GUIDELINE

ASHRAE Guideline 23-2016

Guideline for the Design and Application of Heating, Ventilation, and Air-Conditioning Equipment for Rail Passenger Vehicles

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NOTE

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(This foreword is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

FOREWORD

This guideline was developed in response to a need expressed within the rail passenger vehicle industry to adopt a more consistent approach to the design and application of heating, ventilating, and air-conditioning systems in rail passenger vehicles that can be used as a basis for future designs. This need evolved from informal discussions among the rail vehicle industry's operating, supply, and technical support members and several different professional committees that work to address rail passenger vehicle issues, including the American Public Transit Association (APTA), the American Society of Mechanical Engineers (ASME), and the Rail Transit Standards Committee (RTSC), a Division of the Institute of Electrical and Electronics Engineers (IEEE).

Current inconsistent design approaches and sometimes widely varying requirements for similar applications have resulted in minimal standardization, excessive development efforts for similar equipment, and the resulting inefficiency and disproportionately high cost of equipment. In an attempt to find an approach that would address the concerns of all interested parties, participation was solicited from different areas of the industry, including operating authorities, supply industry, labor, government regulatory authorities, and the industry consulting community. Based on the interest of persons and entities in participating in this effort it was further agreed to form an ASHRAE Guideline Project Committee (GPC) under the supervision of ASHRAE Technical Committee (TC) 9.3, Transportation Air Conditioning to perform this task.

This document conveys what GPC 23 has jointly determined through experience and successful practice to be technically appropriate and reasonable design, application, and testing guidelines for this equipment.

1. PURPOSE

To establish recommended design and application guidelines necessary to achieve an acceptable level of performance and safety for heating, ventilating, and air-conditioning equipment used on rail passenger vehicles operating in the environment of rail transportation systems.

2. SCOPE

This guideline addresses rail passenger vehicles used in regularly scheduled public transportation service.

2.1 The guideline addresses environmental conditions, equipment configurations, air filtration, temperature and humidity controls, determination and test verification of heating and cooling capacity, ventilation standards, passenger comfort criteria, materials, packaging, noise, vibration and shock, refrigerant selection, energy efficiency, corrosion protection, voltage and electrical requirements, power supply, and electromagnetic interference.

3. DEFINITIONS, ABBREVIATIONS, AND ACRONYMS

3.1 Definitions

actual cubic feet per minute: the volume of gas flowing anywhere in a system, independent of its density.

articulation bellows: a flexible enclosed passageway between two semipermanently joined vehicles or vehicle segments in a train.

bump start: a refrigerant compressor-starting control method consisting of short-duration, timed power application pulses employed to minimize potential flooded start damage prior to sustained power application.

catenary: the system of wires suspended above the track, also referred to as the *overhead contact system* (OCS), that supplies power to electrically powered trains equipped with roof-mounted sliding power pickups (pantographs).

consist: a coupled group of rail vehicles that operates as a single unit.

cubic feet per minute: a unit of measurement for the flow of a gas or fluid over time.

duct limit thermostat: a thermostatic control, located with the HVAC system's conditioned supply air, used to prevent excessively high air temperature from ceiling distributors from creating thermal discomfort due to temperature stratification.

head-end power (HEP): electric power for train auxiliary systems provided from a power supply system (alternator, generator, inverter, etc.) and usually located in the lead locomotives of a passenger train.

hermetically sealed unit: refrigeration system having no or a minimum number of mechanical refrigerant system connections.

kazoo: a term used in railcar HVAC applications for a resilient elastomeric device installed on the end of an evaporator coil condensate drain pipe and designed to hold a small column of water to mitigate the undesirable intake of untreated air and other contamination.

microclimate: localized climatic conditions (temperature, humidity, motion of air, etc.) within a relatively small area that may not represent the prevailing climatic conditions.

modulation (capacity): reduction of HVAC system cooling capacity, normally affected by a reduction of the refrigerant compressor net pumping capacity.

multiple unit: self-propelled electric- or diesel-powered (EMU or DMU) rail vehicles designed to operate independently (without locomotives) and equipped with automatic coupler equipment to facilitate efficient additions or separations of vehicles from the train consist with minimal manual intervention.

pull-down/pull-up: HVAC system operation mode/period where the system is activated in a space to be conditioned following a period where the space has been allowed to stabilize at the prevailing external ambient conditions.

rail transit vehicle:

> ***rail transit vehicle (commuter):*** rail passenger vehicles typically used in medium- to high-density public transit

service between suburban areas and metropolitan areas (sometimes referred to as *suburban or regional rail service*). Typical train configurations include locomotive-hauled, push-pull (locomotive either "pushes" unpowered coaches from behind with controlling cab car in the lead position or "pulls" and controls from a lead position) consist or self-propelled electric or diesel multiple-unit (MU) train consists. Passenger coach interiors normally are equipped with high-density upholstered seating with proportionately limited space for standing passengers. Service is characterized by multiple but less frequent stops and door openings (typically 5 to 10 minutes between stops) as compared to urban vehicle service.

rail transit vehicle (intercity or long distance): rail passenger vehicles typically used in long-distance transit service on main line railways between metropolitan areas. Train configuration is typically electric or diesel-electric locomotive hauled. Passenger vehicles used in this service may be equipped with toilet rooms, food service facilities and dining areas, sleeping compartments, and related amenities and typically draw electrical power from an auxiliary power supply unit on the locomotive. Passenger coach interiors are typically fitted with comfortably spaced and configured seating and vestibule-isolated exit and entry doors. Service is characterized by infrequent stops (typically 15 to 30 minutes or more) at large metropolitan area stations.

rail transit vehicles (urban): rail passenger vehicles used in high-density urban passenger public transportation service. This category of vehicles most commonly encompasses two major subcategories of vehicles that are electric powered from a third rail or overhead-wire high-voltage DC power source: light rail vehicles and subway and subway/elevated cars (sometimes referred to as *rapid transit vehicles*). Typical vehicle configuration consists are multiple-unit with limited austere seating and proportionately large standing areas. Urban rail transit vehicle operating conditions normally include short-duration rides; rapidly changing high-occupancy passenger loads (mostly standing) during peak commute travel times; and frequent (typically 1 to 5 minutes), short-duration station stop intervals and corresponding door openings.

a. ***light rail vehicle (LRV):*** an urban rail transit vehicle that is typically a bidirectional unit with an operating cab on each end and made up of two or more articulated sections. LRVs are normally powered by an overhead electric contact wire and are designed to operate either as a single vehicle or in multiple vehicle consists. LRVs are designed to operate and load/unload passengers at street level, adjacent to normal street traffic, as well as on fixed exclusive at-grade, subway, or elevated rights-of-way. Street cars and trams are similar to LRVs in configuration and service but typically operate at lower speeds in inner urban applications. They are included in this category with regard to HVAC design.
b. ***rapid transit vehicle:*** an urban rail transit vehicle that is typically used in large-city subway or subway/surface/elevated service. Individual rapid transit vehicles are normally shorter in length than intercity rail transit and commuter vehicles and are usually operated in electric multiple consists powered from a high-voltage DC contact rail. Passenger access is from fixed station platforms level with multiple side-door openings (2 to 4 doorways per side) for rapid passenger loading/unloading.

self-contained system: see *unitized system*.

split system: an HVAC system consisting of two or more components and/or assemblies that are installed separately and must be piped and/or wired together after installation.

standard cubic feet per minute: the volumetric rate of flow of air that is at standard conditions.

stratification (thermal): division into a series of layers of thermal gradients across a stream.

superelevation (track): special track geometry used in a railroad curve whereby the outsidemost rail is raised above the level of the inside rail to counteract unbalanced dynamic lateral forces on the railcars and passengers when traversing the curve.

thermal short/thermal bridge: a low thermal resistance path connecting two surfaces.

third rail: a high-voltage DC electrical power bus located adjacent to certain railroad tracks that serves as a power source for railcars equipped with sliding contact power pickup shoes.

unitized system: an HVAC system in which all of the major system components are contained within a single unit designed for simple removal and replacement (also referred to as a *packaged*, *self-contained*, or *modular system*).

3.2 Acronyms

AC	alternating current
acfm	actual cubic feet per minute
AFS	airflow switch
APS	auxiliary power supply
APU	auxiliary power unit
APTA	American Public Transit Association
ASME	American Society of Mechanical Engineers
cfm	cubic feet per minute
CFR	Code of Federal Regulations
CR	climate room
CRT	climate room test
db	dry-bulb temperature
DC	direct current
DMU	diesel multiple unit
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMU	electric multiple unit
EN	European Norm
EPA	Environmental Protection Agency
ESP	external static pressure

EUT	equipment under test
HCFC	hydrochlorofluorocarbon
HEP	head-end power (see Section 3.1)
HFC	hydrofluorocarbon
HVAC	heating, ventilating, and air conditioning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LRV	light rail vehicle
LST	local standard time
MOPD	maximum operating pressure differential
MPS	modulating pressure switch
MU	multiple unit (see Section 3.1 for definition)
NFPA	National Fire Protection Agency
OCS	overhead contact system
OEM	original equipment manufacturer
PAX	number of passengers
PTU	portable test unit
PTE	portal test equipment
PVB	polyvinyl butyral
RTVISC	Rail Transit Vehicle Interface Standards Committee (subdivision of IEEE)
SC	shading coefficient
scfm	standard cubic feet per minute
SHGC	solar heat gain coefficient
rh	relative humidity
TPU	thermoplastic polyurethane
TXV	thermal expansion valve
UA (factor)	overall heat transfer coefficient
UL	Underwriters Laboratory
wb	wet-bulb temperature

4. COMFORT CRITERIA

The purpose of this section is to define guidelines that have been found to be successful in achieving acceptable thermal comfort in passenger railcars equipped with HVAC equipment.

4.1 General Comfort Considerations. The type of rail transportation service (i.e., urban rapid transit, commuter, long distance, etc.) and the corresponding expectation of comfort are important factors for the designer to consider in selecting the temperature and humidity control parameters and in designing the air-conditioning equipment to meet them. ASHRAE Standard 55 [1] may be referenced to determine the railcar interior thermal environmental factors that will provide environmental conditions acceptable to a majority of the passengers. The following factors typically encountered during rail travel should also be considered:

a. Changes in regional microclimates caused by local geography along the railcar's route
b. Air infiltration, drafts, and rapid temperature changes associated with door openings
c. Thermal stratification (vertical air temperature variation)
d. Velocity of air at passenger level (seated and standing passengers)
e. Radiation effects of windows and structure
f. Solar loading variation due to dynamically changing solar orientation
g. Clothing insulation
h. Temperature recovery capability and preconditioning for passenger occupancy
i. Contribution of HVAC system to overall vehicle noise (See Section 8.)
j. Length of journey

4.2 Guideline Comfort Criteria. The comfort criteria guideline parameters and design features stated herein are based on practices that have been used by the rail transit industry and have resulted in acceptable levels of railcar comfort. The operating authority and designer should determine if these guidelines are suitable for the application intended and make adjustments accordingly. Many of these parameters are interdependent. It is recommended that a designer/operator wishing to consider the interaction of all the factors consult ASHRAE Standard 55 [1].

Unless otherwise indicated, the comfort criteria contained herein assumes that all HVAC equipment is operating as intended and that thermal conditions have stabilized.

4.2.1 Air Motion. Controlling air motion within an acceptable range in a passenger railcar is an essential element of passenger comfort. Compared to a residential or commercial building HVAC system, the high occupant density and restricted space of a typical rail passenger vehicle make air distribution very challenging. Higher air velocities are normally desirable during high temperature and humidity operation when maximum cooling is required; whereas high velocities constitute uncomfortable drafts when in heating or low-level cooling operation. Ideally, a variable-air delivery system would help tailor the air delivery volume/air velocity to the optimal condition, but because most existing railcar HVAC systems have a nonvariable airflow design, a range must be selected that will best accommodate both extremes. In some areas, most notably the operator's cab, the benefit of variable-air velocity is achieved by individual adjustable means, such as locally controlled fans or adjustable spot diffusers, as there are wide differences in personal preference. These type controls are also possible in certain long-distance coach applications but are generally not practical for application in the passenger areas of urban or commuter rail vehicles. The air velocity limits shown in Table 4-1 are recommended in conjunction with the corresponding temperature and humidity control guidelines contained in Table 4-2.

4.2.2 Temperature Variation (Table 4-3). Depending on the type of service (e.g., urban, commuter, or intercity), conditions that influence the temperature balance in the passenger compartment can change rapidly. Frequent exterior door openings and the entry and egress of passengers through multiple doorways exposed directly to the passenger-occupied areas characterize urban and some commuter rail operations.

TABLE 4-1 Maximum Air Velocity, fpm

	Urban	Commuter	Intercity
Floor to 43 in. above floor	70	60	50
43 to 67 in. above floor	100	85	70
Berthing areas	—	—	40

TABLE 4-2 Typical Temperature Design Range Guidelines (60% maximum rh), °F

	Urban	Commuter	Intercity
Cooling mode design range [a]	71 to 75	71 to 75	71 to 75
Heating mode design range [a]	61 to 68	64 to 70	68 to 72

a. Cooling/heating temperature control mode transition is usually affected based on exterior ambient temperature. It can be manually selected but is more often an automatic function. Typically, the changeover occurs at a specific temperature in the 40°F to 50°F (4.4°C to 10°C) exterior ambient temperature band. In other cases, a proportional shift of the interior control setpoint occurs over a corresponding band of exterior temperature. Whichever scheme is selected, the changeover should be sufficiently buffered so that abrupt temporary ambient temperature changes, such as those that may be encountered in tunnel entry/ exit and in protected stations, will not cause the HVAC equipment to attempt rapid overcompensation that would result in interior temperature discomfort.

TABLE 4-3 Temperature Variation Guidelines [a], °F

	Urban	Commuter	Intercity
Vertical (transverse plane) The maximum difference between any two points located in any plane situated perpendicular to the longitudinal axis of the car, one point at 4 in. (102 mm) above floor and the other point at 43 in. (1090 mm) above the floor, not closer than 6 in. (150 mm) from wall, and not closer than 20 in. (500 mm) from exterior doors.	7	6	4
Horizontal Plane The average temperature in a horizontal plane measured 4 in. (102 mm), 43 in. (1090 mm), and 67 in. (1702 mm) from the floor and any other point in that plane, not closer than 6 in. (150 mm) from walls and not closer than 20 in. (500 mm) from exterior doors.	±3	±3	±2
At return-air grilles, the maximum variation with one or more cycles from a steady-state average.	±1.5		

a. For multilevel-vehicle designs, each level may be evaluated independently.

Intercity coaches more often have far less frequent station stops, and passengers typically enter and egress the vehicles through end-of-car vestibules that contain a secondary door that provides an additional level of environmental isolation from the passenger compartment. Because it is highly impractical to accurately simulate these dynamic conditions in a test environment, evaluation of these criteria are best made under stabilized conditions with all doors closed for the duration of the evaluation measurements. Additional separate tests are normally performed to evaluate the ability of the vehicle's HVAC system to recover from the rapid in-service changes encountered, such as door openings at stations.

Another important factor to consider when specifying and evaluating temperature uniformity is the thermal load contribution of the occupants. When evaluating temperature uniformity during low exterior ambient winter design conditions, the evaluation is most often made without any passenger load since this condition (without the thermal contribution of passenger load) represents the maximum heating demand and all apparatus is operating at or near full capacity. When temperature uniformity is evaluated in high ambient cooling design conditions, the design passenger sensible and latent load is usually simulated, as this test is also used to verify that the air conditioning and dehumidification capacity requirements are met. However, the passenger and solar-heat-load simulation apparatus location and distribution relative to the temperature and humidity measuring sensors can inaccurately skew the results.

For this reason, the temperature uniformity results obtained with simulated thermal loads should be considered secondary in accuracy to the temperature balance results of the low ambient heating temperature balance results.

4.3 Temperature and Humidity Design Range. Table 4-2 provides suggested design ranges for different types of passenger rail service. These design ranges apply to the rated environmental conditions and passenger load under design conditions, which in most cases will be tested in a climate lab test for conformance. Actual interior temperatures may be expected to exceed the design range in when a combination of extreme environmental conditions, passenger overload, or operation occur beyond the rating conditions. The limits to which interior temperature may exceed the design range are defined in some cases in the equipment section and may have a specific test or analysis requirement for confor-

mance. In any case, these events are considered temporary in nature and may result in a higher percentage of discomfort for some people.

The maximum recommended relative humidity during rated design cooling mode operation is 60%.

During low ambient temperature operation, when heating is required, it is generally assumed that urban service passengers will be dressed in appropriate overclothes, which they will keep on during the relatively short duration of their trip; therefore, the recommended design range is several degrees lower than other service recommendations. Intercity passengers typically remove warm outer clothing for a journey of a longer duration; therefore the suggested temperature range is higher. Commuter passenger station stop frequency and length of journey are between the two extremes, also the passengers may or may not remove their outer clothing during the commute; therefore, these recommendations are adjusted accordingly. The customer specification will normally provide the specific requirements in this regard taking into account other factors such as regional differences in passenger expectations.

The suggested temperature design ranges shown in Table 4-2 represent current common practice, but to allow for unanticipated conditions that may influence the optimum comfort settings, it is recommended that the control logic be provided with sufficient adjustable parameters to allow the operator's authorized maintenance personnel to adjust the control range up or down by at least 3°F (1.5°C).

Humidity levels are normally not specified for heating season operation, but it is recommended that the design consider humidity control during moderate ambient operation as a means of preventing surface condensation in these conditions. During operation at moderate ambient conditions, cooling equipment operation may not be necessary to satisfy the dry-bulb temperature control point. Current designs typically employ open-ended dehumidification control (humidity sensors are uncommon) by maintaining part-load air-conditioning operation after the dry-bulb temperatures are satisfied. Under this mode of operation, interior temperature is typically maintained by reheating the conditioned air with electric heating elements downstream of the evaporator coil. Although this simple method of maintaining dehumidification during low-load conditions has proven to be effective and reliable, its high energy use has come under increased scrutiny. Newer designs should consider means of minimizing the use of reheat control such as the use of reliable humidity sensors to restrict operation to only those times when necessary.

4.4 Thermal Recovery Rate. The need for a properly designed passenger railcar HVAC system to maintain stable interior environmental comfort throughout its specified range of external ambient conditions and changing passenger loads is of primary importance. However, consideration must also be given to the ability of heating and cooling equipment to respond quickly to sudden changes in the thermal load, which is a common occurrence in a rail passenger vehicle. Two related specified criteria are the pull-up/pull-down time and the thermal recovery following door open/closed cycles for passenger loading and unloading.

4.4.1 Pull-Up and Pull-Down Time. The pull-up/pull down time is the time required to raise (heating mode) or reduce (cooling mode) the temperature of the vehicle from an initial average air temperature, before passengers occupy the vehicles, to the specified temperature control range. The initial condition may be specified to be at an energy-conserving standby/setback control temperature (commonly called layover temperature), or the pull-up/pull-down requirement may be specified to start at a maximum heat- or cold-soak temperature, intended to simulate a vehicle being stored for a long period of time with the HVAC system turned off. The criteria are normally evaluated from the time the HVAC system is activated to the time when the average temperature reaches the design range. Key considerations in calculating the time required to reach the control temperature range are the available heating or cooling capacity, the car body thermal insulation, and the thermal inertia of the interior fittings, seating, and lining materials. Criteria for pull-up/pull-down time vary widely for different types of equipment, prevailing design ambient conditions, and operating practices, but times typically vary from 15 to 30 minutes from layover to control temperature range and from 30 minutes to 1 hour from cold/heat-soak to control temperature range.

Overly demanding requirements should be avoided as they may require oversized, inefficient equipment. Closing fresh air dampers (when automatic damper control is provided) can greatly reduce pull-up/pull-down time by closing off the outdoor air completely when the vehicle is in pull-up/pull-down mode prior to passenger loading.

4.4.2 Temperature Recovery During Revenue Operation With Door Cycling. Another condition where thermal recovery is important in passenger rail service is the ability to respond rapidly to unconditioned air entrance and resulting abrupt interior air temperature changes from door openings and passenger ingress and egress during normal revenue service. This condition is most prevalent in multidoor urban transit service, but is also a factor to a lesser extent on commuter and long-distance service. The main means of mitigation for door openings is car pressurization, as it tends to maintain an outflow of interior conditioned air and minimize the inrush of unconditioned outdoor air through the doorways. Unlike the pull-down/pull-up condition, the thermal inertia of preconditioned interior appointments helps to retain interior comfort despite rapid air changes if the door openings are of short duration. Under revenue service door-cycling conditions it is normally not possible to maintain the same level of interior temperature uniformity specified at stabilized conditions. However, under these conditions, the HVAC system, as a minimum, should be able to quickly recover the average interior temperature within the average door-closed interval and maintain this performance indefinitely without degradation of the average interior temperature.

In some applications, particularly areas directly adjacent to doorways, supplementary equipment such as wind screens, air curtains, and forced-air heaters are used to help mitigate the rapid temperature changes caused by door openings.

4.5 Surface Temperatures

4.5.1 Influence on Thermal Comfort. In addition to the previously discussed temperature and humidity conditions that influence the passenger environment, passenger comfort

can be adversely influenced by excessive nonuniform thermal radiation from the surrounding surfaces. This parameter is referred to as "radiant temperature asymmetry." Guidance on local discomfort caused by radiant asymmetry can be found in ASHRAE Standard 55 [1]. Typically, maximum acceptable levels in passenger railcars are based on 20% dissatisfied occupants.

4.5.2 Safety Considerations. To minimize the potential for injury, the design of heating apparatus should not produce excessive temperatures on surfaces that may be exposed to passengers or crew members. Recommended maximums in this regard are 125°F (52°C) for metallic surfaces and 145°F (63°C) for nonmetallic surfaces.

4.6 Solar Radiation Mitigation. Glazing specifically designed to reduce the effects of solar thermal radiation and to reduce interior car thermal loads is recommended for all vehicles that operate exposed to the exterior environment. Shades are recommended on intercity trains.

4.7 Spaces Separated from the Main Passenger Compartment. Some vehicles, mostly long-distance intercity type and some used in commuter service, have transient areas, such as vestibules and toilet rooms, that are not intended for prolonged occupancy and have less demanding thermal comfort requirements than the passenger-occupied areas. Some are indirectly controlled, relying solely on branch conditioned air ducts from the passenger compartment, while other applications have thermostatically controlled local heaters. Few if any have local air-conditioning devices or controls for unoccupied areas. The required comfort criteria in these areas can vary widely depending on the level of service and passenger expectations. At a minimum, temperature criteria for vestibule areas during stabilized conditions should prevent ice formation on the floor at minimum specified ambient operating conditions. During maximum ambient operating conditions, stabilized average vestibule temperature should not be more than 15°F (8.5°C) higher than the stabilized interior temperature. The minimum recommended criteria for stabilized average toilet room temperatures are that they should not vary more than 10°F (5.5°C) from the stabilized interior temperature when operating at all specified ambient conditions.

4.8 Supply Air Temperature. The majority of rail passenger vehicle HVAC systems distribute conditioned air from ceiling-mounted grilles or diffusers. Floor and sidewall distribution systems are also used in some applications but are not specifically addressed in this guideline. Care must be exercised in the layout, design, and adjustment of the air distribution devices to ensure uniform air distribution and mixing while avoiding uncomfortable drafts. Recommendations regarding air velocity are addressed in Section 4.2. The following recommendations apply to conditioned supply air temperature.

4.8.1 Heating Supply Air Temperature. With the HVAC equipment working in stable conditions, it is recommended that the supply air temperature be controlled several degrees above the interior temperature control point (approximately 3°F to 5°F [1.5°C to 3°C] is recommended, but no greater than 10°F [5.5°C]). Refer also to Section 8.3.1. Discharge temperature swings below setpoint will increase the possibility of discomfort from normal air circulation. Conversely, significant higher temperature excursions beyond this range have proven to result in thermal stratification that may cause passenger discomfort from the vertical temperature nonuniformity. In addition, the resulting uppermost high-temperature thermal strata can also significantly bias the temperature control sensors in or near the ceiling.

4.8.2 Cooling Supply Air Temperature. With the HVAC equipment working in stable conditions, supply air temperature during cooling operation should not be more than 25°F (14°C) below the average vehicle interior temperature. The design, insulation, and thermal isolation of the air distribution ducts and diffusers should be such as to prevent surrounding surface temperatures from falling below the conditioned area's dew-point temperature to help avoid condensation formation.

5. VENTILATION

5.1 Scope. This section provides recommended guidelines for the supply of outdoor ventilation air into air-conditioned passenger railcars where smoking is not permitted.

5.2 Ventilation, General. Outdoor air is typically introduced into a rail passenger vehicle's HVAC system return airstream by means of a separate ventilation fan or is drawn into the return airstream by the HVAC system's main supply air blower. The outdoor air passes through separate outdoor air filters or combined outdoor/recirculated air filters prior to entering the HVAC system cooling, dehumidification, and heating apparatus. In addition, depending on the type of service, number of station stops, and car configuration, some unprocessed outdoor air may also enter the passenger area directly when doors are opened. To mitigate the introduction of unprocessed outdoor air due to door openings, drafts, and air infiltration via door seal leakage when the vehicle is in motion, a positive pressurization of 0.05 to 0.15 in. of water (12.5 to 37.4 Pa) is normally recommended (measured at static conditions). Pressurization is achieved naturally by maintaining a well-sealed carbody structure and environmental seals (outside doors, windows etc.) such that sufficient static pressure is created by the supply of outdoor air and its restricted natural exhaust leakage through small gaps and resilient seals. On particularly well-sealed vehicles it may be necessary to add exhaust grilles (active or static as the application demands). Refer to Section 5.5.

Comprehensive research on the air quality on rail passenger vehicles of different types, passenger density, and service schedules is not currently available; therefore, the ventilation rates recommended in this guideline are based on a combination of accepted current best practice for passenger railcar HVAC design and requirements from similar environments contained in ASHRAE Standard 62.1 [2]. The suggested ventilation rate recommendations provided herein (Table 5-1) are expressed in cubic feet per minute per person at design passenger load. Passenger density on most transit vehicles varies significantly throughout the day from a few passengers during off-peak time to full capacity, including standees, at peak operating periods. The design passenger load, defined in the vehicle technical specification, is the basis for determining the ventilation and cooling capacity sizing of the HVAC equip-

TABLE 5-1 Cubic Feet per Minute per Person at Design Conditions[a]

	Urban Service	Commuter	Intercity
Minimum recommended ventilation rate	7.5	10	12

a. The design passenger and crew (if applicable) occupancy is normally defined in the vehicle specification. If not defined, the typical value used for HVAC design on intercity vehicles is "full seated" (all available seats occupied—also referred to as "AW1" load). For urban and commuter service, the design occupancy is typically defined as full seated plus a low-density standing passenger load. The standing passenger density typically used is 0.37 passengers/ft^2 (4 passengers/m^2), but there is no universally accepted norm in this regard. Airflow rates indicated assume actual cubic feet per minute values. In areas of significant air density difference, appropriate adjustments should be considered.

ment. Exceptional passenger loads above the design capacity may also be defined in the technical specification, but these infrequent short-term conditions are generally not considered in the ventilation criteria. Guidance for outdoor air quantities on other enclosed passenger compartments, such as berthing compartments, can be found in ASHRAE Standard 62.1 [2].

The vehicle and HVAC design should also consider means to address conditions where the vehicles may lose power for a significant amount of time en route and normal powered ventilation may not be available. Under these circumstances, interior temperature and air quality are likely to degrade rapidly to unacceptable conditions depending on passenger load and exterior conditions. Partially openable windows, battery-powered backup ventilation, or other means or procedures consistent with the operator's practice should be implemented to maintain safe conditions until the affected passenger compartments can be relocated or unloaded or power is restored.

5.3 Recommended Ventilation Rates. Recommended ventilation rates are shown in Table 5-1.

5.4 Variable Ventilation Control. Although past passenger railcar HVAC systems usually have staged cooling and heating controls to maintain the desired interior temperature, supply and ventilation airflow is typically fixed at the design airflow rates. Recent increased emphasis on reducing energy consumption, in addition to the improvement in design and reliability of variable-speed motor designs and variable damper controls, have now led to these features being specified in some new vehicle contracts. Some control schemes being considered are indirect means of matching ventilation airflow to passenger load using load (weight) sensors or electronic passenger counting systems. Other more direct means such as CO_2 concentration sensors are also being considered. More research on the effectiveness of variable airflow control schemes is needed before they are widely accepted by the industry.

The use of automatic powered dampers has, however, been adopted on many newer designs based on the ability of the operator to expeditiously shut off outdoor air from the vehicles if smoke or other hazardous exterior conditions are encountered. Another benefit of controlled powered dampers is to temporarily throttle off outdoor air during car start-up to more quickly bring the car temperature to the proper interior temperature after an extended layover period where the HVAC system is shut down.

5.5 Air Exhaust. As previously noted, the oversupply of air in most rail passenger vehicles resulting from the introduction of outdoor ventilation air is normally exhausted naturally by the resulting positive pressurization and exfiltration through the small gaps around structural members and outside door and window seals. Intercity coaches and similar vehicles that have few exterior doors often require static exhaust grilles to relieve excessive pressurization (see informative note below). In addition, in localized areas where concentrated heat is generated (equipment lockers, food galleys, etc.) or objectionable odors may exist (toilets, food preparation areas, etc.), local forced exhaust fans are recommended to direct this undesirable air away and directly to the outside without adversely affecting the surrounding passenger environment. When forced exhaust is required, care must be taken to assure that sufficient outdoor air is introduced to maintain positive pressurization in the passenger section. This may require higher ventilation rates than the minimum recommendation provided in Table 5-1.

Typical exhaust rates for passenger railcar toilet compartments range from 50 cfm (85 m^3/h) to 200 cfm (340 m^3/h) depending on the size of the room. The exhaust of electrical lockers and food preparation apparatus varies significantly depending on the size and design of the equipment. Specific guidance for exhaust design can be found in *ASHRAE Handbook—Fundamentals* [3].

Informative Note: Excessive pressurization can unnecessarily require higher fan power ratings and energy consumption to maintain the required outdoor airflow.

6. CAPACITY CALCULATIONS

6.1 General. An accurate assessment of rail passenger vehicle heating and cooling loads is required for the selection of HVAC equipment that provides acceptable system performance and comfort.

Compared to buildings and other human habitats fixed in a given geographical position, rail passenger vehicles are often subject to significant environmental variation as a result of their motion. These variations include tunnels, changes in elevation, orientation with respect to solar heat gains, heat transfer effects due to wind, etc. These environmental influences affect not only the heating and cooling loads but also the performance of the HVAC equipment.

Compounding these issues are the operational characteristics of rail passenger vehicles. For example, at stations the passenger doors on one and in some cases both sides of subway and intracity vehicles are often opened simultaneously. Combined with the ingress and egress of passengers, significant air infiltration rates may occur. Door-cycling air infiltration can represent a substantial transient heating or cooling load and should be addressed as appropriate in the heating and cooling load analysis.

With the possible exception of building passenger elevators, at design capacity no other form of public transportation exhibits the same degree of passenger loading per unit volume

as subway and intracity rail passenger vehicles. Determining the effect of passenger loading on system performance begins with capacity calculations.

The HVAC system designer should be aware of the effect these environmental and operational influences have on the ultimate goal of providing specification-compliant passenger and operator thermal comfort.

Finally, the designer is reminded that the variables noted above, and others presented in Section 6.4.2.1, make even a detailed heating and cooling load analysis only an approximation of the actual vehicle loads at any given time.

6.2 Methodology. The fact that rail passenger vehicles are not stationary during service indicates that certain aspects of rigorous time-based heating and cooling load analyses primarily developed for buildings, such as the radiant-time series and heat-balance methods, are not applicable. This is especially true for solar radiation, which is normally the primary climatological variable influencing a building or nonsubway rail passenger vehicle cooling load.

To provide a reasonably accurate analysis, a combination of empirical and computational data is often used. Compared to thermal analysis of building structures, an advantage of rail passenger vehicles is their ability to be accommodated by environmental chambers. This allows data collection at carefully controlled conditions simulating those of revenue service. Many carbuilders have gained considerable knowledge of the steady-state and transient thermal performance of their vehicles through testing in these facilities. This section of the guideline will emphasize this knowledge base of empirical data where applicable, for example in carbody conductive heat gains.

6.3 Climatic and Environmental Design Criteria

6.3.1 General Considerations. An excellent source of climatological design data is *ASHRAE Handbook—Fundamentals* [3], Chapter 14, "Climatic Design Information." The designer must verify the applicability of published climatological data to the actual conditions existing throughout the track alignment. In some cases, supplemental surveys of right-of-way environmental characteristics may be used.

6.3.2 Cooling Ambient Design Conditions. ASHRAE 0.4%, 1.0%, and 2.0% cooling dry-bulb temperature/mean coincident wet-bulb temperature data are typically used to determine the required cooling capacity of rail HVAC equipment. The design cooling capacity may be influenced by interior temperature pull-down requirements. Unless otherwise indicated in the project technical specification, the use of 0.4% data is recommended.

6.3.3 Heating Ambient Design Conditions. Unless otherwise indicated in the project technical specification, ASHRAE 99.6% heating dry-bulb temperature data is recommended for determining the required heating capacity of HVAC equipment. The design heating capacity may be influenced by interior temperature pull-up requirements.

6.3.4 Street/Roadbed Temperatures. If applicable to the specific project, the designer should account for heat gain due to thermal radiation from the street or roadbed to the underframe and lower sidewalls of the vehicle, and resultant localized elevated dry-bulb temperatures. In some locations, street and roadbed surface temperatures may exceed 150°F.

Detailed methodology for the precise calculation of this additional heat gain is not addressed in this guideline, but key factors to consider when this level of accuracy is deemed necessary include the following:

a. Elevated street/roadbed temperature due to solar heating
b. Short distance from street/roadbed to underframe
c. High surface thermal emissivities

The net heat flux (in British thermal units per hour or watts) between the two surfaces depends on the thermal emissivity of the exposed exterior floor area and roadbed, surface areas of the roadbed and floor area, temperatures of the two surfaces, and view factor of the two surfaces. Typical thermal emissivity of both surfaces is approximately 0.9.

There may be combinations of vehicle design and operation and environmental conditions that reduce these additional cooling loads to insignificance; however, the designer should consider all of these factors and make an informed judgment as to how they should be addressed in the cooling load assumptions.

6.3.5 Roof-Mounted and Underframe-Mounted Equipment. Localized underframe and roof temperatures may be higher than those calculated from climatological data due to heat rejection from adjacent equipment. These include propulsion motors, braking resistor banks, friction braking systems, HVAC condensing units, and other heat-generating equipment. The effect of these combined convective and radiative heat gains must be accounted for as required.

6.3.6 Elevation. Reduced air density (increased specific volume) at higher elevations can have a significant effect on the volumetric airflow rate necessary to achieve the desired interior conditions. These effects are usually disregarded at elevations less than 1000 ft (305 m). The use of psychrometric software that includes elevation in the calculation algorithms is recommended.

6.4 Carbody Heat Gain

6.4.1 General Considerations

6.4.1.1 Conductive Heat Gain. Where carbody heat transfer data are available from vehicle climate room tests, these data generally do not include the effects of solar radiation. Typical testing involves maintaining the environmental chamber at a constant (low) temperature, with the vehicle interior heated by auxiliary electric heaters or the vehicle's sidewall/floor heating system. Air-moving devices may be used to simulate wind effects on exterior surfaces due to vehicle motion. At thermal equilibrium, the carbody heat loss per unit temperature difference (*UA*-factor) is calculated from the exterior/interior temperature differential and heater power input. The *UA*-factor includes heat loss due to glazing as well as opaque surfaces.

The designer should be aware of the methodology used to determine the vehicle's *UA*-factor. Independent air-circulation fans located throughout the interior may have been used during carbody thermal performance testing to minimize interior temperature stratification and simulate revenue service. The use of these fans may increase the interior convective air

TABLE 6-1 Carbody Thermal Performance for Various Vehicle Types (static conditions; average exterior air velocity < 5 mph)

Application or Vehicle Type	Typical *UA*-Factors (per foot of car length), Btu/h·°F·ft
Intercity and commuter car, single level, stainless steel carbody	10
Subway car, stainless steel carbody	11
Commuter car, single-level, aluminum carbody	13
Bilevel commuter car, stainless steel carbody	14
LRV, steel carbody	14
LRV, double-articulated, composite-clad carbody	14
LRV, aluminum carbody	14
Bilevel commuter car, aluminum carbody	19

Note: Table 6-1 provides typical values for various rail vehicle types and constructions. The values are provided for reference and do not include the effects of solar radiation or the effects of vehicle speed on the exterior convective air film coefficient as detailed in Section 6.4.4.2. Specific vehicle values may vary based on design characteristics including but not limited to insulation type and arrangement, location and number of doors, window design and total area, carbody construction materials, and articulation bellows design and number.

film coefficient, increasing heat transfer to the surroundings. If no air-moving devices were used during testing, thermal stratification may lead to much higher than average air temperatures at the upper areas of glazing and interior surfaces and much lower than average temperatures at the lower areas of glazing and interior surfaces. This is especially evident in testing conducted at significant exterior/interior temperature differentials.

6.4.1.2 Solar Radiation Heat Gain. The total heat gain through glazing is the sum of the solar radiant heat gain and the conductive heat gain due to exterior/interior temperature differentials.

6.4.2 Carbody Conductive Heat Gain

6.4.2.1 Empirical Analysis. As stated in Section 6.2, empirical data from environmental testing may be available to the carbuilder for use in calculating carbody heat transfer. When available, the use of test data is generally recommended in lieu of carbody thermal performance data obtained through computation. Unknown or partially known variables such as thermal bridging, thermal energy flow paths, workmanship effects, thermal energy storage effects, sealing effectiveness, material properties, glazing performance, etc. may lead to assumptions that make computational analysis less accurate.

If environmental chamber testing included use of equipment specifically designed and arranged to simulate solar radiation, carbody conductive heat gain and solar heat gain data are known. If environmental chamber testing did not include solar radiation equipment, carbody glazing and opaque surface solar heat gain must be accounted for per Sections 6.4.3 and 6.4.5.

Typical values of *UA*-factor per unit length are provided in Table 6-1 for various rail passenger vehicle constructions and applications. Values from this table are used in the sample heating and cooling load calculations in Section 6.11.

Using data from Table 6-1, the *UA*-factor for a specific vehicle is calculated as the product of the *UA*-factor per unit length of the car and the vehicle length. Carbody conductive heat gain or loss at design temperatures is the product of the *UA*-factor and the exterior/interior temperature differential.

6.4.2.2 Computational Analysis. If empirical data are not available, or if a computational analysis is desired, the car body conductive heat gain can be calculated using the heat transfer equation:

$$Q = UA(\Delta T)$$

where

Q = thermal energy transfer rate, Btu/h

U = carbody thermal transmittance (includes exterior/interior convective air film coefficients), Btu/h·ft^2·°F

A = carbody thermal envelope area, ft^2

ΔT = exterior to interior temperature differential, °F

This equation assumes an average thermal transmittance for the entire carbody, and uniform interior and exterior temperatures. The thermal envelope area (interior or exterior) may be determined by direct measurement or taken from drawings/three-dimensional models. In practice, vehicle thermal transmittance is a summation of individual transmittance values for specific opaque and glazed sections weighted by their respective areas. Combined with the unknown or partially known thermal-performance variables identified in Section 6.4.2, computational analysis can be a daunting task if accurate vehicle transmittance values are desired. This guideline recommends use of the values in Table 6-1, adjusted as required for specific vehicle construction or carbuilder experience.

Carbody glazing and opaque surface solar heat gain should be accounted for per Sections 6.4.3 and 6.4.5.

Exterior and interior convective air film coefficients should be accounted for per Sections 6.4.4.2 and 6.4.4.3.

6.4.3 Carbody Solar Radiation Heat Gain. To account for the heating effects of solar radiation on opaque surfaces, the sol-air temperature is calculated and used in the heat transfer equation of Section 6.4.2.2. As stated in *ASHRAE*