occupied power wheelchair.

With respect to each of these physical space and structural requirements, the committee finds the following:

- The more than 6,000 airplanes active in the U.S. passenger airline fleet belong to fewer than 10 major airplane families, each consisting of different models. While specific interior layouts can differ widely among these models and even among individual airplanes of a given model, certain dimensions such as doorway and cabin interior widths are uniform for all airplanes in a given family. Airplanes in just two of the families of narrow-body aircraft, the Boeing 737 and the Airbus A320, are predominant in the fleet and account for most domestic airline enplanements and departures. Therefore, an assessment centered on the ability of these two ubiquitous airplane families to provide the needed interior clearances and clear spaces is more manageable and can provide critical insight into whether physical space is likely be a major technical challenge for ensuring that securement systems can be installed on enough airplanes to achieve meaningful levels of air transportation service (e.g., service availability in at least all high-demand markets).

- The current population of manual and power wheelchairs in the United States consists of hundreds of models with differing sizes, performance levels, and configurations; however, the vast majority have dimensions and operating capabilities that enable them to maneuver within the clearance and clear space parameters specified in the Americans with Disabilities Act (ADA) access guidelines. The parameters in these widely used and influential guidelines, which have the effect of creating some uniformity in certain wheelchair dimensions, enable the committee to estimate maximum wheelchair dimensions for the purpose of estimating minimum cabin space and clearance requirements. On the basis of these estimates, the committee concludes that the passenger cabins of airplanes that provide much of the country's airline service would have sufficient space for the securement of most occupied wheelchairs.
- Comprehensive testing data of common power wheelchair models enable a reliable estimate that 850 lb is the maximum occupied weight of a wheelchair that would need to be supported by an airplane's structure at the securement location.
- Door dimensions of all airplanes in the U.S. passenger fleet are known. They indicate that the boarding door openings of the vast majority of airplanes could accommodate passage into and out of the cabin by a large majority of wheelchairs. The data indicate that the left forward door is the widest on most airplanes and would provide the fewest physical constraints on access, both with respect to clearing the doorway and accessing the door from the airport gate through the usual positioning of passenger boarding bridges.
- Maneuvering the wheelchair between the entryway and cabin aisle entails the execution of a 90-degree turn requiring two

perpendicular 36- × 60-in. clear spaces. Irrespective of the door used by the wheelchair to enter and exit the airplane, many airplanes would have one or more interior features that intrude on these clear spaces to impede the 90-degree turn. These features would need to be resized or relocated to provide the needed space.

- A securement area located near the door used for boarding and deplaning is likely to require fewer changes to aisle widths than a location deeper into the cabin because aisle widths in nearly all airplanes are too narrow for the vast majority of personal wheelchairs to pass through unimpeded.
- The removal of two successive rows of seats should provide a securement area with sufficient floor and underlying structural support for the load imparted by an occupied power wheelchair, employing pallet systems that are commonly used for distributing loads across seat tracks and structure.
- The removal of two successive rows of seats should provide sufficient room for a 30- × 60-in. space for a wheelchair securement as specified in the ADA and wheelchair industry guidelines for requisite clear spaces. That space should also be sufficient for the wheelchair to maneuver laterally between the aisle and the securement space without requiring changes to other seating or to aisle widths.

Although confident that (1) the main boarding doors on airplanes accounting for much of the country's airline service have sufficient clearance to accommodate wheelchairs and (2) the removal of two successive rows of seats would provide the needed space and structural support for a securement location, the committee notes that the heterogeneity of airplane interiors precludes definitive determinations about the specific interior modifications that would be required to remove, resize, or relocate features that could impede a wheelchair maneuvering the 90-degree turn between the entryway and passenger seating area. In some airplanes, these modifications might present major technical challenges, particularly if the affected feature is an essential galley or lavatory that cannot be relocated. The challenges associated with relocating such a feature could make the implementation of a securement system infeasible for some airplanes.

While the precise number of airplanes in the airline fleet that could not accommodate a wheelchair securement system due to unalterable or immovable interior features cannot be determined from available information, physical constraints of this type are not likely to be a problem for a large share of airplanes because the most common interior layout of airplanes in the ubiquitous Boeing 737 family would only require the removal or resizing of an entryway closet. The common and similarly sized airplanes in the

Airbus A320 family, where a closet in the same location is the norm, would add further to the share of the fleet that would not appear to have a major physical constraint to the placement of a wheelchair securement location at the very front of the passenger cabin.

Findings on FAA Crashworthiness Requirements

FAA has not established safety standards that apply to wheelchair securement systems or wheelchairs being used as seats in airplanes. The main body of FAA safety regulations that applies to passenger cabins focuses on ensuring that airplane seats are crashworthy and do not impede the ability of occupants to rapidly evacuate in the event of a survivable crash or emergency landing. The committee cannot know how FAA would treat secured wheelchairs in terms of requiring strict compliance with all crashworthiness criteria. Personal wheelchairs are not optimized for airplane transportation and crash environments, and their specific designs with custom features will vary far more than conventional airplane seats that must be certified by FAA. Wheelchairs have not been tested comprehensively for compliance with FAA crashworthiness criteria applicable to airplanes, and securement systems intended specifically for airplane cabin applications have not been developed for such wheelchair crashworthiness testing and evaluation.

With respect to the crash performance of wheelchairs, the committee finds, on the basis of motor vehicle crash performance standards, that personal wheelchairs can be, and often are, designed and constructed to do the following:

- Retain their form, stay upright with the restrained occupant remaining in a seated posture, and retain their battery when subject to 20-*g* impact forces characteristic of a 30-mph frontal motor vehicle crash when the wheelchair is secured to the vehicle by a system demonstrating satisfactory performance under this dynamic loading;
- Accommodate a wheelchair-anchored pelvic safety belt that will stay in place and restrain the occupant during a frontal crash; and
- Provide four standardized points with slot-type geometries (e.g., brackets) for attaching tiedown straps for in-vehicle securement.

The committee finds that the ability of wheelchair securement systems to meet these motor vehicle crash performance standards, which require testing that has some commonalities with the testing required for demonstrating airplane seat crashworthiness, is suggestive that wheelchair securement and occupant restraint systems could also be designed for airplane installation. Specifically, the findings suggest that systems could be designed to do the following:

- Accommodate wheelchairs equipped with standardized four-point brackets for connecting tiedown straps and that otherwise comply with motor vehicle crashworthiness criteria (including many wheelchairs in use today and wheelchairs that can be designed to this standard in the future);
- Keep a crashworthy wheelchair secured to withstand the dynamic forces of a survivable frontal airplane impact with the occupant remaining seated, upright, and restrained; and
- Protect the occupant of a crashworthy wheelchair and other passengers from serious head and leg injuries as long as the wheelchair is secured in a 30- × 60-in. zone that is clear of objects and structure.

However, in the absence of comprehensive testing and evaluation data for the crash performance of wheelchairs and their securement systems in accordance with FAA crashworthiness criteria, it is not possible to confirm the technical feasibility of designing and implementing an airplane-specific wheelchair securement and occupant restraint system that would demonstrate the requisite airplane crashworthiness capabilities. It merits noting, however, that during a committee meeting, the nonprofit organization All Wheels Up,[1] which advocates for wheelchair accommodation on airplanes, described the exploratory testing that it has sponsored on the performance of a wheelchair securement and occupant restraint system. The test results, as described to the committee, demonstrated how a power wheelchair (occupied with a mid-size male test dummy) that is secured by tiedown straps normally used for motor vehicle transportation could keep the wheelchair secured and upright with no damage to the straps when tested according to FAA dynamic criteria. While the tested wheelchair is reported to have retained all items of mass, including the battery, the tests were designed to assess the airplane crash performance of a standard tiedown system. The exploratory tests were not designed to demonstrate airplane crash performance (in accordance with FAA criteria) of a range of common wheelchairs, including their ability to protect the occupant from serious injury when restrained only by a wheelchair-anchored pelvic belt and to retain the battery and other items of mass. The All Wheels Up test data are proprietary; thus, they were neither included in a published external technical review nor shared with the committee. The committee concludes, however, that more comprehensive and externally reviewable testing of this type is essential for

[1] See https://www.allwheelsup.org.

assessing the feasibility and informing the design of wheelchair securement systems for in-cabin applications.

The committee finds that the most uncertain technical issue pertaining to cabin crashworthiness criteria, and one that warrants further information gathering and evaluation, is whether the population of personal wheelchairs themselves, including those designed to meet motor vehicle crash performance standards, would satisfy the FAA requirements for airplane crashworthiness. The review indicates the following:

- RESNA's crash performance test for WC19 wheelchairs has some similarities with one of FAA's two dynamic crash tests for airplane seats in which the predominant impact vector is horizontal. FAA's horizontal test requires an airplane seat to demonstrate the ability to avoid severe deformation, retain items of mass, and protect the occupant from severe head and leg injuries from a 16-*g* peak dynamic loading along the airplane's longitudinal axis, such as from a survivable crash or emergency landing impact when the airplane is primarily moving forward. To meet the WC19 standard, secured wheelchairs must demonstrate crashworthiness, occupant restraint, and battery and component retention in a frontal motor vehicle crash occurring at 30 mph. The horizontal test condition in this case creates a dynamic loading that averages 20 *g*, which is higher than the peak 16-*g* loading of the FAA test, and also assumes a nearly instantaneous deceleration from 30 to 0 mph.
- RESNA's WC19 standard does not include a test condition comparable to FAA's second dynamic crash test in which the predominant impact vector is vertical. This second test is also intended to demonstrate the seat structure's ability to avoid severe deformation, retain items of mass, and protect the occupant from spinal injury but under vertical loadings characteristic of a survivable airplane crash during an attempted takeoff or emergency landing with a high descent rate. In the absence of a WC19 vertical test, technical evaluations are needed to determine the crash and injury protection performance of wheelchairs when subject to such vertical forces, which seldom occur in motor vehicle crashes. Likewise, RESNA's flammability testing standards for wheelchairs differ from FAA's standards for airline seats. While wheelchairs that meet crashworthiness standards for motor vehicle transportation must also meet industry standards for resistance to ignition by a cigarette and match, FAA standards are different and thus technical evaluations are needed to gauge the ability of wheelchairs to satisfy FAA criteria for resistance to post-crash fires.

Given these identified information gaps and knowing the variability in wheelchair designs, the committee has no current basis for gauging whether wheelchairs could satisfy FAA criteria with respect to these crashworthiness criteria. The committee is optimistic, however, that future efforts to fill the gaps in technical information will benefit from RESNA's crashworthiness standards for wheelchairs. The standards provide a performance minimum, or widely applicable baseline, for wheelchair evaluations on the basis of FAA test criteria, as many commonly used wheelchairs comply with the RESNA standards today and more wheelchairs could be designed to comply with them in the future. If the WC19 and other RESNA standards did not exist to provide such a common baseline, the job of evaluating a heterogeneous population of personal wheelchairs for compliance with FAA criteria could be technically daunting and potentially impractical.

Finally, it merits noting that in briefing the committee, FAA representatives cited instances where some cabin installations or design features were granted exemptions from specific crashworthiness criteria when demonstrating compliance would be extremely difficult to do and when the applicability of the criteria may be limited. A cited example was an in-cabin medical stretcher installation, which was exempted from demonstrating compliance with the dynamic loading criteria for passenger seats.[2] In providing the reasoning for the exemptions, FAA acknowledged that the applicants' ability to demonstrate compliance would be difficult, if possible at all. Nevertheless, the agency pointed out that the dynamic testing criteria for passenger seats were originally established based on a regulatory calculation that the added safety benefit to passengers would significantly exceed the cost of designing and engineering the compliant seats. This net benefit calculation, however, was based on design and engineering costs amortized across potentially hundreds of seats in an airplane, which would not be the case for a single stretcher installation. Expecting medical stretchers to be limited to one or two installations per applicable airplane and not used on every flight, FAA granted the exemptions under the premise that it would not be "precedent-setting" and on the condition that the stretcher would be installed in such a way that it would not reduce the level of protection afforded to other occupants of the airplane.

A presumption of this feasibility study is that FAA would apply its crashworthiness regulatory criteria established specifically for airplane seats and cabin interiors to wheelchair securement systems. As these exemption examples indicate, however, the technical challenge will be to design a system that will satisfy FAA determinations about how safe the system must be in accordance with the statutory goals and obligations that underpin those

[2] Exemption No. 10197, Regulatory Docket No. FAA-2010-0989, issued January 21, 2011; Exemption No. 10457, Regulatory Docket No. FAA-2011-1389, issued February 23, 2012.

criteria. The purpose of further testing and evaluation of wheelchairs and wheelchair securement systems would inform such safety determinations.

AIRLINE OPERATIONAL AND PASSENGER ACCOMMODATION ISSUES

The implementation of an in-cabin wheelchair securement system, if technically feasible, would invariably require airlines to address a range of practical issues associated with passenger use of the securement system on individual flights as well as other challenges associated with ensuring adequate and reliable service through modifications to reservation systems and the coordination of flight offerings and flight schedules. Indeed, the study's Statement of Task, under the rubric of "accommodation," asks the study committee to address the following questions:

- How will airlines be able to use the systems to provide an equal level of service to air travelers with significant disabilities?
- What will be the implications of removing standard aircraft seats to create the space needed for a restrained, occupied wheelchair in the cabin?
- What will be the implications on cabin interior designs and furnishings (e.g., aircraft doors, aisles, galleys, lavatories)?
- What will be the implications on boarding and deplaning procedures and staff training?
- What will be the implications on reservation procedures?
- How will the batteries of power wheelchairs be treated and handled prior to and during flight?

All but a few of these issues have already been addressed as part of the study's review of the technical issues associated with developing and implementing an in-cabin wheelchair securement system. Starting with the question about "equal level of service," the committee interpreted this interest to mean that people who have significant disabilities and cannot currently fly safely in a passenger airplane will be able to do so much like people who can fly in an airplane seat. In particular, the emphasis of this report has been on examining the technical feasibility of securement systems that can be installed on enough airplanes to allow people with significant disabilities to fly seated in their personal wheelchairs (as opposed to wheelchairs specialized for use in airplanes) and be "equal" with other travelers in the sense that they will have equitable service, be able to fly comfortably, and have access to a reasonable number of flights to and from places they want to go. Accordingly, the committee's assessments of the technical issues associated with safety, airplane structure, and cabin space have been based on the premise that *personal* wheelchairs will be used and that common types of airplanes would be equipped. The report's assessments of the interior modifications required to implement the systems assume that the secured passengers will have access to the same in-cabin amenities and safety features as other passengers, including access to entertainment systems, call buttons, and oxygen masks.

While the report's technical assessments suggest that the removal of two rows of seats should be needed and sufficient to free up enough room and structural capacity for a wheelchair securement system, the specific cabin location most suitable for installation of the system would depend on operational as well as technical considerations. From a technical perspective that considers cabin space requirements only, the ideal location would depend on the door used for entering and exiting the cabin with the wheelchair, because any location far from the boarding door would require the removal of additional seats to create sufficient aisle width for access. The choice of a boarding door, in turn, would depend on the doorway having sufficiently wide clearance for the wheelchair. It would also depend on considerations about whether and which interior features might need to be modified or relocated to enable a wheelchair to navigate the turn between the doorway and passenger seating area. Additionally, from an operational standpoint, the choice of a boarding door for travelers using a wheelchair could also depend on an airline's desire to board and deplane all passengers through the same door in accordance with its standard boarding practices.

When taking into account all of these considerations, the designation of a wheelchair securement area at the very front of the passenger cabin, as assumed for most of the scenarios developed in this report, appears to be the strongest candidate for a common placement. From both technical and operational standpoints this location has many advantages, including the prospect of fewer airplanes requiring major interior modifications than if the securement system was located elsewhere in the cabin. This forward location would allow passengers, including wheelchair users, to board and deplane through the same left forward door that is in common use today, resulting in little, if any, disruption to existing airline boarding and deplaning procedures. The use of a single door for all boarding would not only minimize airline operational impacts but also result in more equal service treatment for ambulatory and nonambulatory passengers. Likewise, there is good reason to believe that this forward securement location would require no more than an ordinary level of interior design and engineering effort for an airline to ensure that passengers in and near the securement zone would be afforded the same amenities as other passengers in the cabin. The innovative seating configurations and amenity offerings in first class cabins today are indicative of how cabin interior designers and engineers can be flexible and adaptive to such circumstances.

A passenger flying in a wheelchair may or may not require assistance from a flight attendant or customer service agent during boarding and deplaning, but is likely to require assistance with securing and releasing the wheelchair. It is already the case that the International Air Transport Association's (IATA's) special service request (SSR) codes identify passengers requiring boarding and deplaning assistance. For instance, the SSR codes for wheelchair assistance include WCHS—passenger can walk a short distance but not up or down stairs; WCHC—passenger cannot walk any distance and will require an aisle chair to board in cabin; and WCLB—passenger traveling with a lithium ion battery–powered wheelchair. The creation of in-cabin wheelchair seating capability is likely to require a new SSR code that alerts airline personnel and wheelchair assistance providers about the presence of a passenger traveling in a personal wheelchair.

Currently, most nonambulatory people who fly are transferred between their personal wheelchair and a boarding or aisle wheelchair and then assisted into and out of the conventional passenger seat by a customer service agent. Presumably, the same agent could be trained to provide assistance to the passenger as needed when maneuvering the wheelchair into and out of the cabin and securement area and when securing the wheelchair and occupant restraint system. Indeed, this assistance may be provided more quickly than the current process of assisting the passenger when transferring between the personal wheelchair and boarding chair, in maneuvering the boarding chair in the cabin, and in transferring between the chair and airplane seat. The agent's new duty could include verifying that a small ramp on either side of the airplane sill is available and in place if needed for the wheelchair to clear the boarding doorway. While procedures would need to be established for properly securing and releasing the wheelchair, the level of training needed for this procedure could be comparable to the highest quality training provided to operators of surface transportation vehicles such as transit buses. Flight attendants would need to be able to visually inspect the securement and a checklist would need to be in place for the handoff from the customer service agent to the flight crew. Flight attendants may need training on visual standards for indications of proper wheelchair securement and occupant restraint, as well as any other necessary adaptions to procedures before, during, and after the flight. For most matters, such as emergency evacuation protocols, the occupant of the wheelchair would presumably be treated like other nonambulatory passengers seated in a conventional seat—and thus, of course, not be expected to evacuate in the wheelchair.

In this report's assessment of technical feasibility, it was pointed out that FAA will need to determine whether personal wheelchairs that meet WC19 standards will satisfy airplane cabin crashworthiness requirements or whether the wheelchair will need to meet additional criteria and conditions to be eligible for in-cabin securement. If WC19 compliance is considered to be at least one eligibility condition, one might expect airlines to design their securement mechanisms to take advantage of the four-point securement brackets and anchors for a lap belt specified by the standard. While some people with significant disabilities are mostly homebound and may have wheelchairs designed for indoor use only that are not WC19 compliant, it is reasonable to assume that people who are interested in flying while seated in their own wheelchairs will seek out equipment that is WC19 compliant (and labeled accordingly) and mandatory for air travel. Inasmuch as in-cabin securement systems are likely to be used disproportionately by people in power wheelchairs, WC19 compliance is desirable for transportation generally because these wheelchairs are frequently used as seats in motor vehicles.[3] Ideally, methods would be developed to confirm that the wheelchair satisfies applicable eligibility criteria during ticketing for verification at check-in. Thus, presumably in advance of boarding, the customer service or gate agent would need to inspect the wheelchair to verify that it is equipped with the requisite securement brackets and lap belt, which can be done visually and verified by checking for a WC19 label. Where the verification process could become more complex, however, is if the agent is expected to examine the wheelchair for deviations from the standard or other eligibility conditions; to ensure that the battery is adequately secured and sufficiently charged; and to ensure that removable items on the wheelchair, from packs to control devices and essential accessories (such as a ventilator and oxygen dispenser), are in compliance with all relevant FAA and airline requirements.

While not knowing the specific eligibility requirements that would be in place for wheelchairs to be used as seats in airplanes, a reasonable expectation is that eligibility would be ascertained by determining if a given wheelchair is of a type or model that has been preapproved as conforming to the requirements. A specifically trained agent may be required to verify at airports that an individual wheelchair is an eligible model and in a condition to be secured. The imposition of any additional requirements on wheelchair owners to periodically demonstrate that their wheelchair continues to comply with all of the eligibility requirements met by the model would need to be carefully considered for practicality and avoidance of excessive cost and burden.

Adaptions to airline reservation systems will be critical for accommodating travelers who want to use the wheelchair securement systems.

[3] Indeed, wheelchair manufacturers' voluntary provision of information on WC19 compliance of their wheelchair models to aid consumers shows that 153 wheelchair models from 18 major manufacturers meet WC19 standards. See University of Michigan Transportation Research Institute. 2020. "Wheelchair Product List–WC19 Full Compliance." http://wc-transportation-safety.umtri.umich.edu/crash-tested-product-lists/wheelchairs and https://docs.google.com/spreadsheets/d/1qf6Mlm5FB-QLOpeFGLf-dNcFksZdbqF-buuY5M-sQ4M/edit#gid=2.

At the pre-travel phase, when searching for fare and service offerings, the traveler would need information about the availability of a system on each flight and to be assured that boarding bridges and trained customer support agents are available at all airports on the itinerary. Likewise, the airline would want this assurance before a booking takes place to minimize the potential for problems during check-in. Reservation systems would therefore need to be adapted to allow travelers to find flights that meet these requirements. The reservation system might also need to ask, for instance, for the customer to confirm that the wheelchair is WC19 compliant.

The search for flight offerings would be facilitated if a large portion of airplanes was equipped with securement systems. If securement system implementation is limited to a few airplanes or city-pair markets, its utility would be greatly limited. As discussed in Chapter 2, many cities have nonstop service to only a handful of destinations, and thus connecting service is the norm. The search for securement service could therefore be particularly complicated for itineraries that require airplane transfers. Passengers would need to be assured that a wheelchair securement system would be available for all flight segments. However, as the number of flight segments increases, so too does the risk that one or more of the flights would not be able to accommodate a wheelchair for a variety of reasons after the booking has been made, including the airline needing to make a last-minute substitution of equipment due to mechanical problems, weather delays, and air traffic control holds. The reservation system will need to be able to provide the traveler with advance notification and a means of rescheduling in the event that a suitable airplane is not available. Advance notice, however, may not be possible once travel is under way, and therefore any of the above circumstances, or simply a missed connection to the only suitably equipped airplane, could leave the traveler stranded en route.

The extent to which such service availability issues will create challenges for travelers will depend in large part on passenger demand for in-cabin wheelchair service, because the level of demand will affect both the likelihood of a traveler finding a wheelchair space that has not already been booked and an airline's motivation to equip more airplanes with securement systems. That demand is difficult to know at this point, because it would presumably depend in part on whether people who do not fly now because of troubles with transferring to and from an airplane seat would be willing to fly if they could travel seated in their personal wheelchair. Still another component of this demand would be passengers who are able to transfer to an airplane seat and check their wheelchair in the cargo hold but who do not fly as often as they would like because of the discomfort or risks associated with the transfer and/or the potential for the stowed wheelchair to be damaged or lost in transit. Gauging demand for in-cabin wheelchair service is therefore a complicated but potentially critical step for making decisions about equipping airplanes with wheelchair securements.

With regard to the handling of wheelchair batteries, FAA regulations state that batteries may remain on a wheelchair stowed in the cargo hold but must be disconnected or otherwise disengaged to avoid unintentional activation.[4] The exception is lithium ion batteries, which may need to be removed from the wheelchair and stored in the cabin. Neither FAA regulations nor industry standards developed by IATA[5] (in partnership with airlines and the battery industry) address the issues of battery engagement, power activation, and seating function availability when wheelchairs are in the cabin. It would be important for the battery to remain engaged for most portions of the flight to allow the occupant of the wheelchair to make certain medically necessary seating adjustments, such as tilt and recline. Assuming battery retention can be demonstrated for a wide range of wheelchairs in accordance with FAA crash performance requirements, the battery's engagement and disengagement during flight would need to be addressed by standards along with the temporary disabling of certain seat functions during some periods of flight. Seat functions are activated by the occupant and will stop when the electronic control mechanism is released and when the power is disengaged. However, if inadvertent activation is a concern, it is reasonable to assume that wheelchair manufacturers could develop a pre-programmed "airplane mode" controller function that could be enabled at the flight attendant's direction to temporarily disable certain seat functions during critical flight phases, such as takeoff and landing and during turbulence. It is also reasonable to assume that flight attendants would be trained to provide such instructions to passengers occupying wheelchairs during critical flight phases similar to those required for passengers in regular airline seats (e.g., to fasten seat belts and adjust seats to the required position for turbulence, takeoff, and landing).

Finally, it is not possible to identify and examine all of the implications of more people with significant disabilities flying, but a thorough assessment of these implications would be needed if airplanes were equipped with wheelchair securement systems. For instance, a review of emergency evacuation standards and procedures might be in order to ensure that they remain effective and appropriate if more passengers with significant disabilities occupy the cabin.

---

[4] 49 CFR, § 175.10; see https://www.ecfr.gov/cgi-bin/retrieveECFR?gp=1&SID=bba5ad06518b529c94e1d67a3270196b&ty=HTML&h=L&r=SECTION&n=49y2.1.1.3.12.1.25.5e-DFR.

[5] See IATA. 2021. *Battery Powered Wheelchair and Mobility Aid Guidance Document.* https://www.iata.org/contentassets/6fea26dd84d24b26a7a1fd5788561d6e/mobility-aid-guidance-document.pdf.

CONCLUSIONS AND RECOMMENDATIONS

After reviewing the available information, as summarized in the findings above, the committee did not identify any issues in this preliminary assessment of technical feasibility that seem likely to present design and engineering challenges so formidable that they call into question the technical feasibility of an in-cabin wheelchair securement system and the value of exploring the concept further. While the report's analyses and findings suggest that equipping enough airplanes with securement systems to provide meaningful levels of airline service would require substantial effort, the types of cabin modifications required to provide the needed space and structural support would likely be of moderate technical complexity for many individual airplanes. Further assessments, including efforts to fill the information gaps identified in this report, would appear to be warranted, particularly to understand how secured personal wheelchairs are likely to perform relative to FAA's safety criteria in restraining and protecting occupants during a survivable airplane crash or emergency landing. The committee believes that such follow-on assessments are warranted because the many feasibility issues that could indeed be assessed using the information at hand appear to be manageable from a technical perspective. Concerted efforts to understand the remaining technical uncertainties through more focused analysis and testing, as described in the recommendations offered next by the committee, would enable more informed public policy decisions about the feasibility and desirability of in-cabin wheelchair securement systems.

- **The U.S. Department of Transportation and the Federal Aviation Administration (FAA) should establish a program of research, in collaboration with the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) and the assistive technology industry, to test and evaluate an appropriate selection of WC19-compliant wheelchairs in accordance with applicable FAA crashworthiness and safety performance criteria.** The research program should address, but not be limited to, assessing the performance of WC19 wheelchairs secured in an airplane cabin during a survivable crash, an emergency landing, and severe turbulence by maintaining their form, restraining their occupants and protecting them from injury, retaining batteries and other items of mass, and providing adequate fire resistance. Consideration should be given to different conditions experienced in flight, such as the occurrence of unexpected severe turbulence while a wheelchair's seat position functions are activated (e.g., leg elevation, recline, and tilt). The research should be conducted to inform decisions that may need to be made by the U.S. Department of Transportation (U.S. DOT) and FAA in response to petitions and other requests for in-cabin wheelchair securement systems to be allowed or even required on passenger airplanes; by RESNA and the assistive technology industry to identify opportunities to align existing wheelchair transportation safety standards with performance criteria required for airplane transportation; and by the airline and aircraft industries to more fully understand the implications of and opportunities for providing travelers who are nonambulatory and have significant disabilities the ability to remain seated in their personal wheelchairs during flight.

- **The U.S. Access Board should sponsor studies that assess the likely demand for air travel by people who are nonambulatory if they could remain seated in their personal wheelchairs in flight.** The studies should estimate the total demand for this service as well as the nature of this demand, including the demand by people with varying degrees of impairment. The studies should assess both the extent to which and how people with different disabilities are likely to use the securement systems, which could better define the space needed in the airplane cabin for wheelchair maneuvering and securement, provide insight into passenger support and service assistance requirements, and inform airline decisions about needed levels of fleet coverage and flight availability.

Ideally, these recommended next steps of research, testing, and evaluation would be planned and programmed in a systematic manner—or in accordance with a high-level "roadmap"—that takes into account the series of follow-on decisions and work that would be needed depending on the research, testing, and evaluation results. Numerous issues would need to be addressed in concert and stepwise. For instance, it would be important to find ways to ensure that wheelchairs brought on board an airplane cabin do not create security issues and are kept crashworthy as they age and are potentially modified. A fuller understanding of the training requirements for airline personnel will be needed along with testing and simulations to confirm the actual amount of cabin space required for wheelchair maneuvering and securement, and the in-flight use of essential wheelchair seat position functions. A more in-depth understanding of the likely travel experience of passengers using the systems will be needed, along with the implications of their installation and use on airline operations and economics.

A strategic roadmap that identifies and connects these issues and follow-on requirements could be important for sustained progress toward the realization of in-cabin wheelchair securement systems should evaluations indicate continued promise. The roadmap could contain key decision points where information from the results of testing and analyses can be assessed for confidence and on the basis of risk analysis to define and prioritize next steps for information gathering and for furthering engineering and design activities, standards and regulation development, and practical requirements for implementation (e.g., personnel training requirements). U.S. DOT would be the logical lead for the development of such a roadmap in collaboration with the agencies and entities identified in the recommendations above and with consultation and input from a wide range of interests and experts, including the airlines and their passenger service personnel, airframe manufacturers and interior component suppliers, people with disabilities and their advocates, and the assistive technology industry.

Inasmuch as Congress called for this study, the committee trusts that Congress will consider these recommendations and the need for agency resources to execute them.

Appendix A

Legislative Request

FEDERAL AVIATION ADMINISTRATION REAUTHORIZATION ACT OF 2018

SECTION 432 STUDY ON THE FEASIBILITY OF IN-CABIN WHEELCHAIR RESTRAINT SYSTEMS

SEC. 432. STUDY ON IN-CABIN WHEELCHAIR RESTRAINT SYSTEMS.

(a) STUDY.—Not later than 2 years after the date of enactment of this Act, the Architectural and Transportation Barriers Compliance Board, in consultation with the Secretary of Transportation, aircraft manufacturers, air carriers, and disability advocates, shall conduct a study to determine—

(1) the feasibility of in-cabin wheelchair restraint systems; and
(2) if feasible, the ways in which individuals with significant disabilities using wheelchairs, including power wheelchairs, can be accommodated with in-cabin wheelchair restraint systems.

(b) REPORT.—Not later than 1 year after the initiation of the study under subsection (a), the Architectural and Transportation Barriers Compliance Board shall submit to the appropriate committees of Congress a report on the findings of the study.

Appendix B

Committee Biographical Information

Alan M. Jette (NAM) (*Chair*) is a professor and the dean emeritus at the Boston University Sargent College of Health & Rehabilitation Sciences. He also serves as a professor of rehabilitation sciences at the Massachusetts General Hospital Institute of Health Professions. He was a professor of health policy and management at the Boston University School of Public Health from 2005 to 2017. He is an international expert on rehabilitation and a leader in developing patient-centered rehabilitation outcome measures in a range of challenging clinical areas such as work disability; post-acute care; spinal cord injury; and neurological, orthopedic, and geriatric conditions. He has authored more than 250 publications in the rehabilitation sciences field and served as a principal investigator for numerous studies funded by the National Institutes of Health; the National Institute on Disability, Independent Living, and Rehabilitation Research; the Agency for Healthcare Research and Quality; and several foundations. He has served as a member of more than a dozen National Academies boards and committees. He chaired the Institute of Medicine (IOM) committee that authored the 2007 report *The Future of Disability in America*. In addition to co-chairing the IOM Forum on Aging, Disability, and Independence, he was the chair of the IOM Committee on the Use of Selected Assistive Products and Technologies in Eliminating or Reducing the Effects of Impairments. Dr. Jette has received numerous professional awards and honors, including the American Physical Therapy Association's McMillan Award and the Foundation for Physical Therapy's Charles M. Magistro Distinguished Service Award. He was elected to the National Academy of Medicine in 2013. He earned a bachelor's degree in physical therapy from the State University of New York at Buffalo and a master's degree and a Ph.D. in public health from the University of Michigan.

Naomi Armenta is the principal planner in the Oakland, California, office of Nelson\Nygaard, which is a transportation and mobility planning consultancy. Her expertise is in planning accessible transportation with a focus on people with disabilities, seniors, and equity issues. She served as the paratransit coordinator for the Alameda County Transportation Commission from 2006 to 2016. She has also worked on projects in Contra Costa and Santa Clara Counties and for the Bay Area Rapid Transit system, the Metropolitan Transportation Commission (MTC), and the California State Transportation Agency. She has been affiliated with Nelson\Nygaard for 15 years. Prior to starting her career in transportation, she worked in the field of human resources for the U.S. Army, the U.S. Air Force Exchange Service, and the City College of San Francisco. She is the chair of the Bay Area Regional Mobility Management Group and is active in the Women's Transportation Seminar (WTS). In 2014, she received the Bay Area WTS Rosa Parks Diversity in Leadership Award and the MTC Doris W. Kahn Accessible Transportation Award. She earned a bachelor's degree from the University of California, Berkeley, in anthropology and psychology, and a master's degree in transportation management from the Mineta Transportation Institute at San José State University.

Peter W. Axelson is the founder and the director of research and development of Beneficial Designs, Inc., a rehabilitation engineering design firm that works toward universal access through research, design, and education. The company has developed a variety of technologies to improve seating and mobility systems for people who use wheelchairs, as well as design improvements for recreational and fitness equipment for people with mobility impairments. Beneficial Designs has guided the development of universal design standards for sidewalks, trails, ski areas, amusement parks, playgrounds, and other outdoor recreation environments. Mr. Axelson has served on the American Trails Board of Directors, standards committees for the Recreation Access Advisory Committee to the U.S. Access Board, and the Regulatory Negotiation Committee on Outdoor Developed Area Guidelines. He is the secretary of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) Standards Committee on Adaptive Ski Equipment and the RESNA Standards Committee on Wheelchairs. He serves on the Board of Directors of the Paralyzed Veterans of America Research Foundation. He is a regular guest lecturer in the Perspectives in Assistive Technology course at Stanford University. He earned bachelor's and master's degrees in mechanical engineering and product design from Stanford University.

Rory A. Cooper is the assistant vice chancellor for research at the University of Pittsburgh and a Distinguished Professor and the FISA Foundation and Paralyzed Veterans of America Professor of Rehabilitation Engineering in the School of Health and Rehabilitation Sciences at the University of Pittsburgh. He holds appointments in the Departments of Bioengineering and Physical Medicine and Rehabilitation. He is also an adjunct professor of computer science at Carnegie Mellon University (Robotics Institute) and physical medicine and rehabilitation at the Uniformed Services University of the Health Sciences. He is the founder, the director, and the chief executive officer of the U.S. Department of Veterans Affairs' (VA's) Human Engineering Research Laboratories at the University of Pittsburgh and the senior research career scientist and the research center director for the VA. From 1997 to 2018, he served as the chair of the Department of Rehabilitation Science and Technology at the University of Pittsburgh. His research has centered on the engineering, invention, design, evaluation, and transfer of assistive technologies, including wheelchairs, robotics, and smart devices. He has authored more than 375 peer-reviewed journal papers and 10 books in the field of rehabilitation science and engineering and holds more than 20 patents. Among his many honors, he has been named a fellow of the American Association for the Advancement of Science, the Royal Society of Medicine, the National Academy of Inventors, and the Biomedical Engineering Society. He was a member of the National Academies Committee on the Use of Selected Assistive Products and Technologies in Eliminating or Reducing the Effects of Impairments. Dr. Cooper earned a B.S. and an M.S. in electrical engineering from California Polytechnic State University and a Ph.D. in electrical and computer engineering from the University of California, Santa Barbara.

Karen J. Erazo is the retired manager of legal affairs at Sun Country Airlines, where she worked for 28 years, including as a customer service agent and a customer service manager. At Sun Country, she was responsible for ensuring compliance with several federal statutory and regulatory requirements, including those from the Aviation Disaster Family Assistance Act and the Air Carrier Access Act. She responded to employee and passenger complaints filed with the Equal Employment Opportunity Commission, the U.S. Department of Transportation (U.S. DOT), and the Occupational Safety and Health Administration and investigated passenger claims for injury, loss, and harassment. She was responsible for establishing the airline's policies and procedures for ensuring compliance with federal regulations on non-discrimination on the basis of disability in air travel, including responsibility for training employees on compliance. She led the development of the airline's initial Critical Incident Response Plan program for flight attendants. As Sun Country's representative, she attended U.S. DOT's

Access Advisory Committee for a 2016 negotiated rulemaking on accessible in-flight entertainment, lavatories, and the definition of service animals. She earned a bachelor's degree from the University of Minnesota.

Francis S. Heming, Jr., is an independent consultant specializing in the testing and certification of aircraft seating systems, including dynamic test planning, implementation, and witnessing. For nearly 25 years, he worked for Goodrich Interiors, retiring as the chief engineer for certification in 2015. While working for Goodrich Interiors, he served as the vice chair and the chair of the Society of Automotive Engineers Aircraft Seat Committee, which is responsible for the development of aircraft seat systems design and performance standards in conformance with the Federal Aviation Administration (FAA) and international regulations. He is an FAA Designated Engineering Representative for aircraft seats and interior arrangements. Before joining Goodrich Interiors, he worked for 20 years at the U.S. Department of the Air Force, retiring as a program manager in 1990. He holds a bachelor's degree in engineering mechanics from the U.S. Air Force Academy, a master's degree in applied mechanics from Stanford University, and a Ph.D. in mechanical engineering from Carnegie Mellon University.

Kevin L. Hiatt is a safety practitioner who consults on the application of safety management systems in the transportation industry. He is a retired airline pilot and executive. He has more than 40 years of aviation industry experience, including in the areas of flight operations, safety and security, and environmental administration. From 2015 to 2017, he was the director of flight safety for JetBlue Airways, where he oversaw flight operational safety issues and aided in the development and implementation of the airline's safety management system. Prior to joining JetBlue, he served as the senior vice president of safety and flight operations for the International Air Transport Association (IATA), where he was responsible for six worldwide operational and safety divisions with more than 100 team members. Before joining IATA, he was the president and the chief executive officer of the Flight Safety Foundation, an international nonprofit organization that provides independent expert safety guidance and resources for the aviation and aerospace industry. Prior to joining the Flight Safety Foundation, he was the vice president of safety and security at World Airways and worked for 26 years as a pilot for Delta Air Lines. He retired from Delta as a captain and the chief pilot for international operations. He is the recipient of several aviation safety awards, including the Flight Safety Foundation's President's Award, a Royal Aeronautical Society Fellow, and the SAFE Industry's General Spruance Award for outstanding safety education programs. He earned a bachelor's degree in aviation from Purdue University.

Katharine M. Hunter-Zaworski is an associate professor in the School of Civil and Construction Engineering at Oregon State University, where she also serves as the chair of the Subcommittee on Gerontology for the Center on Healthy Aging Research. Her area of expertise is in rehabilitation and transportation engineering for accessible transportation. From 2003 to 2014, she was the director of the National Center for Accessible Transportation, and from 2003 to 2009, she was the director of the Rehabilitation Engineering Research Center for Accessible Public Transportation. During her 40-year career, she has authored numerous journal papers and served as the principal investigator (PI) for dozens of studies on improving bus, rail, and airline accessibility for persons with disabilities; wheelchair securement and restraint in public transportation vehicles; and the barriers and safety risks for transportation-disadvantaged air travelers. She has consulted extensively on accessible transportation, including on projects for rail and transit systems in Vancouver and elsewhere in British Columbia and Canada. She has worked on making train and aircraft lavatories more accessible. She is an emeritus member of the Transportation Research Board's (TRB's) Committee on Accessible Transportation and Mobility, a member of the TRB Rail Rolling Stock and Motive Power Committee, and a past member of the TRB Airport Terminals and Ground Access Committee. She was the PI for Transit Cooperative Research Program (TCRP) Report 171, *Use of Mobility Devices on Paratransit Vehicles and Buses*, and TCRP Report 189, *Manual to Improve Rail Transit Safety at Platform/Train and Platform/Guideway Interfaces*. She is currently the PI for the Airport Cooperative Research Program synthesis project on escalator falls. She earned a B.S. in mechanical engineering from the University of British Columbia, an M.S. in engineering science and mechanics from the University of Tennessee, Knoxville, and a Ph.D. in civil engineering from Oregon State University.

George A. Lesieutre is the associate dean for research and graduate programs in the College of Engineering at The Pennsylvania State University. From 2004 to 2016, he served as a professor and the head of the Department of Aerospace Engineering, and from 2005 to 2018 he was the director of the Center for Acoustics and Vibration. His expertise is in aerospace structural dynamics and adaptive structures, and he is an instrument-rated private pilot. Prior to joining Penn State in 1989, he held positions at SPARTA, Rockwell Satellite Systems, Allison Gas Turbines, and the Argonne National Laboratory. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), which he has served in numerous capacities, including as the director-at-large; the chair for the Adaptive Structures Technical Committee; and the general chair for the AIAA Science and Technology Forum (SciTech 2015), the world's largest aerospace-focused conference. Dr.

Lesieutre has received several awards, including the SPIE Lifetime Achievement Award in Smart Structures and Materials (2020), the AIAA Structural Dynamics and Materials Lecturer (2014), the AIAA Zarem Educator Award, and the AIAA Sustained Service Award, in addition to five national best paper awards from multiple engineering societies (AIAA, the American Society of Mechanical Engineers, the American Helicopter Society [known as the Vertical Flight Society], and the Institute of Noise Control Engineering). He was a member of the Materials Panel of the National Academies' Aeronautics and Space Engineering Board's National Aeronautics and Space Administration Technology Roadmap. He earned a B.S. in aeronautics and astronautics from the Massachusetts Institute of Technology and a Ph.D. in aerospace engineering from the University of California, Los Angeles.

Miriam A. Manary is the lead research engineer in the Biosciences Group of the University of Michigan Transportation Research Institute (UMTRI). She has worked for UMTRI for more than 30 years, conducting research in the fields of wheelchair transportation safety, child passenger safety, occupant protection, vehicle ergonomics, and occupant accommodation. She conducts and supervises sled-impact evaluations of child restraints, wheelchairs, wheelchair securement systems, and wheelchair occupant restraint systems. In addition to her expertise in wheelchair transportation safety, she has extensive experience in the analysis of motor vehicle crashes, crash dummy design, injury criteria development, occupant anthropometry and posture qualification, engineering analysis of federal motor vehicle safety standards, child passenger safety, and the factors affecting child restraint installation errors. She is the chair of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) Committee on Wheelchairs and Transportation and led the 2012 and 2017 revisions of the RESNA Standards on Wheelchairs and Transportation. She has served as the head of the U.S. delegation for International Organization for Standardization (ISO) TC173/SC1/WG6 and has led the development efforts on ISO 7176-19 (Wheelchairs Used as Seats in Motor Vehicles) and ISO 10542-1 (Wheelchair Tiedowns and Occupant Restraint Systems). She also participates in Society of Automotive Engineers and ISO committees focused on child restraints. She holds a bachelor's degree in biomedical engineering from Tulane University and a master's degree in bioengineering from the University of Michigan.

Clinton V. Oster, Jr., is a professor emeritus and the former associate dean for the Paul H. O'Neill School of Public and Environmental Affairs at Indiana University. His research has centered on aviation safety, airline economics and competition policy, energy policy, and environmental and natural resource policy. He has co-authored five books on various aspects of air transportation, including *Deregulation and the Future of Intercity Passenger Travel* with John Meyer, and *Why Airplanes Crash* with John Strong and C. Kurt Zorn. He has chaired and served on numerous National Academies committees, including as the chair of the Committee for the Study of Traffic Safety Lessons from Benchmark Nations, the chair of the Committee on the Federal Employers' Liability Act, the chair of the Committee on the Effects of Commuting on Pilot Fatigue, and the co-chair of the Committee on the National Aeronautics and Space Administration's National Aviation Operational Monitoring Service Project. He was a member of the Committee for Guidance on Setting and Enforcing Speed Limits, the Committee for a Study on Air Passenger Service and Safety Since Deregulation, and the Committee on the Intercity Passenger Travel: Opportunities and Issues in Short-Haul Markets. He holds a bachelor's degree in engineering from Princeton University, a master's degree in public affairs from Carnegie Mellon University, and a Ph.D. in economics from Harvard University.

Gary M. Weissel is the founder and the managing officer of Tronos Aviation Consulting, which provides a wide variety of services to airlines, leasing companies, original equipment manufacturers (OEMs), and suppliers in the aviation industry, including services pertaining to aircraft interiors and modifications and conversions. In this position, he leads all of the firm's activities, including asset management, aircraft specification and interior management, market forecasting, and OEM strategy consulting. Prior to starting Tronos, he was the co-managing officer of aviation and aerospace practice at ICF International's Simat, Hellisen and Eichner, Inc. (ICF SH&E), known since 2014 as ICF Aviation, where he led the firm's staff of more than 50 consultants in 7 offices worldwide. Before joining ICF SH&E, he was a senior program manager with B/E Aerospace's Seating Products Group, where he ran numerous seating programs for major international airlines. Prior to that, he spent 9 years with Delta Air Lines in various positions within its engineering and technical specification departments. He is a member of the Senior Advisory Board and a guest lecturer for the Georgia Institute of Technology School of Aerospace Engineering. He was the lead author for the International Air Transport Association's Best Practices Guide for cabin interior retrofits and entry into service programs. He is a frequent speaker at industry conferences, is regularly quoted in industry publications, and has appeared on CNN and *NBC Nightly News* as an aviation expert. He holds a bachelor's degree in aerospace engineering from the Georgia Institute of Technology.

Appendix C

Disclosure of Unavoidable Conflicts of Interest

The conflict of interest policy of the National Academies of Sciences, Engineering, and Medicine (http://www.nationalacademies.org/coi) prohibits the appointment of an individual to a committee authoring a Consensus Study Report if the individual has a conflict of interest that is relevant to the task to be performed. An exception to this prohibition is permitted if the National Academies determines that the conflict is unavoidable and the conflict is publicly disclosed. A determination of a conflict of interest for an individual is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

Dr. Francis S. Heming, Jr., has a conflict of interest in relation to his service on the Committee for a Study on the Feasibility of Wheelchair Restraint Systems in Passenger Aircraft because he consults for an aerospace company that supplies aircraft seats; other cabin interior products; and other aviation systems, equipment, and services to airlines and other owners of aircraft.

The National Academies has concluded that for this committee to accomplish the tasks for which it was established, its membership must include at least one person who has detailed knowledge of federal and international standards governing the safety of aircraft seats and expertise in the engineering, testing, and certification of seats to meet these standards. It is reasonable to assume that these safety standards would need to be met by wheelchairs when used as passenger seats on aircraft. As described in his biographical summary, Dr. Heming has extensive experience and specialized expertise in the testing and certification of aircraft seats, including lengthy past service on relevant standards committees.

The National Academies has determined that the experience and expertise of Dr. Heming is needed for the committee to accomplish the task for which it has been established. The National Academies could not find another available individual with the equivalent experience and expertise who does not have a conflict of interest. Therefore, the National Academies has concluded that the conflict is unavoidable.

The National Academies believes that Dr. Heming can serve effectively as a member of the committee, and the committee can produce an objective report, taking into account the composition of the committee, the work to be performed, and the procedures to be followed in completing the study.

Mr. Gary M. Weissel has a conflict of interest in relation to his service on the Committee for a Study on the Feasibility of Wheelchair Restraint Systems in Passenger Aircraft because his firm has consulting agreements with airlines, including consulting on aircraft cabin interior planning and management.

The National Academies has concluded that for this committee to accomplish the tasks for which it was established, its membership must include at least one person who has current experience in airline cabin interior arrangements. As described in his biographical summary, Mr. Weissel has extensive and broad current experience pertaining to aircraft interior design, modification, and conversions.

The National Academies has determined that the experience and expertise of Mr. Weissel is needed for the committee to accomplish the task for which it has been established. The National Academies could not find another available individual with the equivalent experience and expertise who does not have a conflict of interest. Therefore, the National Academies has concluded that the conflict is unavoidable.

The National Academies believes that Mr. Weissel can serve effectively as a member of the committee, and the committee can produce an objective report, taking into account the composition of the committee, the work to be performed, and the procedures to be followed in completing the study.