Related Commercial Resources

CHAPTER 11

MASS TRANSIT

THIS chapter describes air-conditioning and heating systems for buses, rail cars, and fixed-guideway vehicles that transport large numbers of people, often in crowded conditions. Air-conditioning systems for these vehicles generally use commercial components, but are packaged specifically for each application, often integral with the styling. Mass, envelope, power consumption, maintainability, and reliability are important factors. Power sources may be electrical (ac or dc), engine crankshaft, compressed air, or hydraulic. These sources are often limited, variable, and interruptible. Characteristics specific to each application are discussed in the following sections. Design aspects common to all mass-transit HVAC systems include passenger comfort (ventilation, thermal comfort, air quality, expectation) and thermal load analysis (passenger dynamic metabolic rate, solar loading, infiltration, multiple climates, vehicle velocity, and, in urban applications, rapid interior load change).

1. VENTILATION AND THERMAL COMFORT

The requirements of ASHRAE *Standards* 55 and 62.1 apply for transportation applications, with special considerations, because passengers in transit have different perceptions and expectations than typical building occupants. These considerations involve length of occupancy, occupancy turnover, infiltration, outdoor air quality, frequency and duration of door openings, personal preference, interior contamination sources such as smoking, and exterior contamination sources such as engine exhaust.

Historically, in nonsmoking air-conditioning and heating applications, outdoor air has been supplied to the vehicle interior by fans at 2.5 to 5 L/s per passenger at a predetermined nominal passenger loading. Nominal passenger load is based on the number of seats and may include a number of standees, up to the maximum number of standees possible if this type of loading is frequent. There are a few examples of no outdoor air being supplied by fans, but they are on short-duration trips such as people movers or urban buses with frequent door openings. Besides providing for survival, ventilation provides odor and contamination control. The amount needed for survival is less than the latter. Contamination control from interior sources is a factor in building design, but is less of a factor in vehicle design because of the ratio of people to furnishings and the lack of interior processes such as copy machines. Exterior contamination, such as from tunnel fumes, can be a problem, however. Door openings, if frequent enough, provide some additional intermittent ventilation, although this infiltration should be minimized for thermal comfort. Ventilation from doors may not be effective in controlling odors away from the doors. Fan-supplied outdoor air must be distributed equally in the vehicle for effective ventilation. Symptoms of inadequate ventilation are odors noticeable to passengers initially entering an occupied vehicle or when moving from section to section. Passengers on board who are exposed to slowly increasing odor levels may not be aware of them.

Based on ASHRAE research, ASHRAE *Standard* 161 established a ventilation rate for aircraft passengers at 3.5 L/s per passenger. This rate was based in part on the consideration that not all spaces in the enclosed area achieve 100% ventilation effectiveness. The minimum effective ventilation rate for several crowded but larger-volume spaces, as defined in ASHRAE *Standard* 62.1, is 2.5 L/s per person. It is recommended that ground mass transit applications use 3.5 L/s of outdoor air per passenger for most transit applications.

Emergency ventilation, such as windows or exits that can be opened or battery-powered ventilators, should be provided in case other systems fail. For example, a power interruption or a propulsion system failure may strand passengers in a situation where exit is not possible. Emergency situations include overtemperature, oxygen depletion, smoke, or toxic fumes. Operator-controlled dampers are now provided on some vehicles to close off fresh air when smoke or toxic fumes are encountered in tunnels. The duration that the dampers remain closed must be limited to avoid oxygen depletion, even though the air-conditioning system remains in operation. Fresh-air supply alone or battery-powered ventilators will not prevent overtemperatures when a full passenger load is present and/or a solar load exists in combination with high ambient temperature. Each emergency situation requires an independent solution.

The nature of the transit service may be roughly categorized by average journey time per passenger and interval between station stops, and this service type affects the necessary interior conditions in the vehicle. For example, a commuter rail or intercity bus passenger may have a journey time of an hour or more, with few stops; passengers may remove heavy outer clothing before being seated. In contrast, a subway or transit urban bus rider typically does not remove heavy clothing during a 10 min ride. Clothing and the environment from which passengers come, including how long they were exposed to those conditions and what they were doing (e.g., waiting for the train outdoors in winter), are important factors in transit comfort. At the opposite extreme, many subway stations are not climate controlled, and often reach dry-bulb temperatures over 38°C in the summer. Thus, when boarding a climate-controlled vehicle, these passengers immediately perceive a significant in-crease in comfort. However, a passenger adjusts to a new environment in about 10 to 20 min; after that, the traditional comfort indices begin to apply, and the same interior conditions that were perceived as comfortable may now be perceived as less than comfortable. Before stabilization, a passenger may prefer higher-velocity air or cooler or warmer temperatures, depending to some extent on clothing. At the same time, other passengers may already have stabilized and have completely different comfort control desires. Therefore, the transit system designer is presented with a number of unusual requirements in providing comfort for all.

Jones et al. (1994) evaluated the heat load imposed by people under transient weather and activity conditions as opposed to traditional steady-state metabolic rates. An application program, TRANMOD, was developed that allows a designer to predict the thermal loads imposed by passengers (Jones and He 1993). Variables are activity, clothing, wet- and dry-bulb temperatures, and precipitation.

The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.

European Committee for Standardization (CEN) *Standard* EN 13129-1 provides guidance in the area of railroad passenger comfort. Although this standard does not apply to countries outside the CEN, the information is valuable and may not be readily available elsewhere.

2. THERMAL LOAD ANALYSIS

Cooling Design Considerations

Thermal load analysis for transit applications differs from stationary, building-based systems because vehicle orientation and occupant density change regularly on street-level and subway vehicles and, to a lesser degree, on commuter and long-distance transportation. Summer operation is particularly affected because cooling load is affected more by solar and passenger heat gain than by outdoor air conditions. ASHRAE *Standard* 55 design parameters for occupant comfort may not always apply. Vehicle construction does not allow the low thermal conductivity levels of buildings, and fenestration material must have safety features not necessary in other applications. For these reasons, thermal loads must be calculated differently. Because main-line passenger rail cars and buses must operate in various parts of the country, the air conditioning must be designed to handle the national seasonal extreme design days. Commuter and local transit vehicles operate in a small geographical area, so only local design ambient conditions need be considered.

The following cooling load components should be considered:

- Ambient air conditions for locations in North America and worldwide are given in Chapter 14 of the 2013 *ASHRAE Handbook—Fundamentals*. For vehicles operating in an urban area, the heat island effect should be considered if the Handbook design values are derived from remote reporting stations. For subway car operation, tunnel temperatures should be considered. In humid regions, consider the wet-bulb temperature coincident with dry-bulb temperature relative to fresh-air loads.
- For vehicle interior comfort conditions, consult Figure 5 in Chapter 9 of the 2013 *ASHRAE Handbook—Fundamentals*. Total heat gain from passengers depends on passenger activity before boarding the vehicle, waiting time, journey time, and whether they are standing or seated during the journey. Representative values are given in Table 1 in Chapter 18 of the 2013 *ASHRAE Handbook—Fundamentals*.
- Ventilation air loads should be calculated using the method in Chapter 18 of the 2013 *ASHRAE Handbook—Fundamentals*, in the section on Infiltration and Moisture Migration Heat Gains. Air leakage and air entering during door dwell time should be taken into account.
- Interior heat includes that produced by the evaporator fan motor, indoor lighting, and electrical controls.
- The vehicle's conductivity, in W/K, should be provided by the vehicle designers. For outdoor skin temperature guidance, use the values in Table 1 in Chapter 29 of the 1997 *ASHRAE Handbook—Fundamentals*; however, consider that air over a vehicle in motion reduces these temperatures The car design dry bulb should be used as the interior temperature.
- The instantaneous solar gain through the glazing should be calculated using summer midafternoon data listed in Chapter 29 of the 1997 *ASHRAE Handbook—Fundamentals*, and the glass shading coefficient. The glass shading coefficient must be obtained from the window supplier. Adjustments for frequent change in vehicle direction or intermittent solar exposure may be justified. Additional information is shown in Chapter 15 of the 2013 *ASHRAE Handbook—Fundamentals*

The summer cooling analysis should be completed for different times of the day and different passenger densities to verify a reliable result. Cooling equipment capacity should consider fouling and eventual deterioration of heat transfer surfaces.

Heating Design Considerations

Winter outdoor design conditions can be taken from Chapter 14 of the 2013 *ASHRAE Handbook—Fundamentals*. Interior temperatures can be taken from Figure 5 in Chapter 9 of the 2013 *ASHRAE Handbook—Fundamentals*. During winter, conductivity is the major heat loss. The heat required to temper ventilation air and to counteract infiltration through the body and during door openings must also be considered.

Other Considerations

Harsh environments and the incursion of dirt and dust inhibit the efficiency of HVAC units. Specifications should include precise maintenance instructions to avoid capacity loss and compromised passenger comfort.

3. BUS AIR CONDITIONING

In general, bus air-conditioning systems can be classified as interurban, urban, or small/shuttle bus systems. Bus air-conditioning design differs from other air-conditioning applications because of climatic conditions in which the bus operates, equipment size limitations, vehicle engine, electrical generator, and compressor rev/s. Providing a comfortable climate inside a bus passenger compartment is challenging because the occupancy rate per unit of surface and air recirculation volume is high, glazed area is very large, and outdoor conditions are highly variable. Factors such as high ambient temperatures, dust, rain, snow, road shocks, hail, and sleet should be considered in the design. Units should operate satisfactorily in ambient conditions from –30 to 50°C.

Ambient air quality must also be considered. Air intakes are usually subjected to thermal contamination from road surfaces, condenser air recirculation, or vehicle engine radiator air discharge. Vehicle motion also introduces pressure variables that affect condenser fan performance. In addition, engine speed governs compressor speed, which affects compressor capacity. R-134a is the current refrigerant of choice, but some units operate with refrigerants such as R-22 (pre-2010 production) and R-407C.

Bus air conditioners are initially performance-tested as units in a climate-controlled test cell. Performance tests encompass unit operation at different compressor speeds to make sure the compressor performance parameters [e.g., unit operation at maximum and minimum ambient conditions, thermostatic expansion valve (TXV) sizing, oil return, and vibration/shock] are within boundaries. In addition, individual components should be qualified before use. Larger test cells that can hold a bus are commonly used to verify installed unit performance. These tests are to measure the amount of time required to reduce the vehicle's interior temperature to a specified value, and they vary in performance and time requirements. Some commonly accepted tests include the Houston pulldown (extreme heat or performance when using higher-pressure refrigerant gas such as R-407C), modified pulldown (mild to hot climates with R-134a or equivalent), white book pulldown (mild to hot climates), and the profile test (mild to hot climates, 35 and 46.1°C ambient). All these tests are described in American Public Transportation Association (APTA) standard bus procurement and recommended practices for transit bus HVAC system instrumentation and performance testing.

Reliability and ease of maintenance are also important design considerations. All parts requiring service or regular maintenance should be readily accessible, and repairs should be achievable without removing any additional components and within a minimum time.

Heat Load

The main parameters that must be considered in bus air-conditioning system design include

- Occupancy data (number of passengers, distance traveled, distance traveled between stops, typical permanence time)
- Dimensions and optical properties of glass
- Outdoor weather conditions (temperature, relative humidity, solar radiation)
- Dimensions and thermal properties of materials in bus body
- Indoor design conditions (temperature, humidity, air velocity)
- Power and torque limitations of bus engine

The heating or cooling load in a passenger bus may be estimated by summing the heat flux from the following loads:

- Solid walls (side panels, roof, floor)
- Glass (side, front, and rear windows)
- Passengers
- Engine and ventilation (difference in enthalpy between outdoor and indoor air)
- Evaporator fan motor

Extreme loads for both summer and winter should be calculated. The cooling load is the most difficult load to handle; the heating load is normally handled by heat recovered from the engine, external heater, or electrical heat elements. An exception is that an idling engine provides marginal heat in very cold climates. Andre et al. (1994) and Jones and He (1993) describe computational models for calculating the heat load in vehicles, as well as for simulating the thermal behavior of the passenger compartment.

The following conditions can be assumed for calculating the summer heat load in an interurban vehicle similar to that shown in Figure 1:

- Capacity of 50 passengers
- Insulation thickness of 25 to 40 mm
- Double-pane tinted windows
- Outdoor air intake of 190 L/s
- Road speed of 100 km/h
- Indoor design temperatures of 16 to 27°C and 50% rh
- Ambient temperatures for location as listed in Chapter 14 of the 2013 *ASHRAE Handbook—Fundamentals*

Loads from 12 to 35 kW are calculated, depending on outdoor weather conditions and geographic location. The typical distribution of the different heat loads during a summer day at 40° north latitude is shown in Figure 2.

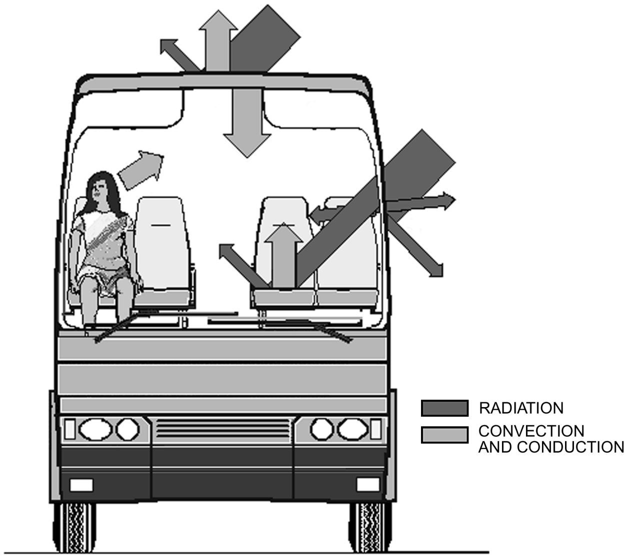

Fig. 1 Distribution of Heat Load (Summer)

Air Distribution

Air-conditioning units are configured to deliver air through ducts to outlets above the windows and to the middle aisle or to act as free-blow units. In the case of free-blow units, louvers guide the air distribution inside the bus.

Interurban Buses

These buses are designed to accommodate up to 56 passengers. The air-conditioning system is usually designed to handle extreme conditions. Interurban buses produced in North America are likely to have the evaporator and heater located under the passenger compartment floor. A four- or six-cylinder reciprocating compressor, in which some cylinders are equipped with unloaders, is popular. Some interurban buses have a separate engine-driven compressor, preferably scroll, to give more constant system performance. Figure 3 shows a typical air-conditioning arrangement for an interurban bus.

Urban Buses

Urban bus heating and cooling loads are greater than those of the interurban bus. A city bus may seat up to 50 passengers and carry a "crush load" of standing passengers. The fresh-air load is greater because of the number of door openings and the infiltration around

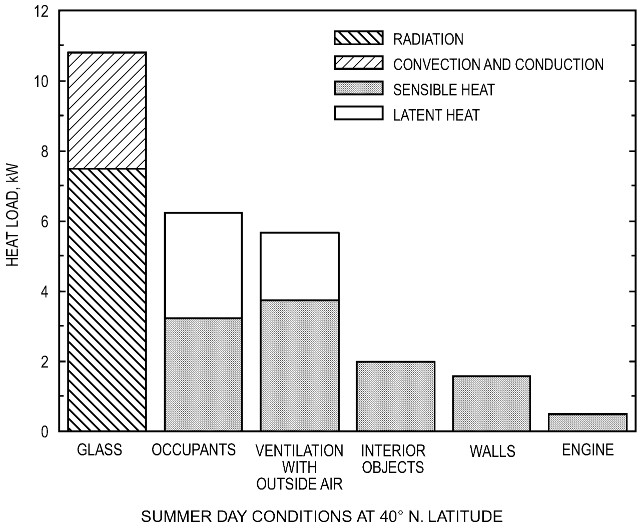

Fig. 2 Typical Main Heat Fluxes in Bus

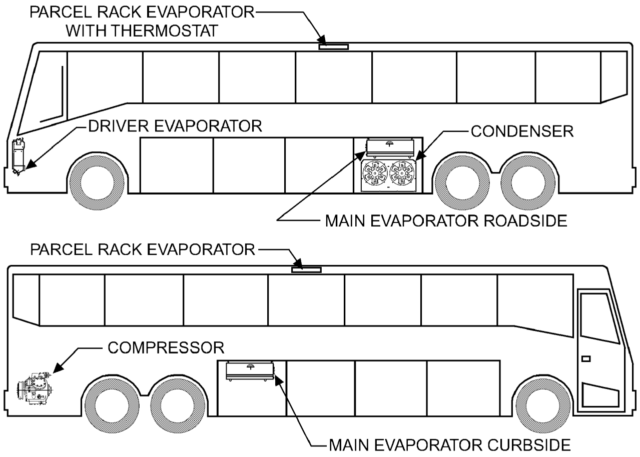

Fig. 3 Typical Arrangement of Air-Conditioning in Interurban Bus

doors. Cooling capacity required for a typical 50-seat urban bus is from 20 to 35 kW. The buses are usually equipped with a roof- or rear-mounted unit, as shown in Figure 4. One or two compressors are usually belt- or shaft-driven from the propulsion engine. Capacity control is very important, because the compressor may turn more quickly than necessary at high engine speeds. Therefore, capacity control must compensate for not only the thermal load but also the engine-induced load. Cylinder unloaders are the primary means of capacity control, although evaporator pressure regulators have been used with non-unloading compressors, as shown in Figure 4. This configuration was used on buses produced between 1975 and 1995.

The heater is located just downstream of the evaporator. Hot coolant from the engine-cooling system provides sufficient heat for most operations; however, additional sources may be required in colder climates for longer idling durations. Additional floor heaters may also be required to reduce the effects of stratification. Conditioned air is delivered through overhead combination light fixture/diffuser ducts (see Figure 5).

Low-profile, self-contained, rooftop-mounted units are used for urban and interurban buses. These units contain the entire air-conditioning system except for the compressor, which is shaft- or belt-driven from the bus engine (see Figure 6).

Because of increased air pollution and other environmental issues (e.g., noise, fuel consumption, unnecessary engine wear), using traditional engine-driven compressors for interurban, urban, or school bus or motor home air comfort systems is a great disadvantage, especially for parked vehicles. In response to these issues, most modern and efficient buses use **unitized electric packaged air-conditioning (UEPAC)** units, as shown in Figures 7 and 8. UEPACs have a self-contained, lightweight, integrated, modular design incorporating evaporators, condensers, valves, liquid receiver, filter-drier, electric heater elements, automatic climate controls, and scroll compressors. Electric power is supplied to the UEPAC system from onboard sources for hybrid electric and fuel-cell buses, or by a main-engine-driven generator on more traditional fuel or hybrid applications without an accessory power option. These systems enable use of shore (wayside) power while parked, eliminating idling where power is available.

Small or Shuttle Buses

For small or shuttle buses such as those typically operating around airports or for schools, the evaporator is usually mounted in the rear and the condenser on the side or the roof of the bus. The evaporator unit is typically a free-blow unit.

Refrigerant Piping

See Chapters 1 and 8 of the 2014 *ASHRAE Handbook—Refrigeration* for standard refrigerant piping practices. All components in the bus air-conditioning system are interconnected by copper tubing

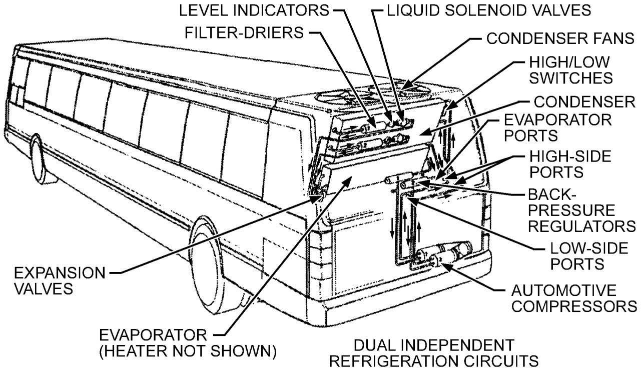

Fig. 4 Typical Mounting Location of Urban Bus Air-Conditioning Equipment

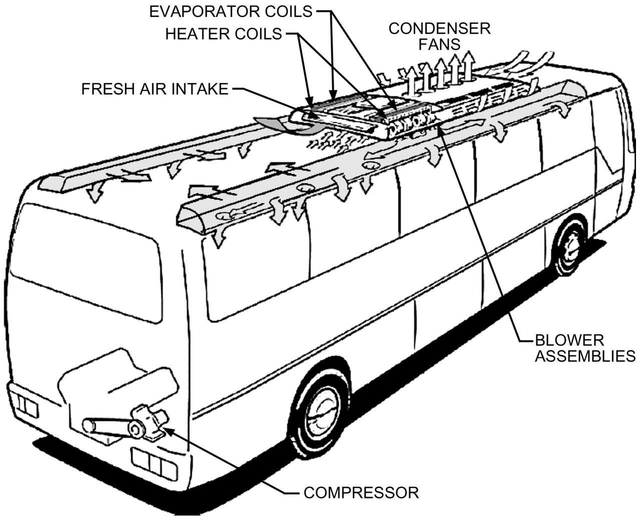

Fig. 6 Typical Mounting Location of Roof-Mounted Urban Bus Air-Conditioning Equipment with Single Compressor

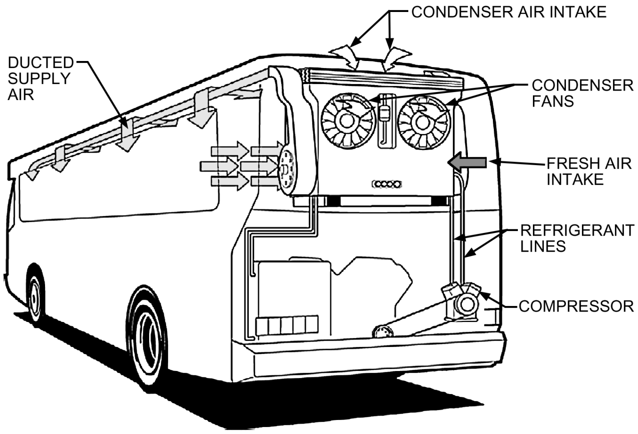

Fig. 5 Typical Mounting Location of Urban Bus Air-Conditioning Equipment with Single Compressor

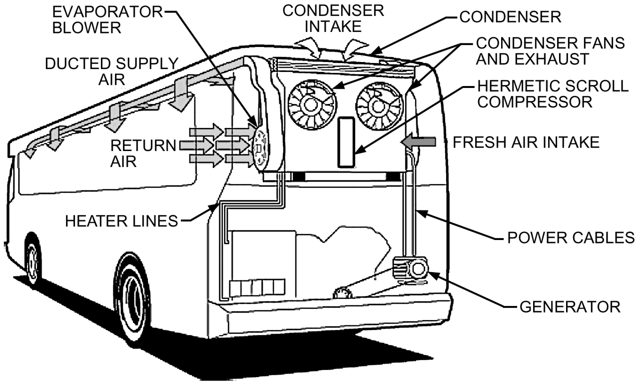

Fig. 7 Typical Mounting Location of Urban Bus Fully Electric Rear-Mounted Air-Conditioning Equipment with ac Generator

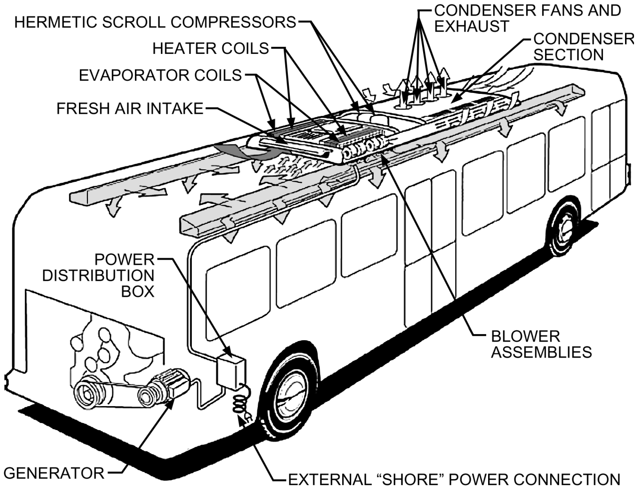

Fig. 8 Typical Mounting Location of Urban Bus Fully Electric Roof-Mounted Air Conditioning Equipment with ac Generator

or refrigerant hose. When using copper tubing, care should be taken to analyze the effect of vibration on the tubing. Vibrational effects can be minimized by using vibration absorbers or other shock-cushioning devices. When using refrigerant hose, properties such as moisture ingression, effusion, maximum operating temperature, and burst pressure need to be taken into account. The refrigerant hose chosen should have the minimum amount of wax extractables on interaction with oil and the refrigerant.

Shock and Vibration

Most transport air-conditioning manufacturers design components for shock loading and vibrational inputs. Vibration eliminators, flexible lines, and other shock-cushioning devices interconnect the various air-conditioning components. The vibration characteristics of each component are different; in addition, the evaporator and the condenser must undergo individual vibration and shake tests. The input levels for the shake test can be based on the worst road conditions that the bus will encounter. This input level will vary because of the mass of the unit and its mounting.

System Safety

Per the U.S. Department of Transportation, all buses with air-conditioning systems operating in North America should conform to Federal Motor Vehicle Safety *Standard* (FMVSS) 302 for flammability standards. In addition, all evaporator units inside the vehicle should be mounted away from the head impact zone, as specified by FMVSS 222.

Controls

Most buses have a simple driver control to select air conditioning, heating, or automatic operation (air conditioning, heating, and reheat). In both modes, a thermal sensing element controls these systems with on/off circuitry and actuators. Many systems use solid-state control modules to interpret the bus interior and outdoor ambient temperatures and to generate signals to operate full or partial cooling, reheat, or heating functions. These systems use thermistor temperature sensors, which are usually more stable and reliable than electromechanical controls. Control systems for urban buses can also include an outdoor-air ventilation cycle. The percentage of fresh-air intake during the ventilation cycle can vary based on individual requirements.

4. RAIL CAR AIR CONDITIONING

Passenger rail car air-conditioning systems are generally electromechanical, direct-expansion units. R-22, a hydrochlorofluorocarbon (HCFC), has been the refrigerant most commonly used since the phase-out for R-12. R-134a, a medium-pressure refrigerant, has been used as a retrofit refrigerant in North America on systems originally designed to operate with R-12, and is commonly used in Europe for new equipment, mainly variable-speed screw compressors that are competitive in mass to R-22 reciprocating compressors. Most equipment placed in service before the January 1, 2010, ban on manufacturing new R-22 equipment has used R-407C as the refrigerant. R-410A has been used in some equipment; however, it can only be used in relatively mild climates because the condensing temperatures found in transit applications may approach the refrigerant's critical point. In 2009, the U.S. Environmental Protection Agency (EPA) added R-438A to its significant new alternatives policy (SNAP) list of approved refrigerants for motor vehicle air conditioning use.

Electronic, automatic controls are common, with a trend toward microprocessor control with increasing capability for fault monitoring and logging. Electric heating elements in the air-conditioning unit or supply duct temper outdoor air brought in for ventilation and are also used to control humidity by reheating the conditioned supply air during cooling partial-load conditions.

Air-cycle technology has been tested for passenger rail car air conditioning in Germany (Giles et al. 1997); however, issues of greater mass, higher cost, and low efficiency need to be addressed before it is widely accepted.

Vehicle Types

Main-line intercity passenger rail service generally operates single and multilevel cars hauled by a locomotive. Locomotive-driven alternators or solid-state inverters distribute power via an intercar cable power bus to air-conditioning equipment in each car. A typical rail car has a control package and two air-conditioning systems. The units are usually either split, with the compressor/condenser units located in the car undercarriage area and the evaporator-blower portion mounted in the ceiling area, or self-contained packages mounted in interior equipment rooms. Underfloor and roof-mounted package units are less common in intercity cars.

Commuter cars used to provide passenger service from the suburbs into and around large cities are similar in size to main-line cars. Air-conditioning equipment generally consists of two evaporator-heater fan units mounted above the ceiling with a common or two separate underfloor-mounted compressor-condenser unit(s) and a control package, or self-contained packaged units mounted on the roof. These cars may be locomotive hauled, with air-conditioning arrangements similar to main-line intercity cars, but they are often self propelled by high-voltage direct-current (dc) or alternating-current (ac) power supplied from an overhead catenary or from a dc-supplied third-rail system. On such cars, the air conditioning may operate on ac or dc power. Self-propelled diesel-driven vehicles that use onboard-generated power for the air-conditioning systems still operate in a few areas.

Subway and **elevated rapid-transit cars** usually operate on a third-rail dc power supply. In the past, the air-conditioning system motors were commonly powered directly from the third-rail dc supply voltage. Most new equipment operates from three-phase ac power provided by a solid-state inverter. The inverter may be either an independent system or a component of the HVAC system. Split air-conditioning systems are common, with evaporators in the interior ceiling area and underfloor-mounted condensing sections, although unitary package units mounted on the roof or under the floor are increasingly common.

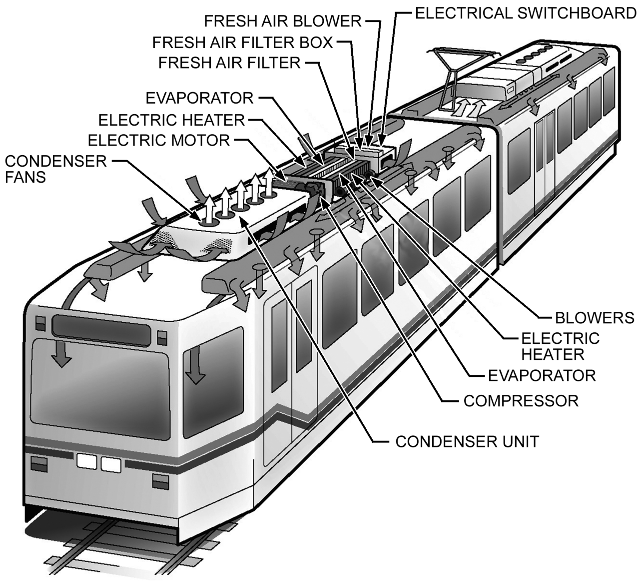

Fig. 9 Typical Light Rail Vehicle with Roof-Mounted HVAC System

Streetcars and **light-rail vehicles** usually run on ac or dc power transmitted via an overhead catenary wire, and have air-conditioning equipment similar to rapid-transit cars. Roof-mounted packages are used more often than undercar or split systems. This is largely because of the lack of undercar space. Figure 9 shows a typical configuration for these vehicles.

Equipment Design Considerations

Design considerations unique to transit HVAC equipment include the characteristics of the available power supply, mass limits, type of vehicle, and vehicle service parameters. Thus, ac-powered, semihermetic or hermetic compressors, which are lighter than open machines with dc motor drives, are a common choice. However, each car design must be examined in this respect because dc/ac inverters may increase not only the total mass, but also the total power draw, because of conversion losses.

Other concerns in equipment selection include the space required, location, accessibility, reliability, and maintainability. Interior and exterior equipment noise levels must be considered both during the early stages of design and later, when the equipment is coordinated with the car builder's ductwork and grilles.

Compressors. Reciprocating and vane compressors are commonly used, although scroll compressors are becoming increasingly common. The scroll compressor is inherently more tolerant of flooded starts and liquid slugging common in the rail application than any other type of positive-displacement compressor. The low clearance volume of the scroll compressor allows it to operate at high discharge pressure more effectively than reciprocating compressors. Lower mass and less vibration and noise are benefits, as well.

Power Supply Characteristics. Vehicles that draw their power from a stationary supply, such as a third rail or overhead catenary wire, are subject to frequent power interruptions as the train passes through gaps in the third rail or phase breaks in the overhead. These interruptions cause the HVAC equipment to shut down independently of the control system, and the design must take into account these losses of power and the subsequent need to restart the equipment. Vehicles that generate electrical power from an onboard source are less affected by power interruptions, although their capacity is limited. In either case, HVAC system control design must be coordinated with the vehicle's power supply and distribution system to avoid overloading vehicle systems during both steady-state and start-up (in-rush current) conditions. Additionally, it is desirable to prevent the vehicle's power supply from intentionally removing power from the HVAC equipment without an orderly shutdown sequence (including a pump-down cycle, if necessary).

Configuration and Space Constraints. Space underneath and inside a rail car is at a premium. Components are usually built to fit the configuration of the available space. Overall car height, roof profile, ceiling cavity, and wayside clearance restrictions often determine the shape and size of equipment.

Special Environmental Considerations. Dirt and corrosion constitute an important design factor, especially if the equipment is beneath the car floor, where it is subject to extremes of weather and severe dirt conditions. For this reason, corrosion-resistant materials and coatings must be selected. Aluminum has not proved durable in exterior exposed applications; the sandblasting effect tends to degrade any surface treatment on it. Because dirt pickup cannot be avoided, the equipment must be designed for quick and easy cleaning; access doors should be provided, and evaporator and condenser fin spacing is usually limited to 2.5 to 3.2 mm. Closer spacing causes more rapid dirt build-up and higher cleaning costs. Dirt and severe environmental conditions must also be considered in selecting motors and controls.

Maintenance Provisions. Railroad HVAC equipment is subjected to mechanical shock and vibration during operation, is frequently required to operate under conditions of elevated condensing temperature and pressure, and is subjected to frequent on/off cycling because of power supply interruptions and other conditions that are not typical for a stationary application. As a consequence, the rail HVAC system's components are more highly stressed than equivalent components in a stationary system, and thus require more frequent maintenance and servicing. Because a passenger rail car with sealed windows and a well-insulated structure becomes almost unusable if the air conditioning fails, high reliability is important. Equipment design needs to consider the ease of routine service and time needed to diagnose and repair the system. The control equipment thus often incorporates monitoring and diagnostic capabilities to allow quick diagnosis and correction of a failure. However, many trains are designed with several individual vehicles permanently coupled together, in which case the failure of a single HVAC unit causes multiple cars to become unavailable for service while the HVAC system is diagnosed and repaired. The time to diagnose and repair a system varies. Railroads, by their nature, are schedule driven, and varying, unknown repair time is incompatible with the need to provide scheduled service. Therefore, many users are moving away from fully on-car-serviceable air conditioners and toward modular, self-contained units with hermetically sealed refrigerant systems. These units are designed for rapid removal and replacement to allow the vehicle to return to service in a short, predictable time. The faulty HVAC equipment is diagnosed and repaired off-car in a dedicated air-conditioning service area.

Safety. Security of the air-conditioning equipment attachment to the vehicle must be considered, especially on equipment located beneath the car. Vibration isolators and supports should be designed to safely retain the equipment on the vehicle, even if the vibration isolators or fasteners fail completely. A piece of equipment that dangles or drops off could cause a train derailment. All belt drives and other rotating equipment must be safety guarded. High-voltage controls and equipment must be labeled by approved warning signs. Pressure vessels and coils must meet ASME test specifications for protection of passengers and maintenance personnel. Materials selection criteria include low flammability, low toxicity, and low smoke emission.

Special Design Considerations. The design, location, and installation of air-cooled condenser sections must allow for the possibility of hot condenser discharge air recirculation into the condenser inlet (in the case of split systems), or into the outdoor air intakes (in the case of roof-mounted unitary systems), as well as hot condenser discharge from trains on adjacent tracks that may occur at passenger loading platforms or in tunnels. To prevent a total system shutdown because of high discharge pressure, a capacity reduction control device is typically used to reduce the cooling capacity before system pressure reaches the high-pressure safety switch setting, thus temporarily reducing discharge pressure.

Even with coordination between the HVAC controls and the vehicle's power supply or distribution system, abrupt shutdown of the refrigeration system caused by power loss is common. The typical split-system arrangement places the compressor at or near the low point in the system. The combination of these factors results in undesired migration of refrigerant to the compressor during the *off* cycle. To reduce the likelihood of flooded compressor starts, using a suction line accumulator and crankcase heater is recommended.

Other Requirements

Most cars are equipped with both overhead and floor heat, typically provided by electric resistance elements. The control design commonly uses overhead heat to raise the temperature of the recirculated and ventilation air mixture to slightly above the car design temperature, while floor heat offsets heat loss through the car body. This arrangement is intended to limit stratification in the passenger compartment by promoting buoyant, convective air circulation. Times of maximum occupancy, outdoor ambient, and solar gain must be ascertained. The peak cooling load on urban transit cars usually coincides with the evening rush hour, and the peak load on intercity rail cars occurs in the midafternoon.

Heating capacity for the car depends on body construction, car size, and the design area-averaged relative wind-vehicle velocity. In some instances, minimum car warm-up time may be the governing factor. On long-distance trains, the toilets, galley, and lounges often have exhaust fans. Ventilation airflow must exceed forced exhaust air rates sufficiently to maintain positive car pressure. Ventilation air pressurizes the car and reduces infiltration.

Air Distribution and Ventilation

The most common air distribution system is a centerline supply duct running the length of the car between the ceiling and the roof. Air outlets are usually ceiling-mounted linear slot air diffusers. Louvered or egg crate recirculation grilles are positioned in the ceiling beneath the evaporator units. The main supply duct must be insulated from the ceiling cavity to prevent thermal gain/loss and condensation. Taking ventilation air from both sides of the roof line helps overcome the effect of wind. Adequate snow and rain louvers and, in some cases, internal baffles, must be installed on the outdoor air intakes. Separate outdoor air filters are usually combined with either a return or mixed-air filter. Disposable media or permanent, cleanable air filters are used and are usually serviced every month. Some long-haul cars, such as sleeper cars, require a network of delivered-air and return ducts. Duct design should consider noise and static pressure losses.

Piping Design

Standard refrigerant piping practice is followed. Pipe joints should be accessible for inspection and, on split systems, not concealed in car walls. Evacuation, leak testing, and dehydration must be completed successfully after installation and before charging. Piping should be supported adequately and installed without traps that could retard the flow of lubricant back to the compressor. Pipe sizing and arrangement should be in accordance with Chapter 1 of the 2014 *ASHRAE Handbook—Refrigeration*. Evacuation, dehydration, and charging should be performed as described in Chapter 8 of that volume. Piping on packaged units should also conform to these recommendations.

Control Requirements

Rail HVAC control systems typically automatically transition between cooling and heating operation, based on interior and exterior dry-bulb temperature. The cooling and heating set points are generally different. This difference provides a control dead band to prevent the system from cycling directly between cooling and heating, and accommodates passengers' seasonal clothing. System capacity is matched to part-load conditions with some combination of evaporator coil staging, evaporator fan speed control, compressor cylinder unloading, or variable-speed compressor control in cooling mode, and staging or duty cycling of heat in heating mode. The control system typically does not consider latent heat information in the control algorithm, although reheat is commonly used to increase the apparent interior sensible load as the interior dry-bulb temperature falls below the desired cooling set point, to maintain humidity removal. Unitary systems may use hot-gas bypass for this purpose rather than electric reheat. If the interior dry-bulb temperature falls below the desired cooling set point, even with capacity reduction and reheat, the refrigeration system will shut down and the HVAC system will provide ventilation only. If the interior temperature drops to the heating set point, the system transitions to heating mode. Before the development of analog electronic or microprocessor control systems, this dry-bulb based control algorithm was implemented by banks of thermostats. This arrangement resulted in multiple, load-dependent interior set points as the system established quasi-equilibrium conditions within the dead band of each individual thermostat. When analog electronic controls were introduced in the early 1980s, they emulated this thermostat-based control algorithm, which is still often followed today in North America. Recently, several European and Asian HVAC manufacturers have introduced proportional-integral-derivative (PID) control systems, common in those markets for several years, to the North American market. Higher energy costs and greater environmental concern in Europe and Asia have led some manufacturers to include energy conservation algorithms in controls intended for use in those markets.

The availability of robust, low-cost humidity sensors may lead to the use of latent heat information in control algorithms.

A pumpdown cycle and low-ambient lockout are recommended on split systems to protect the compressor from damage caused by liquid flooding the compressor and subsequent flooded starts. In addition, the compressor may be fitted with a crankcase heater that is energized during the compressor off cycle.

5. FIXED-GUIDEWAY VEHICLE AIR CONDITIONING

Fixed-guideway (FGW) systems, commonly called people movers, can be monorails or rubber-tired cars running on an elevated or grade-level guideway, as seen at airports and in urban areas. The guideway directs and steers the vehicle and provides electrical power to operate the car's traction motors (in some cases, the vehicle is propelled by a metal cable, driven by a motor mounted at the end of the guideway), lighting, electronics, air conditioner, and heater. People movers are usually unstaffed and computer-controlled from a central point. Operations control determines vehicle speed, headway, and the length of time doors stay open, based on telemetry from individual cars or trains. Therefore, reliable and effective environmental control is essential.

People movers are usually smaller than most other mass-transit vehicles, generally having spaces for 8 to 40 seated passengers and generous floor space for standing passengers. Under some conditions of passenger loading, a 12 m car can accommodate 100 passengers. The wide range of passenger loading and solar exposure make it essential that the car's air conditioner be especially responsive to the amount of cooling required at a given moment.

System Types

The HVAC for a people mover is usually one of three types:

- Conventional undercar condensing unit and compressor unit (which includes control box) connected with refrigerant piping to an evaporator/blower unit mounted above the car ceiling
- Packaged, roof-mounted unit having all components in one enclosure and mated to an air distribution system built into the car ceiling
- Packaged, undercar-mounted unit mated to supply and return air ducts built into the car body

Some vehicles are equipped with two systems, one at each end; each system provides one-half of the maximum cooling requirement. U.S. systems usually operate on the guideway's power supply of 460 to 600 V (ac), 60 Hz. Some newer systems with dc track power operate on 240 V (ac), 60 Hz from an inverter. Figures 10 and 11 show some arrangements used with fixed-guideway people mover vehicles, although similar arrangements could also apply to rail.

Refrigeration Components

Because commercial electrical power is available, standard semihermetic reciprocating compressors and commercially available fan motors and other components can be used. Compressors generally have one or two stages of unloaders, and/or hot-gas bypass is used to maintain cooling at low loads. Newer systems use scroll compressors with speed control, displacement control, or hot-gas bypass to control capacity. Condenser and evaporator coils are copper tube with copper or aluminum fins. Generally, flat fins are preferred for undercar condensers to make it simpler to clean the coils. Evaporator/blower sections must often be designed for the specific vehicle and fitted to its ceiling contours. Condensing units must also be arranged to fit in the limited space available and still ensure good airflow across the condenser coil. Because of the phaseout of R-22, R-407C is commonly used to meet environmental standards (zero ozone depletion potential). Some existing R-22 systems are being retrofitted with R-407C and R-422D.

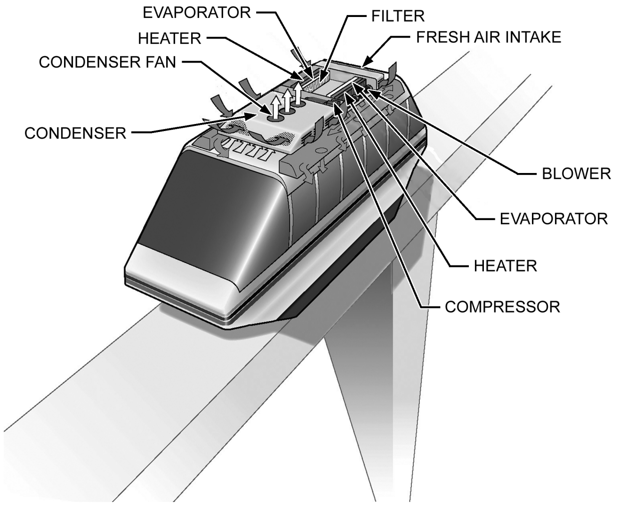

Fig. 10 Typical Small Fixed-Guideway Vehicle with Roof-Mounted HVAC System

Heating

Where heating must be provided, electric resistance heaters that operate on the guideway power supply are installed at the evaporator unit discharge. One or two stages of heat control are used, depending on the size of the heaters.

Controls

A solid-state control is usually used to maintain interior conditions, although newer systems use programmable logic controller (PLC) microprocessor-based controllers. The cooling set point is typically between 23 and 24°C. For heating, the set point is 15.6 to 20°C. Some controls provide humidity control by using electric heat. Between the cooling and heating set points, blowers continue to operate on a ventilation cycle. On rare occasions, two-speed blower motors are used, switching to low speed for the heating cycle. Some controls have internal diagnostic capability and can signal the operations center when a cooling or heating malfunction occurs.

Ventilation

With overhead air-handling equipment, outdoor air is introduced into the return airstream at the evaporator entrance. Outdoor air is usually taken from a grilled or louvered opening in the end or side of the car. Depending on the configuration of components, fresh air is filtered separately or directed so that the return air filter can handle both airstreams. For undercar systems, a similar procedure is used, except air is introduced into the system through an intake in the undercar enclosure. In some cases, a separate fan is used to induce outdoor air into the system.

The amount of mechanical outdoor air ventilation is usually expressed as litres per second per passenger on a full-load continuous basis. Passenger loading is not continuous at full load in this application, with the net result that more outdoor air is provided

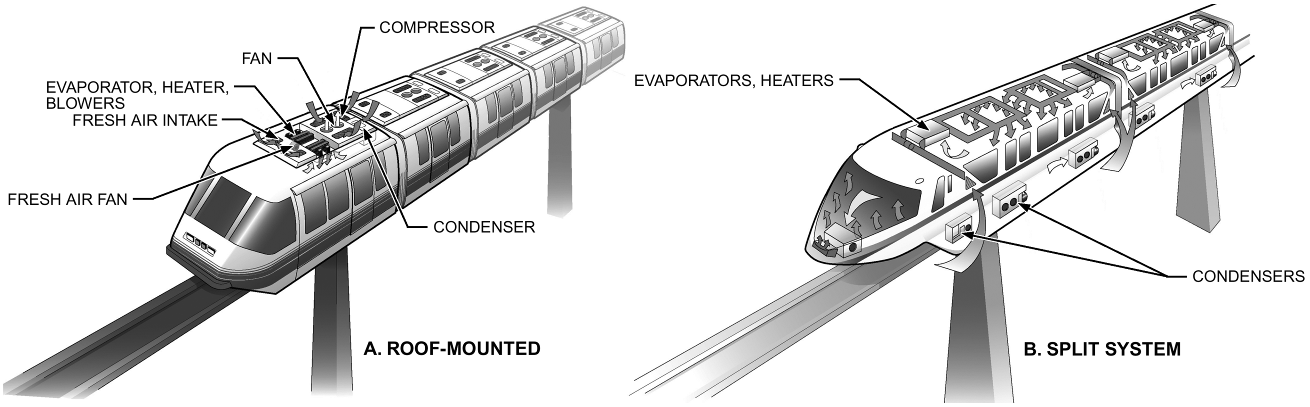

Fig. 11 Example Monorail HVAC System Configurations

than indicated. The passengers may load and unload in groups, which causes additional air exchange with the outdoors. Frequent door openings, sometimes on both sides at once, allows additional natural ventilation. The effective outdoor air ventilation per passenger is a summation of all these factors. The amount of outdoor air introduced through the HVAC system varies. Some new vehicles have no mechanical outdoor air supply, whereas others provide up to 4.25 L/s per passenger. Lower values of mechanical ventilation, typically 1.4 to 2.4 L/s or less per passenger, are associated with travel times of less than 2 min and large passenger turnover. Longer rides justify higher rates of mechanical ventilation.

Green initiatives have caused designers to take a closer look at all aspects of energy savings. Some systems are now designed with variable outdoor air rates, which are automatically lowered under low passenger load conditions or extreme temperature loads. This approach yields lower system cooling capacities and saves energy.

Air Distribution

With overhead equipment, air is distributed through linear ceiling diffusers that are often constructed as a part of the overhead lighting fixtures. Undercar equipment usually makes use of the void spaces in the sidewalls and below fixed seating. In all cases, the spaces used for air supply must be adequately insulated to prevent condensation on surfaces and, in the case of voids below seating, to avoid cold seating surfaces. The supply air discharge from undercar systems can be from overhead diffusers through sidewall duct or a windowsill diffuser. Recirculation air from overhead equipment flows through ceiling-mounted grilles. For undercar systems, return air grilles are usually found in the door wells or beneath seats.

Because of the vehicle's typical small size and low ceilings, care must be taken to design the air supply so that it does not blow directly on passengers' heads or shoulders. Because high flow rates are necessary to achieve capacities, diffuser design and placement are important. Some systems are designed so the air supply discharge hugs the vehicle's ceiling and walls to avoid drafts on passengers. Total air quantity and discharge temperature must be carefully calculated to provide passenger comfort. Interior noise levels are typically 72 to 74 dBA for a stationary vehicle with doors shut.

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