

Chapter 2

Advanced Transport Systems: Operations and Technologies

2.1 Introduction

This chapter describes BRT (Bus Rapid Transit) as an advanced mature public transport system operating in many urban and suburban areas round the world, high-speed tilting passenger trains operating along medium- to long-distance passenger corridors/markets in many countries worldwide, and an advanced subsonic commercial aircraft—the Boeing B787-8, which has recently started commercial operation.

The BRT systems are considered as advanced compared to the conventional urban bus systems mainly thanks to advanced operations. A BRT system can be defined as a “rapid modes of transportation that combines the quality of rail transit and flexibility of buses” (Thomson 2001).

High-speed tilting trains transport users/passengers along the curved segments of the conventional rail lines/tracks at higher speeds than their conventional counterparts thanks to advanced technology—the tilting mechanism. This compensates increased centrifugal and centripetal forces due to higher speed in the curved segments of the line by tilting on the opposite side from the direction of the force, i.e., if the force is directed to the left, the train tilts to the right, and vice versa. Such a tilting mechanism makes these trains advanced transport means/vehicles in terms of technology, despite the fact that some other components influencing their performances remain similar to those of their conventional counterparts.

The subsonic commercial aircraft (Boeing B787-8) is considered advanced thanks to its innovative design and the new materials used in its construction, and perceived superior economic and environmental performances as compared to those of its conventional counterparts.

2.2 Bus Rapid Transit Systems

1974	The first BRT (Bus Rapid Transit) system in the world—the “Integrated Transportation Network”—begins operations in Curitiba (Brazil)
1999/2000	The world’s largest BRT system—Transmilenio—begins operations in Bogota (Columbia)

2.2.1 Definition, Development, and Use

The BRT (Bus Rapid Transit) systems are considered as a flexible rubber-tired rapid transit mode that combines stations, vehicles, services, running ways, and ITS (Intelligent Transport System) into an integrated system with a strong positive image and identity. Flexibility implies that these systems can be incrementally implemented as permanently integrated systems of facilities, services, and amenities that collectively improve the speed, reliability, and identity of bus transit in a variety of environments. In many respects, BRT systems can be considered as a rubber-tired LRT (Light Rail Transit)-like systems but with greater operating flexibility and potentially lower capital and operating costs (Levinson et al. 2002).

The BRT systems started in the U.S. (United States) in the 1960s through the implementation of exclusive bus lanes. After the first truly dedicated bus way of the length of several kilometers was set up in 1972 in Lima (Peru), the step forward in developing the BRT system concept was made in 1974; the first bus-based public transport network was developed in Curitiba (Brazil) using the bus-way corridors spread as the route/line network throughout the city. Since the mid-1990s, the BRT has been intensively promoted in U.S. cities as an advanced urban transit system to alleviate the adverse effects of traffic congestion compared to the conventional urban bus transit systems at the lower investment/capital costs compared to rail-based urban transit systems such as LRT (Light Rail Transit). At the same time, it has been expected to increase the transport capacity and make the accessibility of dense urban agglomerations/regions more effective and efficient. Designed and implemented on a case-by-case basis in order to meet the specific needs and characteristics of the given urban and suburban areas, the BRT systems have been characterized by the dedicated bus corridors, terminals/stations, vehicles/buses, fare collection system, ITS technology, operational concepts (timetable), and branding elements. Consequently, they have offered more effective, efficient, faster, reliable, and punctual transport services under given conditions than conventional bus transit systems, which have approached or even exceeded the services of the rail-based systems (LRT). The main objectives behind implementation of the BRT concept have been to approach to the capacity and quality of services of LRT while at the same time benefiting from savings in infrastructure investment costs, flexibility of the bus transit system, and comparable fares for users/passengers.

Table 2.1 Some characteristics of BRT systems in the world (http://en.wikipedia.org/wiki/Bus_rapid_transit)

Region	Number of cities/urban agglomerations	Network length (km)	% of the total	Transport volume(s) (passengers/day) (million)	% of the total
Europe	42	636	17	0.937	3.8
North America	20	585	15.6	0.849	3.5
South America	50	1,250	33.4	15.694	64.1
Asia	25	882	23.6	6.439	26.3
Africa	3	62	1.7	0.238	1.0
Oceania	7	326	8.7	0.327	1.3

The BRT systems have shown flexibility in terms of feasibility of implementation in urban agglomerations with a population of between 0.2 and 10 million. As such, in many transit corridors/routes, they have represented a test bed before implementing a rail-based urban transit system such as LRT.

Depending on the layout of the city/urban agglomeration, the BRT system can operate along radial and/or star-shape corridors exclusively or as a complement/connection to the rail transit systems/lines. In addition to ‘Full BRT’ systems operating exclusively along dedicated bus-ways, ‘BRT Lite’ systems mainly operate along the mixed traffic lanes except in cases of passing through important intersections where it is given exclusive lanes.

Currently, BRT systems operate in 147 cities/metropolitan areas on all continents. The total length of the dedicated bus-ways is about 3,741 km. The total daily number of passengers using the systems is about 24.5 million. Table 2.1 gives additional characteristics of the BRT systems used around the world.

Regarding the above-mentioned characteristics, the BRT system has been developed and consequently mostly used in South America and Asia, and the least in Africa. The relative market share of the system in the total number of daily commuting users/passengers indirectly reflects such developments. In addition, the daily number of users/passengers tends to increase almost exponentially as the BRT system network is extended as shown in Fig. 2.1.

This indicates that the system is attractive for both existing users of public transit systems and those abandoning their cars for the first time.

LRT (Light Rail Transit), often considered as a strong competitor to the BRT system, can be defined as an electric railway system with a “light volume” capacity for passengers as compared to conventional (heavy) rail. Its performances are partially presented for comparative purposes. At present, 24 LRT systems operate in the U.S. In Europe, LRT systems have often been considered together with urban tramway systems. Some evidence indicates that 170 tram and LRT systems, comprising 941 lines of a total length of 8,060 km are in operation. In 21 cities, 154 existing lines have been extended by about 154 km and 21 new lines of a length of 455 km are under construction (ERRAC 2005).

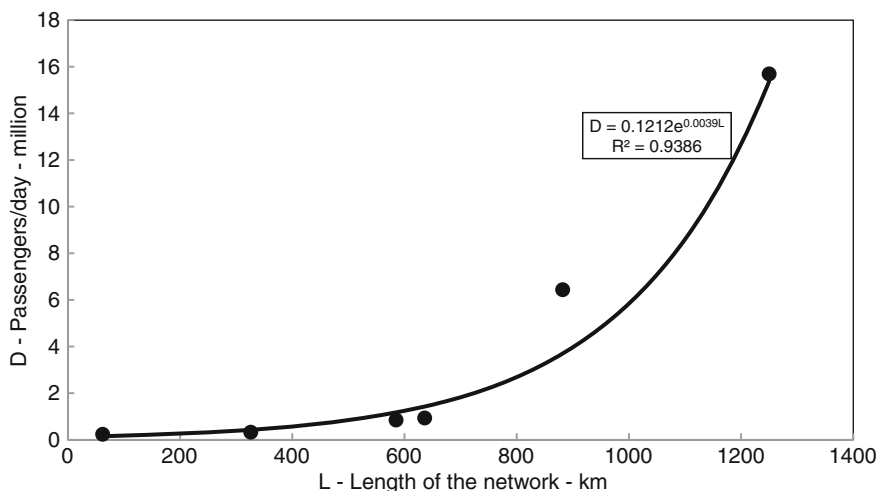


Fig. 2.1 Relationship between the daily number of passengers and the length of the BRT network in particular regions/continents (http://en.wikipedia.org/wiki/Bus_rapid_transit)

LRT systems may use shared or exclusive rights-of-way, high or low platform for users/passengers boarding/off-boarding, and multi- and/or single-car trains.

2.2.2 Analyzing and Modeling Performances

2.2.2.1 Background

The BRT systems are characterized by infrastructural, technical/technological, operational, economic, environmental, and social/policy performances. Considered together, they allow the BRT system(s) to be distinguished generally in seven features as compared to conventional/standard urban bus transit system(s) as given in Table 2.2 (GAO 2012).

The performances of the BRT system are analyzed, modeled, and evaluated using indicators and their measures. Their values are synthesized as averages from 40 BRT systems operating around the world—13 in Latin and South America, seven in Asia, three in Australia, eight in Europe, and nine in the U.S. and Canada (Wright and Hook 2007).

2.2.2.2 Infrastructural Performances

The main indicators of the infrastructural performances of BRT systems refer to the spatial layout of their networks/corridors/routes, the number/density of stations along the corridors/routes, and other characteristics.

Table 2.2 Distinguishing features of the BRT systems compared to conventional bus systems (GAO 2012; Levinson et al. 2003a, b)

Feature	Description
Running ways	Segregated and dedicated busways or bus-only roadways
Terminals/stations	Enhanced environment (information provided through real-time schedule systems and additional amenities—safety improvements, public art, landscaping, etc.)
Vehicles/buses	Standard/articulated, different engine technology (diesel, gas hybrid diesel/electric, electric), quieter, higher capacity, wider (usually low-floor) doors
Services	Faster, more frequent, punctual, and reliable
Fare collection	Prepaid or electronic passes—speedy fare collection, and boarding on/off convenience
Branding	Marketed as a distinguished service at the terminals/stations and vehicles/buses
ITS (Intelligent Transportation Systems)	Prioritization of services at intersections and traffic lights, monitoring headways between vehicles, real-time information on vehicle position and schedule

Spatial layout of the network

The BRT system networks operate under the assumption of having regular and sufficient passenger/commuter demand to be served by the relatively frequent transport (bus, trolleybus) services over a given period of time (hour, day, year) (for example, $\geq 8,000$ passenger/h/direction). Consequently, the transport infrastructure network consisting of the corridors/routes with dedicated busways and terminals/stations spread over, pass by and/or through densely populated/demand attractive areas of the given urban agglomeration—the city center(s) or CBDs (Central Business District(s)). A simplified spatial layout of the BRT network is shown in Fig. 2.2.

The BRT dedicated busways passing through the high density area continue outside it as right-of-way bus lanes. Both are connected to the freeway(s) surrounding the densely populated area(s) (CBDs). In some cases, the BRT dedicated busways or bus-only roadways are built along old rail corridors/lines. The dedicated busways are usually provided as two-way lanes in different directions in mixed traffic, as two-way lines on the same side or in the middle, or as a single line in each direction on different sides of the given corridor/route. In some cases, the bus-way is split into two one-way lanes/segments. The grade separation and elevation of BRT system routes is also provided, if needed, particularly at intersections of the routes themselves and with those of other traffic. Particular BRT busways can also be painted (red, yellow, green) in order to enhance visibility and recognition—by both the other drivers and users/passengers.

Typically, the single BRT corridor spreads between two agglomerations, one of which could be housing and the other CDB, or both CDBs. Given the length of this corridor usually defined as the distance between the initial and the end terminal/

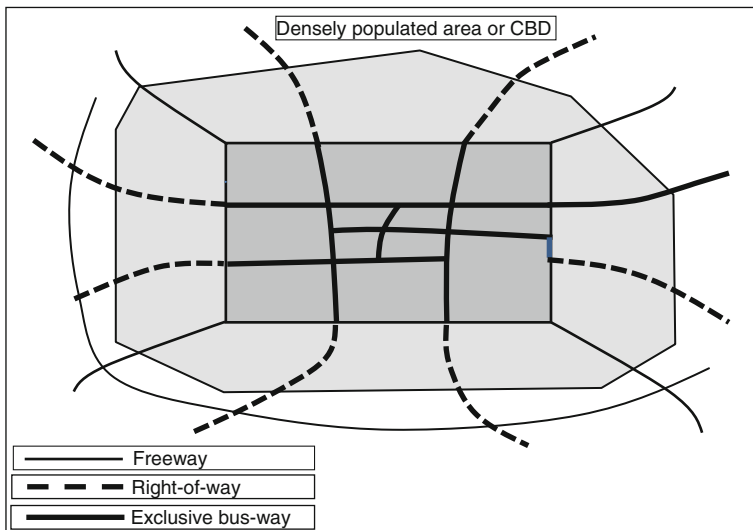


Fig. 2.2 Schematic layout of a hypothetical BRT network

station, width, and the number and area of the terminals/stations along it, the total area of land directly taken for building this infrastructure can be estimated as follows (Vuchic 2007):

$$A = L * D + n(ld) \quad (2.1)$$

where

L is the length of corridor (km);

D is the width of the corridor (m);

N is the number of stations/platforms along the corridor; and

l, d is the length and width of the plot of land occupied by the terminal/station (m), respectively.

For example, the width D of the exclusive bus-way (both directions) within the BRT corridor varies depending on the speed from 10.4–11.6 m (for moderate speeds ≤ 70 km/h) to 14.60 m (for speeds up to 90 km/h). The typical length of the bus stops varies from $l = 18$ –26 m depending on the bus length (for a single bus). The minimum width of the bus stop at the terminal/station is about $d = 3.0$ –3.5 m. However, the width of the area occupied by the terminal/station itself with the supporting facilities and equipment could be up to 9.0 m. For comparison, the typical (minimum) width of the corridor for building a double track LRT line respecting the vehicle's dynamic envelope is about 7.5 m. The track gauge is 1,435 mm. The typical area of the platform of the LRT station can be from 12×50 m (surface) to 20×90 m (grade separated) (Vuchic 2007; Wright and Hook 2007).

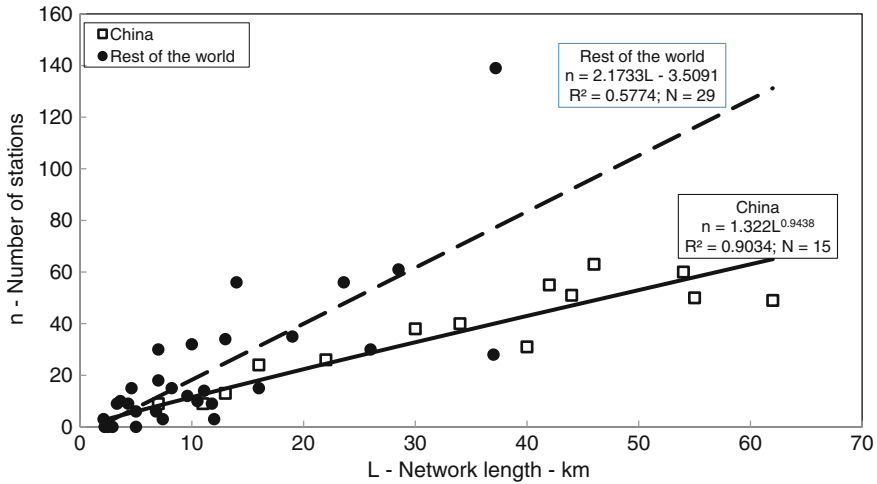


Fig. 2.3 Relationship between the number of stations and the length of the BRT system network (Levinson et al. 2003a, b; Wright and Hook 2007; http://en.wikipedia.org/wiki/Bus_rapid_transit)

Number/density of stations

The terminals/stations are important elements for the safe, efficient, and effective inter and multimodal transfers on the one hand, and for demonstrating the identity and image of the given BRT system on the other. A BRT terminal/station can be a simple stop, an enhanced stop, designated station, intermodal terminal, and/or transit center. The number and density of stations mainly depends and increases in line with the length of the BRT system network as shown in Fig. 2.3. In BRT systems around the world, except those in the People's Republic of China, this increase is of an average rate of 2.0/km. For systems in the PR of China, the average rate is 1.0/km. The network length varies from about 2 to 60 km.

BRT terminals/stations usually have passing lanes and sometimes multiple stopping/docking bays, which enable the conveying of busses in different combinations, if needed. The number of stopping/docking bays influences the required length of the given terminal/station as shown in Fig. 2.4.

Evidently, the length of the BRT terminal/station generally increases more than proportionally compared to the increase in the number of stopping/docking bays. This length and other dimensions can be larger if the BRT terminal/station is integrated with terminals/stations of other public transport modes, for example, those of the underground public transport system.

Passenger access to the BRT terminals/stations—either on foot, by bike, car/taxi, and other public transport systems—should be safe, efficient, and effective. This implies good integration including parking and short stop spaces at the rear of the stations, as well as providing convenient connections/passages to/from the bus platforms. In particular, at the BRT feeder-trunk systems, cross-platform transfers

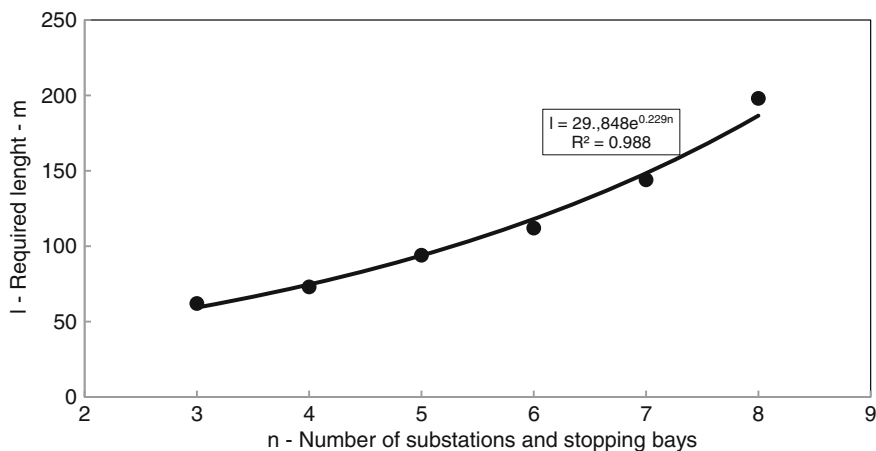


Fig. 2.4 Dependence of the required length of terminal/station on the number of substations and stopping/docking bays of the BRT system (Wright and Hook 2007)

Table 2.3 Infrastructural performances of the BRT and LRT system—infrastructure (averages) (GAO 2012; Levinson et al. 2003a, b)

Indicator/measure	System	
	BRT	LRT ^c
Number of systems	147	170
Length of the network (km/system)	25.3/15.0 ^c	47.4
Number of corridors/lines per system	2	6
Number of routes per corridor	5	—
Average length of the corridor/line (km)	32 ^a /12.9 ^b (28)	8.6
Width/profile of the lane (m)	10.4–14.6	7.5
Number of stations (-/route)	32 ^a /23 ^b	—
Density of stations (-/km)	1 ^a /2 ^b	—
Location of the station(s) (mainly)	Side/curb/off-lane	Side
Width/length of the station(s) (m)	9.5/50–9.5/75	12.0/50–20.0/70
Type of guideways/lanes—passing lanes	Mostly yes	Yes
Platform height (at the stations)	Low	Low (or High)
Static/spatial capacity of the stations (vehicles/station)	1–3	1–2
Materials used (lanes, stations)	Concrete, asphalt	Iron/steel, concrete, asphalt
Construction time (km/year)	16–20	1–5

^a China; ^b Rest of the world; ^c Europe

from the feeder to the trunk buses, and vice versa, should be provided (see below). Some additional indicators of the infrastructural performances of the BRT system and a comparable LRT system are given in Table 2.3.

2.2.2.3 Technical/Technological Performances

The technical/technological performances of the BRT system mainly relate to: (i) length, space (seats + stands) capacity, weight, type and power of engine(s), and riding comfort of vehicles/buses; and (ii) ITS (Intelligent Transport Systems) including the systems for managing transit services along the network/routes, providing the users/passengers with the online information, and collecting fares.

Vehicles/buses

The BRT systems generally use standard and/or articulated transport vehicles/buses (and trolleybuses) with a typical length of 12, 18, or 24 m, a weight of 13, 17, or 24 tons, and the corresponding capacity (seats + stands) of 75, 100, or 160 passengers, respectively. The buses have 3–4 axles. The buses of the above-mentioned 40 BRT systems are generally powered by four types of engines: diesel and diesel Euro II/III/IV (26), CNG (Compressed Natural/Propane Gas) (7), hybrid (diesel + electricity) (3), and electricity (3). The diesel/buses use diesel fuel for propulsion and electric power for auxiliary equipment. The CNG buses are powered by engines similar to diesel engines, but instead of diesel they use a methane mixture for propulsion. The hybrid diesel–electric vehicles/buses use an onboard diesel engine for producing electricity that charges their batteries. These in turn provide the electricity to run the electric propulsion motors. The electric vehicles—trolleybuses—use electricity from the overhead power supply infrastructure, i.e., from the catenary wire systems, for powering electric motors and auxiliary equipment. The typical engine power of BRT vehicles/buses is about 150–220 kW (kW—kilowatt). A summary of indicators of the technical/technological performances for typical BRT and LRT vehicles is given in Table 2.4:

An important characteristic of BRT vehicles/buses, sometimes more important than their size, is the number and width of doors. This influences utilization of vehicles/buses, consequently the route/line capacity, and other performances such as the average commercial speed. Some longer buses have four doors, each about 1–1.1 m wide. Depending on the location of busways, they can be on the vehicle's right or left side.

ITS (Intelligent Transport Systems)

Systems for managing transit services

The ITS (Intelligent Transport Systems) managing the transit services of BRT systems generally include: (i) automated enforcement systems for exclusive bus lanes; (ii) an AVL (Automatic Vehicle Location) system; (iii) a CAD (Computer-Aided Dispatching) and advanced communications system; (iv) a precision docking at bus stop system; (v) a tight terminal guidance system; and (vi) a warning system.

Table 2.4 Technical/technological performances of the BRT and LRT system vehicles (averages) (AUMA 2007; CE 2008; STSI 2008; Vuchic 2007; Janic 2011)

Indicator/measure	System	
	BRT	LRT
Length of a vehicle (m)	12/18/24 ^a	14–30 ^a
Height of a vehicle (m)	3.0–3.2	4.0–6.9 ^b
Width of a vehicle (m)	2.5–2.6	2.20–2.65
Cars/vehicle	1	2–4
Capacity (spaces/vehicle)	75/100/160	110–250
Seat spacing (m)	0.80	0.75–0.90
Number of axles/vehicle	3/4/4	4/6/8
Tare weight (tons)	13/17/24	25.4–38.8
Engine power (kW)	150–220	200–434
Maximum speed (km/h)	90–100	60–120
Operating speed (km/h)	27–48	40–80

^a Vehicle can be a set consisting of few cars; ^b Including pantograph

- Automated enforcement systems for exclusive bus lanes include the transit signal priority and the queue jump system; the former changes the timing of the traffic signals in various ways in order to give priority to BRT vehicles/buses at intersections (for example, the system turns the red light to green if it “recognizes” the approach of a BRT vehicle to the intersection); the latter enables using the separate lane and receiving the green light signal upon closer approach to the intersection;
- The AVL (Automatic Vehicle Location) System is the computer-based system enabling the real-time tracking of vehicles/buses and providing them with the information for the timely schedule adjustments and equipment substitutions; at the core of this system is GPS (Global Positioning Satellite) technology and GIS (Geographic Information System) displaying the location of the vehicles/buses on the route map grids in the dispatch center;
- The CAD (Computer-Aided Dispatching) and advanced communications system enables adjusting dwell times at vehicle/bus stops or transfer points, vehicle/bus headways, rerouting vehicles/buses, adding vehicles/buses to routes, and dispatching new vehicles/buses to replace incapacitated vehicles/buses; the drivers exchange communications with the dispatch center by radiotelephones, cellular telephones, and/or mobile display terminals;
- The precision docking system uses sensors on the vehicles/buses and on the roadside to indicate the exact place where the vehicle/bus should stop; this enables users/passengers to be in position for immediate boarding, which shortens dwell time(s) at the stops;
- The tight terminal guidance system uses sensors similar to those for precision docking to assist the vehicles/buses in maneuvering in terminals with limited space; the system can contribute to minimizing the amount of space for bus terminal operations, as well as to reducing the overall time the bus spends at the terminal/station; and

- The warning system aims at assisting/warning the vehicle/bus drivers in order to avoid collisions, pedestrian proximity, and low tire friction; this improves the safety, efficiency, and effectiveness of the BRT system's operations.

User/passenger information system

The user/passenger information system at the terminals/stations and onboard the vehicles/buses provides advance information contributing to the efficiency and effectiveness of travel decisions. For the former, displays provide real-time information on forthcoming arrivals/departures, transfer times and locations, and maps of the related routes/lines. For the latter, the system automatically announces the vehicle/bus approaching its next stop, giving sufficient time for preparation, speeding up disembarking and embarking, and consequently shortening dwell time at the terminals/stations (see below).

Fare collection systems

The BRT systems generally use three mainly automated systems for collecting fares: (i) preboard, onboard, and free-fare collection and verification. Of the 40 of the above-mentioned systems, 16 employ preboard, 21 onboard, and 3 free-board fare collection systems. In particular, the onboard system speeds up the fare collection process and eliminates expensive cash handling operations at transit agencies using smart cards. The system uses the read-and-write technology to store the monetary value on a microprocessor chip inside a plastic card. As passengers board a vehicle/bus, the card reader determines the card's value, debits the appropriate amount for the busride, and writes the balance back onto the card, all within a fraction of a second.

2.2.2.4 Operational Performances

Operational performances of the BRT system include demand, capacity, quality of service, size of fleet, and technical productivity. They are analyzed and modeled based on the above-mentioned global BRT systems. The corresponding figures for LRT systems are also provided for comparative purposes.

Demand

In general, the volumes of demand for existing and prospective urban transport systems can be estimated under the assumption of their mutual competition. In such case, the BRT system can compete with the individual passenger car and other public transport systems such as taxi, conventional bus, tram, metro, and LRT. Under such conditions, the users/passengers are assumed to usually choose the including BRT with respect to their own characteristics (age, gender, personal income), trip purpose (work, shopping, entertainment, other), and the system's performances, both in combination reflecting the generalized travel cost. This cost,

usually represented by the disutility function of using the given transit system (i) between given pair of origin and destination (k) and (l), respectively, $U_{i/kl}(T)$, can be estimated from either the aggregated trip generation data or disaggregate passenger survey data, both for a given period of time (T). The MNL (Multinomial) Logit model can then be applied to quantify the market share or the probability of choosing the system (i) as follows (TRB 2008a):

$$p_{i/kl}(T) = \frac{e^{-U_{i/kl}(T)}}{\sum_{i=1}^I e^{-U_{i/kl}(T)}} \quad (2.2a)$$

where

I is the number of transport systems offering transit services between the origin (k) and destination (l).

The number of users/passengers choosing the system (i) can be estimated from Eq. 2.2a as follows:

$$q_{i/kl}(T) = p_{i/kl}(T) * q_{kl}(T) \quad (2.2b)$$

where

$q_{kl}(T)$ is the total number of users/passengers traveling between the origin (i) and destination (k) during the time period (T) by all available transport systems.

The user/passenger demand $q_{kl}(T)$ in Eq. 2.2b can be estimated by applying one of the causal-gravity-type models based on the trip generation/attraction socio-economic forces of the origin (i) and the destination (k), and the travel “resistance” between them (Janic 2010; Vuchic 2004).

The user/passenger demand $q_{i/kl}(T)$ in Eq. 2.2b includes the demand between the origin (k) and destination (l) as well as the demand between each pair of the vehicle/bus stops along the corridor/line (kl) as follows:

$$q_{i/kl}(T) = \bar{q}_{i/kl}(T) + \sum_{m=1}^M [q_{i/km}(T) + q_{i/ml}(t)] + \sum_{m=1}^{M-1} \sum_{n=m+1}^M q_{i/mn}(T) \quad (2.2c)$$

where

$\bar{q}_{i/kl}(T)$ is the user/passenger demand between the origin (k) and destination (l) during the time period (T);

$q_{i/kl}(T), q_{i/ml}(T)$ is the user/passenger demand between the origin (k) and the station/stop (m), and the station/stop (m) and the destination (l), respectively, during the time period (T);

$q_{i/mn}(T)$ is the user/passenger demand between the stations/stops (m) and (n) during the time period (T); and

M is the number of stations/stops along the route (kl).

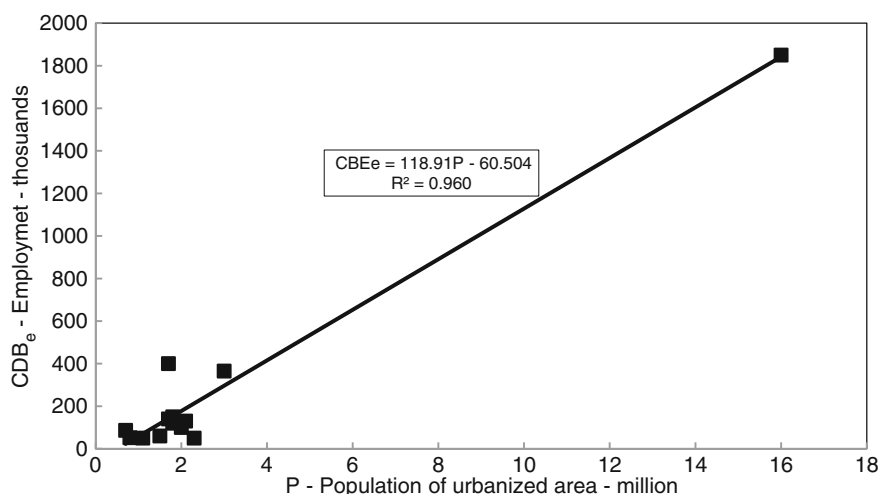


Fig. 2.5 Relationship between population of an urbanized area and employment in the corresponding CDB (Central Business District) (Levinson et al. 2003a, b)

Demand for BRT services mainly consists of daily users/passengers commuting from their home to the place of a given activity (work, shopping, entertainment, others), each located within or outside the given urban agglomeration (or CBD), and vice versa. The potential demand for the BRT, as well as for other urban public transport systems, can be influenced by the size of population, which in turn can influence employment and other commercial and entertainment activities in the given CBD. Figure 2.5 shows an example of the relationship between the size of urban population and employment in a CBD as the potential demand for the given BRT system.

Generally as intuitively expected, a larger urban population can generate proportionally greater employment in the CBD at an average rate of about 118 thousands employees per 1 million of population (as in the above example). Figure 2.6 shows an example of the relationship between the number of employees in CBD and the number of daily (weekday) users/passengers of BRT systems.

As expected, higher employment in the CBD generally generates a higher daily demand for urban transit including, in this case, the BRT.

Capacity

The transit capacity of the BRT system is one of the most important indicators of its operational performances mainly due to the requirement to transport relatively large numbers of users/passengers under given circumstances. This capacity can be considered for a single terminal/station, route/line, and the entire network providing the vehicle/bus capacity is given.

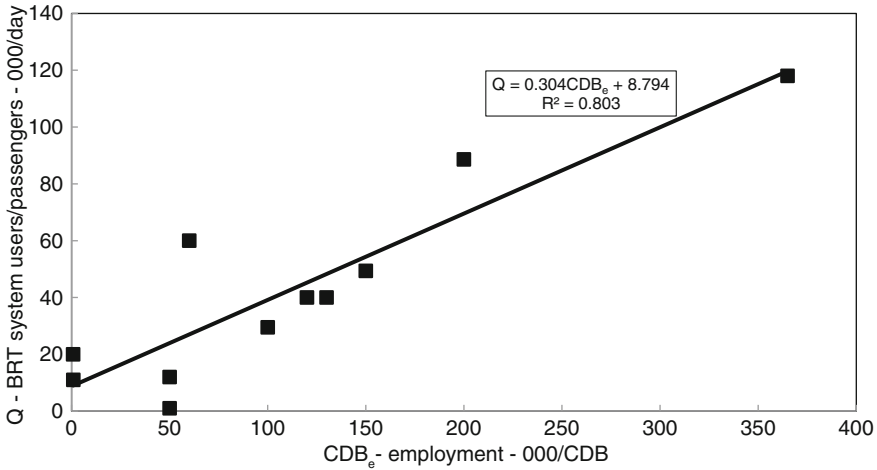
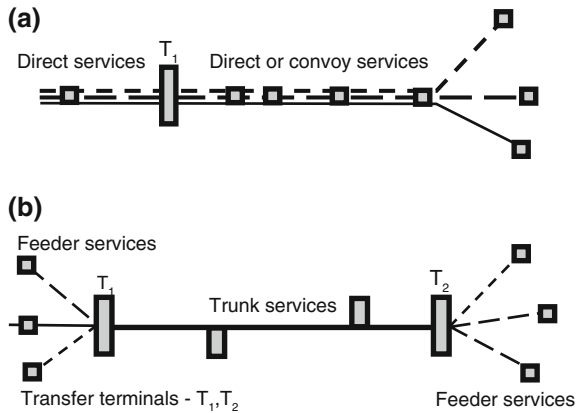


Fig. 2.6 Relationship between the daily number of users/passengers of the BRT system and employment in the CBD (GAO 2012; Levinson et al. 2003a, b; Wright and Hook 2007)

Fig. 2.7 Scheme of a BRT system service network **a** Direct or convoy network **b** Trunk-feeder network



Service network

The BRT system can generally operate as a “direct or convoy”, “trunk-feeder,” and “hybrid” service network. The layout of the former two is shown in Fig. 2.7.

- *Direct or convoy network* consists of routes and related BRT services connecting different user-passenger origins and destinations, which can be both within and outside a given urban agglomeration. In such case, many different bus services/lines connecting particular sets of these origins and destinations operate within the common/main part of the network(s) and then spread outside it toward the periphery of the given agglomeration. Consequently, a high

frequency of mainly direct services (with no or few transfers) is provided to those users/passengers traveling within the parts of the common/main network. The demand served through the main part of the network by the given BRT service/line during the time period (T) estimated as in Eqs. 2.2a–c is: $Q(T) \equiv q_{kl}(T)$, where (k) is the origin ($k = 1, 2, \dots, K$) and (l) is the destination of the user/passenger flow(s) ($l = 1, 2, \dots, L$).

- *Trunk-feeder network* consists of the feeder and trunk part. The feeder part represents the local network connecting the user/passenger origins and destinations to the trunk terminal(s)/station(s) by services usually operated by lower capacity (conventional) vehicles/buses. The trunk terminals are mutually connected by services usually operated by the larger (articulated) and/or bi-articulated vehicles/buses. In any case, the size of vehicles/buses and service frequency can be easily adapted to the volumes of user/passenger demand. However, the users/passengers are forced to change at the trunk terminals/stations, which does not exclude potential necessary changes at the stations between them.
- *Hybrid network* represents a combination of a direct or convoy and trunk network set up to appropriately adjust the offered capacity to changes in user/passenger demand. This implies flexibility in adapting to the time and spatial pattern, volumes, and intensity of this demand. Consequently, this network possesses the combined features of both sub-networks it is comprised of.

The volumes of demand are generally different on the feeder and the trunk route(s) of the trunk-feeder network(s). For example, on the feeder route connecting the origin (k) and the trunk terminal/station T_1 , the volume of this demand during period (T) is: $Q(T) \equiv q_{k,T_1}(T) = \sum_{l=1}^L q_{kl}(T)$ ($k = 1, 2, \dots, K$). On the trunk route between the transfer terminals/stations T_1 and T_2 , this volume is: $Q(T) \equiv q_{T_1,T_2}(T) = \sum_{k=1}^K \sum_{l=1}^L q_{kl}(T)$, for $k \neq 1$. Finally, on the feeder route connecting the trunk terminal/station T_2 and the destination (l), the volume of user/passenger demand is: $Q(T) \equiv q_{T_2,l}(T) = \sum_{k=1}^K q_{kl}(T)$ ($l = 1, 2, \dots, L$). The user/passenger demand $q_{k,T_1}(T)$, $q_{kl}(T)$, and $q_{T_2,l}(T)$ can be estimated as in Eqs. 2.2a–c. Consequently, the main differences between the above two network configurations are as follows:

- At the direct or convoy service network, the lower capacity BRT vehicles/buses directly operate between particular origin and destination terminals/stations. In this case, the volumes of user-passenger demand per origin–destination pair are usually lower, resulting in the lower service frequency and the lower load factor per frequency given the vehicle/bus size/space capacity; as mentioned above, the capacity of these vehicles/buses is usually 70–75 spaces (seats + stands) (12 m length).
- At the trunk-feeder service network, feeder vehicles/buses of a capacity of 70–75 spaces (12 m length) transport users/passengers between their origins and destinations and the trunk terminal(s)/station(s). At these terminals/stations, the users/passenger change for trunk vehicles/buses, usually with a capacity of

160–200 spaces (18–24 length). Thus, the volumes of users/passengers in both the feeder routes and the trunk corridor substantively increase, which generally can justify the increase in the service frequency, the vehicle/bus capacity or both simultaneously, and consequently the load factor. Such a BRT network is thus more effective and efficient.

Furthermore, all above-mentioned types of BRT networks can act as feeder systems to other mass urban (metro, tram, LRT) and inter-urban transit systems (heavyrail).

Station/terminal capacity

The capacity of a station/terminal $\mu_s(t)$ depends on the number of platforms—parking/stopping places—for the vehicles/buses and the average time they occupy them. In general, this capacity can be estimated as follows:

$$\mu_s(T) = P/\bar{t}_s(T) \quad (2.3)$$

where

P is the number of available stopping/docking bays on the given terminal/station; and

$\bar{t}_s(T)$ is the average occupancy time of a single stopping/docking bay (min) during time period T .

The average occupancy time $\bar{t}_s(T)$ of the stopping/docking bay can change over time as indicated by Eq. 2.3. Consequently, the capacity or service rate of the stopping bay can also change under conditions of having all designed spaces available during the time T (i.e., $\mu_s(t) = 1/\bar{t}_s(T)$).

Route/line capacity

The capacity of the route/line can be defined as the maximum number of vehicles/buses (sometimes also the number of passenger spaces), which can pass through its fixed point (i.e., the “reference location”) during the given period of time T (usually 1 h) under conditions of constant demand for service (Vuchic, 2007). This capacity expressed by the service frequency $f_{kl/\max}(T)$ for the route/line connecting the origin (k) and the destination (l) can be estimated as follows:

$$f_{kl/\max}(T) = \left[\frac{T}{\max(H_{kl/w/\min}; H_{kl/s/\min})} \right] \quad (2.4a)$$

where

$H_{kl/w/\min}$ is the minimum headway between the successive vehicles/buses along the particular sections of the route/line (kl) (min); and

$H_{kl/s/\min}$ is the minimum terminal/station headway defined as the inter-arrival time of the successive vehicles/buses at the particular stations along the route/line (kl) (min).

In the case of satisfied demand with the specified average load factor per service, the frequency $f_{kl}(T)$ in Eq. 2.4a can be estimated as follows:

$$f_{kl}(T) = \left[\frac{q_{kl}(T)}{\lambda_{kl}(T)N_{kl}} \right] \quad (2.4b)$$

where

$q_{kl}(T)$ is the user/passenger demand on the route/line (kl) during the period (T) (determined according to Eqs. 2.2a–c) (passengers);
 $\lambda_{kl}(T)$ is the average load factor along the route/line (kl) during time (T), and
 N_{kl} is the vehicle/bus capacity operating along the route (kl) (spaces/vehicle).

In Eq. 2.4a, in most cases: $H_{kl/w/\min} > H_{kl/s/\min}$; thus, the terminal/station headway(s) determines the capacity of the given route/line. Consequently, the capacity $C_{kl}(T)$ expressed by the maximum number of vehicles/buses that can pass through a given “reference location” of the route/line (kl) during the period of time (T) can be estimated based on Eq. 2.4a as follows:

$$C_{kl}(T) = f_{kl/\max}(T) * m_{kl} \quad (2.4c)$$

where

m_{kl} is the number of vehicles/buses per each single departure/service on the route (kl).

The offered capacity of the route/line (kl), $C_{kl/o}(T)$ defined as the number of passenger spaces supplied during the given period of time T can be estimated as follows based on Eq. 2.4c:

$$C_{kl/o}(T) = C_{kl}(T) * N_{kl} \quad (2.4d)$$

where all symbols are analogous to those in the previous equations.

In Eq. 2.4d, the vehicle/busspace capacity N_{kl} depends on its constructive characteristics and is expressed by the number user/passenger spaces (seats + - stands) per vehicle/bus.

Speed

Speed as an indicator of operational performances refers to the operating and commercial speed of vehicles/buses along the routes of a given BRT system network(s). The operating speed includes acceleration, deceleration, and cruising/operating speed, which depends on the vehicle/bus technical/design characteristics and prevailing driving/traffic conditions, while the commercial speed $v_{kl}(d_{kl})$ along the BRT route/line (d_{kl}) includes the operational speed and dwell time at stations/terminals. It can be estimated as follows:

Table 2.5 Operational performances of BRT and LRT system—capacity (averages) (ERRAC 2004; GAO 2012; Levinson et al. 2003a, b; Vuchic 2007; Wright and Hook 2007)

Indicator/measure	System	
	BRT	LRT
Vehicle capacity (passengers seating + standing)	75–160	110–250
Route/line capacity (veh/h)	8–15	5–12
Terminal/station dynamic capacity (veh/h)	8–15	5–12
Network capacity (veh/h)	56–105	30
User-passenger capacity (pass/h/direction)	600–2400	550–3000
Commercial speed (km/h)	26.3	20–25

$$v_{kl}(d_{kl}) = d_{kl}/\tau_{kl}(d_{kl}) \quad (2.5)$$

where

d_{kl} is the length of route between the origin (k) and the destination (l) (km);
and

$\tau_{kl}(d_{kl})$ is the total travel time of a vehicle/bus along the route d_{kl} (min).

Some measures of BRT and LRT system capacity have been estimated using Eqs. 2.4a–2.5 and are given in Table 2.5.

The values in Table 2.5 confirm that on average, BRT systems appear quite comparable and according to some measures even superior to LRT systems. Furthermore, the user/passenger capacity of both large systems can be much higher: 5,000–40,000 for BRT and 6,000–15,000 pass/h/direction for LRT systems, which clearly indicates the superiority of BRT systems (Wright 2003). Nevertheless, the supply of this capacity should be adapted to the volumes of demand as shown in Fig. 2.8.

In general, peak-hour capacity supply increases at a decreasing rate as the volumes of corresponding demand increase. For example, in order to serve 5,000 users/passengers/h/direction, the BRT system needs to engage 92 vehicles/buses ($N \geq 54$). For 10,000 users/passengers, around 172 vehicles/buses are needed ($N \geq 58$). For 20,000 users/passengers, about 323 buses are needed ($N \geq 62$). This indicates that as the peak-hour demand increases, both the number and size of the vehicles/buses engaged tend to increase.

The number and size of vehicles/buses in the operator's fleet also depend on the type of service system/network. For example, the average size of the fleet operating the direct or convoy system/network is about 133 vehicles/buses and of that operating the trunk-feeder system/network 197 (80 trunk articulated and 117 feeder) vehicles/buses. Specifically, the largest BRT TransMilenio (Bogota, Columbia) operates a fleet of 1,420 (1,013 trunk articulated and 407 feeder) vehicles/buses (Wright and Hook 2007).

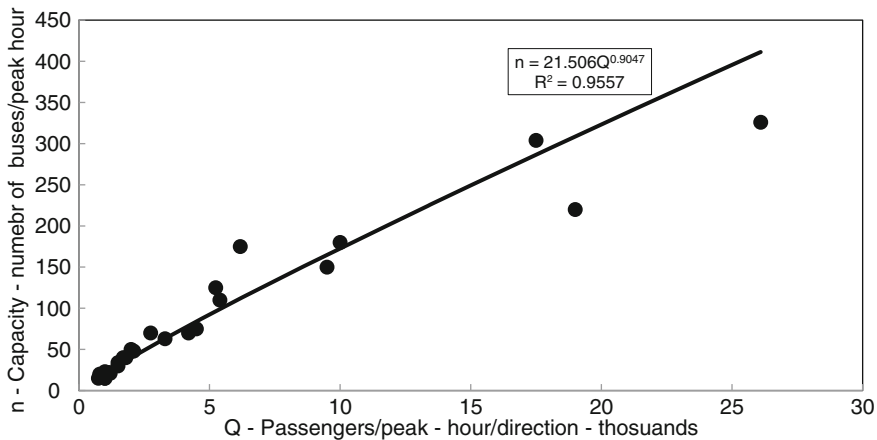


Fig. 2.8 Relationship between peak-hour capacity and demand for the selected BRT systems (Levinson et al. 2003a, b)

Quality of service

The quality of service of the BRT system is expressed by schedule delays, travel time or commercial speed, availability, reliability and punctuality, riding comfort, and the overall accessibility of a given BRT route/line and/or network.

Schedule delay

Schedule delay is defined as the time a passenger has to wait for BRT services at a given terminal/station. Assuming that the users/passengers are familiar with the timetable and arrive at the BRT station/terminal uniformly during any two successive vehicle/bus services, the average schedule delay of a user/passenger can be estimated, based on Eqs. (2.4a, b) as follows:

$$SD(T) = 1/4[T/f(T)] \quad (2.6)$$

where all symbols are as in the previous equations.

Travel time

Travel time depends on the distance of the user/passenger origins and destinations along the given route/line, the vehicle/bus operating speed, and the number and duration of intermediate stops. The duration of stops can be influenced by the number and width of doors of the vehicles/buses, and the number of user/passenger entries and exits at the particular stops (travel time can be extracted from Eq. 2.7b below). The above-mentioned commercial speed, being much higher than that of conventional bus systems (currently between 27 and 48 km/h), can be viewed as an additional measure. As such, it is close to the commercial speed of LRT. For example, the average commercial speed of a TransMilenio (Bogota, Columbia)

BRT service operating along the average route length of 13 kms is about 29.5 km/h (Levinson et al. 2003a, b; Saavedra 2011; Vuchic 2007).

Consequently, thanks to these features, BRT systems are considered “savers” of travel time. Some figures in the U.S. show that, depending on the system, these savings are about 5–35 %, which results in increases in the volumes of user/passenger demand by about 3–60 %, the latter after 1 year of operation, as compared to existing transit services (GAO 2012).

Availability, reliability, and punctuality

In general, BRT system services are considered highly available, reliable, and punctual. Availability is achieved through scheduling services during the entire day. Reliability implies operations without cancelation of the scheduled services due to any reasons. High punctuality implies minor deviations of actual from scheduled arrival times at particular locations/stations along the line(s), which is achieved thanks to operating, in the most cases, along the dedicated bus ways and applying ITS. Such high indicators are comparable to those of LRT systems.

Riding comfort

Riding comfort is usually influenced by the available space for seating and standing onboard the vehicles/buses, internal noise, and smoothness of operations depending, among other factors, on the driving regime and the quality of surface of the bus-ways. Available space per passenger is measured by the seat spacing, which is typically 0.80 m for the vehicles used in most BRT systems. The driving regime is strongly influenced by acceleration/deceleration rates due to the relatively frequent stops along the given route/line. These are about 0.8–1.6/1.1 m/s² for BRT vehicles/buses compared to 0.9–1.3 m/s² for LRT trains (Vuchic 2007).

Accessibility

BRT system services are accessible at terminals/stations located at certain distances along the routes/lines on foot, and/or by bike, car, taxi, and/or other public transport modes. In many cases, pedestrian zones lead directly to BRT terminals/stations, thus making them even more accessible. In addition, good accessibility is achieved through the convenient positioning of BRT routes/lines in the given urban context, by locating terminals/stations at easily accessible places, providing dedicated parking spaces for bikes and vehicles/cars and convenient connections/passages to BRT vehicles/bus platforms.

Table 2.6 gives some averages of the indicators and measures of the service quality of BRT and LRT systems.

This confirms that both systems are quite comparable in terms of the quality of service and as such are mutually substitutable.

Fleet size

The size of fleet of a given BRT system is expressed by the number of vehicles/buses operating during a given period of time under given conditions (service frequency and volume of user/passenger demand). This can be estimated for an

Table 2.6 Operational performances of BRT and LRT system—quality of service (averages) (GAO 2012; Janic 2011; Levinson et al. 2003a, b; Vuchic 2007; Wright and Hook 2007)

Indicator/measure	System	
	BRT	LRT
Service frequency (deep/peak-h)	8–15	5–12
Schedule delay (peak-h) (min)	1.00–1.875	1.25–3.0
Dwell time at stations (s)	24	–
Transit time (min/line)	64	–
<i>Typical operating speed</i> (km/h)		
Freeway/bus-way		
Nonstop	60–80	70–90
All-stop	40–55	40–60
Arterial streets	23–31	–
Acceleration/deceleration rate (m/s ²)	0.8–1.6/1.1	0.9–1.3
Reliability of services	High	High
Punctuality of services	High	High
Riding comfort	High	High

individual route/line and/or entire network. For example, for a route/line (kl) during the period T , the required number of vehicles $n_{kl}(T)$ equals, based on Eqs. 2.4a–d:

$$n_{kl}(T) = f_{kl/\max}(T) * \tau_{kl}(d_{kl}) \quad (2.7a)$$

where all symbols are equivalent to those in the previous equations.

In Eq. 2.7a, $\tau_{kl}(d_{kl})$ is the turnaround time of the vehicles/buses on the route/line d_{kl} , which can be estimated as follows:

$$\tau_{kl}(d_{kl}) = t_{kl/s1} + 2 \left[\sum_{j=1}^{M_{kl}-2} t_{kl/sj} + \sum_{j=1}^{M_{kl}-1} d_{kl/j,j+1} / v_{kl/j,j+1} (d_{kl/j,j+1}) \right] + t_{kl/sM} \quad (2.7b)$$

where

- $t_{skl/1}$, $t_{kl/Mj}$ is the average (scheduled) stop time of the vehicle/bus at the beginning and end station/terminal of the route/line (kl) (min);
- $t_{skl/j}$ is the average (scheduled) stop time of the vehicle/bus at the intermediate station (j) along the route/line (kl) (min);
- $d_{kl//j,j+1}$ is the distance between the (j) and ($j + 1$) station along the route/line (kl) (km);
- $v_{jkl//j,j+1}(d_{jkl//j,j+1})$ is the average operating speed of the vehicle/bus along the segment of the route/line (kl) between (j) and ($j + 1$) station (km/h); and
- M_{kl} is the number of stations along the given route/line (kl).

For example, the average fleet size of BRT systems operating a direct or convoy network is 133 and of those operating a trunk-feeder network 197 vehicles/buses (the latter excludes the TransMilenio system). The average fleet size of a European LRT system is 155 vehicles.

Technical productivity

The technical productivity of an individual route and the entire BRT system network can also be determined. Based on Eqs. 2.4a–2.7b, the technical productivity of the given route/line d_{kl} can be estimated as follows:

$$TP(d_{kl}) = C_{kl/0}(T) * N_{kl} * v_{kl}(d_{kl}) = f_{kl/\max}(T) * m_{kl} * N_{kl} * v_{kl}(d_{kl}) \quad (2.8)$$

where all symbols are as in the previous equations.

For example, the average technical productivity of BRT systems varies depending on their size and scope from 15,780 to 63,120 s-km/h (excluding the TransMilenio system). The corresponding technical productivity of LRT systems in Europe varies from 11,000 to –75,000 s-km/h.

2.2.2.5 Economic Performances

The economic performances of BRT systems refer to their costs and revenues.

Costs

BRT system costs include investment costs in infrastructure, facilities, equipment and in some cases vehicles/buses, as well as operational costs.

The total costs of a given BRT system consist of investment costs and operating costs. For the period of 1 year, these costs can be estimated as follows:

$$C_T = C_I + C_o = A + 365 * V * c_v(V) \quad (2.9a)$$

where

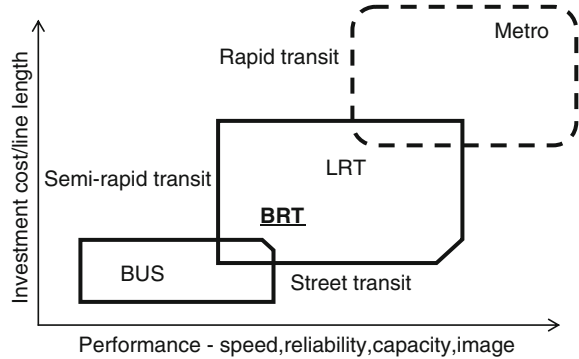
A is the annuity paid for investment and capital maintenance of infrastructure (\$US/year);

V is the average daily utilization of the vehicle/bus fleet (veh-km/day); and

$c_v(V)$ is the average operating cost per unit of system output (\$US/veh-km).

The average volume of vehicle kilometers carried out per day V can be determined as the product of the daily mileage of a single vehicle and the number of vehicles engaged depending on the volume of demand. Operating costs $c_v(V)$ generally decrease more than proportionally as the volume V increases. These costs include annuities on bonds for acquiring the vehicles/buses, vehicle/bus insurance costs, the wages of drivers and other support staff, the costs of vehicle/bus maintenance including wages of personnel and spare parts, energy/fuel costs, and the costs of using the infrastructure (taxes). Table 2.7 gives an example of the typical average costs for selected U.S. BRT and LRT systems.

Fig. 2.9 Relationship between the investment costs and performances for selected urban and suburban passenger transport systems (Vuchic 2007)



The differences in the investment costs between BRT and LRT are mainly due to some specific components needed for LRT and not needed for the BRT system such as, for example, train signal communication, electric power systems with overhead wires to power the trains, and rails, ties, and switches. In addition, a rail maintenance facility must be built if one doesn't already exist. Furthermore, the investment costs in BRT systems differ for dedicated bus lines and for mixed traffic lines. For example, on average these amount to 1.2–6.0 \$US/km for dedicated and 0.03–0.06 million \$US/km for mixed traffic lane(s). The average construction time is about 16/20 km of lines per year. That said, urban and suburban transit systems with higher performances will generally require higher investment costs as shown by the linear qualitative relationship in Fig. 2.9.

In the example given in Table 2.7, the average cost per p-km and vehicle-km is lower in the case of BRT than LRT systems. However, the average cost per passenger is higher in the case of BRT than in LRT, indicating that LRT systems provide services over longer distances.

Table 2.7 Economic performances of selected BRT and LRT systems—cost (averages) (GAO 2001, 2012; Janic 2011)

Cost component	System	
	BRT	LRT
<i>Infrastructure and vehicles</i>		
Infrastructure (millions \$US/km) ^a	8.98	18–25
Vehicle (millions/\$US/unit)	0.4–1.0	1.5–3.4
Amortization period (years)	25	25
Infrastructure		
Vehicles	12–15	25
<i>Operation</i>		
\$US/p-km ^b	0.12	0.23
\$US/veh-km ^c	3.05	8.90
\$US/passenger ^d	3.20	2.57

^a In the U.S. the average investment costs for 29 LRT systems amounted to about 24 million \$US/km; ^b 5 BRT and 15 LRT systems in the U.S.; ^{c, d} Six BRT and LRT systems in the U.S.

Revenues

Revenues from operating given BRT system are gained by collecting fares and from various subsidies. For the period of 1 year, these revenues can be estimated as follows:

$$R = 365 * q_p * p + S_u \quad (2.9b)$$

where

q_p is the daily number of users/passengers (users/passengers/day);
 p is the average fare per user/passenger (\$US/user/passenger); and
 S_u is the annual subsidy to a given BRT system.

For example, the average fare of the above-mentioned 40 BRT systems operating around the world is 1.25\$US/passenger. About 68 % of the systems (27 of 40) need subsidies at an average level of 25–30 %. Similarly, LRT systems also need subsidies at a level of 20–25 % (Tegner 2003; Wright and Hook 2007).

2.2.2.6 Environmental Performances

The environmental performances of BRT systems include energy/fuel consumption and related emissions of GHG (Greenhouse Gases), and land use/take.

Energy consumption and emissions of GHG

The energy consumption and emissions of GHG (Greenhouse Gases) by BRT system(s) can be considered as direct absolute and relative, and in terms of savings in these both thanks to the modal shift from other urban transit systems.

Direct energy/fuel consumption and related emissions of GHG are usually expressed in relative terms, i.e., as the average quantities per unit of the system's output, i.e., g/p-km or g/s-km (grams/passenger-kilometer or grams/space-kilometer). This is usually carried out for the specified vehicle size and occupancy rate (load factor) while always bearing in mind the specific conditions in which a given BRT system operates. Then, the absolute values can be easily obtained by multiplying these relative values by the corresponding volumes of output over the specified period of time, or vice versa.

In particular, relative values are convenient for comparison of BRT system(s) with other urban transport systems as given in Table 2.8.

As indicated, in both BRT systems, conventional buses (12 m long) mainly used in small and medium-sized direct or convoy systems/networks and for feeder services in larger trunk-feeder and hybrid networks consume and generate less energy/fuel and related emissions of GHG (CO₂), respectively, than their larger articulated counterparts (18 m long). In addition, in this respect, BRT systems remain inferior as compared to LRT systems on the one hand, but superior as

Table 2.8 Environmental performances of the selected urban transport systems—energy/fuel consumption and emissions of CO₂ (averages) (Vincent and Jerram 2006; VTT 2004; Wright 2003)

Impact	System				
	BRT ^b		BRT ^c	LRT ^b	Car ^b
Vehicle (length or units)	12 m	18 m	18 m	2 units	1 unit
Energy/fuel consumption (g/p-km) ^a	8.70	11.69	8.09	5.73	40.79
Emissions of GHG (CO ₂) (g/p-km)	27.85	37.41	25.9	18.37	130.53

^a Diesel fuel; ^b U.S. system(s); ^c BRT TransMilenio (Bogota, Columbia) (Based on 75 passengers per BRT and/or LRT vehicle, and 2 passengers per car)

Table 2.9 Environmental performances of the U.S. BRT and LRT systems—emissions of other than CO₂ GHG (averages) (Puchalsky 2005)

Emissions of GHG	System			
	BRT			LRT
	Diesel	Hybrid	CNG ^a	
NO _x (g/p-km//g/s-km)	0.7150	0.439/0.336	0.2300/0.1590	0.0278/0.0115
VOCs (g/p-km//g/s-km)	0.0063	0.003159/0.002418	0.0112/0.0074	0.000177/0.000073
CO (g/p-km//g/s-km)	0.0713	0.00238/0.00182	0.2570/0.1770	0.000522/0.000216

^a CNG Compressed Natural Gas

compared to individual passenger cars on the other. Both BRT and LRT system are superior as compared to individual (diesel-powered) cars. Table 2.9 gives the average relative emissions of the other than CO₂ GHG—VOC (Organic Compounds), NO_x (Nitrogen Oxide), and CO (Carbon Monoxide)—generated by BRT and LRT systems in the U.S.

These values generally confirm again that BRT systems, independently on the energy/fuel used, remain inferior as compared to LRT systems in terms of relative emissions of the specified GHG. However, these emissions of GHG by LRT systems always need to be considered respecting the composition of the primary sources for obtaining electricity.

Savings in the energy/fuel and related emissions of GHG by BRT system(s) can be achieved in different ways. One can be within the system by choosing low energy/emissions vehicle/bus technologies, by designing bus ways as straight and as short as possible, and by maximizing the fuel efficiency of the vehicle/bus operations along the routes under given conditions (avoiding stops in traffic jams, minimizing the dwell time at stations, driving at fuel-optimal speeds, etc.).

The other implies keeping existing users/passengers onboard, attracting those using individual car as the mode (*j*) to shift to BRT system as the mode (*i*), and attracting new users of public transport systems. These direct savings as the average quantities per user/passenger can be estimated as follows:

$$s_{ji} = [(\lambda_i N_i) / \lambda_j N_j] * EC_j - EC_i] * d \quad (2.10)$$

where

- N_i, N_j is the vehicle capacity of transport modes (i) and (j), respectively (spaces);
- λ_i, λ_j is the occupancy rate (i.e., load factor) of vehicles of transport modes (i) and (j), respectively;
- EC_i, EC_j is the average energy/fuel consumption and/or emissions of GHG of transport modes (i) and (j), respectively (g/p-km); and
- d is the travel distance (km).

From Table 2.5 it follows that, for example, a BRT bus carrying 75 passengers can replace 37 individual cars, each with 2 passengers. Assuming, for example, that the average commuting distance is 19 km, the savings in the energy/fuel consumption by such car/BRT modal shift would be about 28.5 (bus—12 m long) and 28.7 (bus—18 m long) kg of diesel fuel. The corresponding savings in the emissions of GHG would be about 91.2 and 91 kgCO₂, respectively (Vincent and Jerram 2006).

Land use

Land use relates the size of land used for setting up the infrastructure for a given BRT system. This consists of land for the segregated bus-ways and stations along them, and for the buses' docking/maneuvering, short- and long-term parking (garages), repairs, and maintenance. The size of acquired land for segregated busways has already been discussed. But what are the potential savings of the parking and operating land due to the potential replacing of individual cars by BRT systems? For example, the parking space for a conventional (12 m long—70 spaces) and for an articulated BRT bus (18 m long—160 spaces) is about 36 and 54 m², respectively. The former can replace 18 and the latter 40 passenger cars (4 seats), each occupying 10 m² of space of at most. The resulting savings of parking space otherwise occupied by cars would be about 144 and 346 m², respectively.

2.2.2.7 Social and Policy Performances

Social/policy performances of BRT system(s) generally include noise, congestion, traffic incidents/accidents (i.e., safety and security) and contribution to social welfare.

Noise

BRT system vehicles/buses generate noise while performing transit services. As in the case of other transport systems, this noise generally depends on their constructive-technical/technological characteristics and the pass by speed. It has already been mentioned that BRT systems operate vehicles/buses powered by different engine technologies, which crucially influence levels of their noise. For example, the

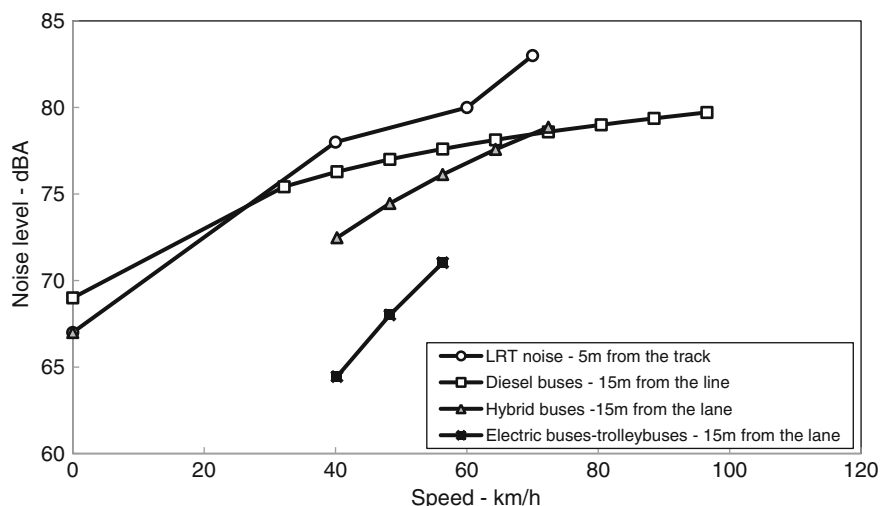


Fig. 2.10 Relationships between the noise and speed of BRT and LRT vehicles (CE 2008; Ross and Staiano 2007)

noise of BRT diesel and CNG buses comes from their exhaust system, engine block, cooling system, air intake components, and tire/pavement interaction. The noise from BRT hybrid vehicles/buses comes from both diesel and electric motors. The main noise sources of BRT trolley buses are interaction between the catenary wire and the pantograph, electric motor, auxiliary equipment, and tire-pavement interaction (Ross and Staiano 2007). In comparison, the noise by LRT vehicles primarily comes from interaction between the catenary wire and the pantograph, electric motors, auxiliary equipment, and wheel-track interaction (CE 2008). Important factors influencing received noise from both BRT and LRT system are: (i) the distance from the noise source, i.e., passing by vehicle(s), and (ii) the existence of noise barriers along the lanes. Figure 2.10 shows an example of the dependency of the noise on speed of BRT and LRT vehicles. BRT vehicles/buses are 12–18 m long, weighting 13–17 tons empty and 32 tons full (vehicle + driver + passengers) with a capacity of 75–100 spaces. LRT vehicles/trains are 20 m long weighting 37–44 tons full (vehicle-couple of cars + driver + 65–162 spaces/passengers).

In the case of BRT vehicles/buses, the noise increases in line with the operating speed at a decreasing rate. In the case of LRT systems, this rate is slightly higher. The noise level from LRT systems is higher than that of BRT buses. One of the reasons is that the distance from the source is three times shorter (5 vs. 15 m) (Urban and suburban buses operating at speeds of about 70 km/h generate noise of about 87.5–92.5 dB at a distance of about 5 m from the source (Cebrián 2008)). Nevertheless, it can be said that respecting their noise levels, BRT and LRT systems appear quite comparable. Noise barriers of a sufficient height along BRT

routes built of brick or concrete contribute to decreasing noise to and below the sustainable level of about 55 dBA (Mishra et al. 2010).

Congestion

BRT system congestion can be considered from three aspects. The first implies congestion caused by interference between the BRT vehicles/buses and other traffic, and vice versa, while operating along mixed traffic bus lanes. The second implies congestion due to the clustering of the BRT buses operating along segregated bus ways—particularly those with single lanes in each direction and without passing lanes at the terminals/stations. This can happen in corridors with several BRT routes/lines operating relatively frequent services. The trunk part of the feeder-trunk network can particularly suffer from this kind of induced congestion causing delays of the affected services. The last implies the contribution of the BRT system to savings of own congestion and that of the other traffic, which both contribute to savings in the overall user/passenger travel time. For example, the savings in travel time compared to previously used transit services vary from 5 to 35 % at 16 U.S. BRT systems (GAO 2012). In addition, as compared to individual traffic, savings of 32 % at TransMilenio (Bogotá, Colombia), 35 % at Metrobús (Mexico City, Mexico), and 45 % at Metrobüs (Istanbul, Turkey) have been reported.

Safety

Traffic incidents/accidents reflect the safety and security of a given BRT system. They are caused by collisions of BRT vehicles/buses with other BRT vehicles/buses and with other vehicles, bikers, and pedestrians, all often resulting in injuries and death, as well as damages to property. The number of events per unit of the system's output—the number of passengers and/or passenger-kilometer is a convenient measure. So far, accidents in BRT systems have been relatively rare, thus indicating that the systems safe, and by all means safer than their conventional bus counterparts as shown in Fig. 2.11.

As can be seen, the rate of collisions and injuries of the conventional bus system operated in Bogota (Columbia) before the BRT system established was about 7.7/million passenger trips. Over the 2000–2005 period, thanks to the BRT TransMilenio, despite increasing the number of trips, this rate dropped to about 1–2/million passenger trips. In comparison, during the same period for the slightly higher number of passenger trips on U.S. LRT systems, this rate was about 1.5–3.0/million passenger trips (RITA 2012; <http://brt.mercedes-benz.com/content/brt/mpc/Safety.html>). That said, both BRT and LRT systems should always be designed and operated to be safe implying that incidents/accidents due to the already known reasons must not occur.

Social welfare

Social welfare of BRT systems relates to their urban and social effects.

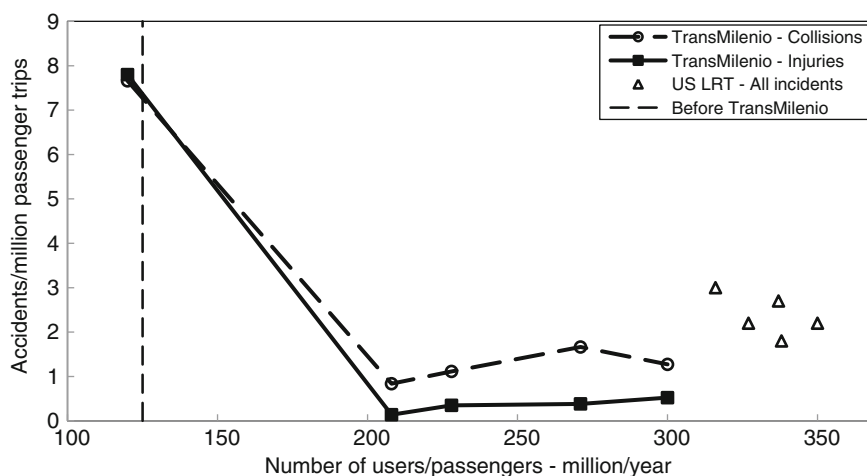


Fig. 2.11 Relationship between the accident rate and the annual volume of traffic at the selected BRT systems (RITA 2012; Saavedra 2011; <http://brt.mercedes-benz.com/content/brt/mpc/Safety.html>)

Urban effects

The urban effects of BRT systems include changing of the land use and the value of land and property, redistributive effects, and preceding other more efficient and effective systems.

- *Changing the land use* implies (i) taking the land for building the BRT infrastructure; and (ii) building economic and residential objects rather than parking spaces along the BRT corridors/routes and particularly around the terminals/stations.
- *Changing the value of land and property* generally implies rising their value faster due to being located closer to BRT system terminals/stations and corridors/routes. This is because the proximity of the BRT system can save time and monetary cost of commuting, thus making the properties nearby generally commercially more attractive for new developments or redevelopments than otherwise. However, in some cases, the value of land and properties can diminish due to increased noise and emissions of GHG caused by the BRT system (Levinson et al. 2003a).
- *Redistributive effects* imply the contribution of BRT systems to the potential relocation of particular businesses/firms from the suburban areas closer to the city center, and vice versa, i.e., urbanization and de-urbanization of employment.
- *Preceding other more efficient and effective systems* implies that BRT corridors are sometimes used to test the overall feasibility of LRT systems (GAO 2012).

Social effects

The main social effects of BRT systems are their contribution to direct and indirect employment, social equity, and personal meetings and interactions.

- *Direct employment* is needed for planning, designing and constructing the BRT system, and later on for its operating.
- *Indirect employment* includes institutional and supportive employment (in entertainment, other amenities-hotels, hospitals, etc.) generated purely because of the implementation of the BRT system(s).
- *Social equity* reflects the ability of the BRT system to, like other urban transport systems, facilitate accessibility and promote social equity within a city. For example, cheap BRT systems give lower income groups greater access to public services and economic opportunities (Wright and Hook 2007).
- *Personal meetings and interactions* imply that effective, efficient, safe, and cheap BRT systems can bring different groups of people in terms of age, gender, and income group to places where they can meet and interact with each other in different ways. Such interactions can diminish tensions and improve the mutual understanding between such groups.

2.2.3 Evaluation

BRT systems possess both advantages (Strengths and Opportunities) and disadvantages (Weaknesses and Threats) as compared to other potentially substitutable urban (mass) transit systems, such as conventional bus transit and LRT systems.

Comparison with conventional urban bus transit systems

Advantages

Users/passengers

- Relatively strong spatial coverage of a given urban area with corridors, routes, and lines guaranteeing relatively high quality of the spatial accessibility of the system's services;
- Relatively high service frequency, particularly during peak periods contributing to reducing schedule delay(s) and consequently the urge to shift to other systems/modes;
- Relatively fast and reliable services thanks to running along dedicated busways not affected by other traffic at higher operating speeds with minimal dwell times at the terminals/stations and stops along the routes/lines;
- Less delays due to general congestion, traffic signals, right turns, and passenger stops; and
- Higher riding comfort thanks to operating rubber-tired, low floor vehicle/buses of a suitable capacity, a sufficient number of wide doorways offering easy boarding and internal comfort, and the information system inside the vehicles/buses and at the terminals/stations/stops.

Transport operators, policy makers, and community members

- Increasing efficiency and effectiveness of operating the available vehicle/bus fleet thanks to deploying ITS;
- Offering more competitive services contributing to diminishing use of individual cars and consequently the negative impacts on the environment and society such as energy/fuel consumption and related emissions of GHG, noise, and congestion throughout the network—along the routes/lines and at parking lots;
- Affecting stronger urbanization and suburbanization along particular corridors/routes including development of new commercial and social activities;
- Contributing to increasing numbers of users/passengers switching to public urban transport systems; and
- Contributing to integrating transit and land use planning.

Disadvantages*Users/passengers*

- Some confusion due to clustering too many lines/services at the same stops/stations, particularly at feeder-trunk service systems/networks; and
- Diminishing quality of service if operating along mixed traffic lanes.

Transport operators, policy makers, and community members

- Relatively substantial investments in infrastructure, vehicles/buses, and supporting facilities and equipment (for example, building tunnels or acquiring CNG (Compressed Natural Gas) or hybrid buses) including the time of commercialization;
- Affecting the space for other traffic and the urban content of the given area/city by building the BRT infrastructure, the former can temporarily contribute to increasing congestion, while the latter can deteriorate urban green areas;
- Increasing energy/fuel consumption and related emissions of GHG and noise due to more voluminous operations despite using more technologically advanced vehicles/buses (hybrid, CNG, etc.); and
- Needing subsidies for services in many cases.

Comparison with LRT (Light Rail Transit) systems**Advantages**

- Flexibility and convenience of implementation in a wide range of urban and suburban areas;
- Gradual implementation and extension of the route network;
- Higher frequency and flexibility of services in terms of adjusting to variable daily demand and re-routing due to any reason, respectively;
- Comparable and flexible transport capacity; and
- Lower investment and comparable operational costs.

Disadvantages

- Generally requiring more space for setting up the infrastructure;
- Lower riding comfort due to the less sizeable and comfortable seats onboard (for passengers);
- Higher energy consumption and related emissions of GHG independently of the technology used and not absolutely free from traffic congestion;
- Rather negative image due to the general perception of LRT usually being slow, noisy, and polluting;
- Lower effects in creating greater land and property value along the corridors/routes; and
- Lower preferences by developers to locate social-economic activities along the inherently unstable bus routes/stations rather than along more permanent LRT routes/stations.

Finally, what can be said for BRT transport systems? They are advanced public transit systems primarily characterized by the advanced organization of transport services carried out by matured but gradually improving vehicle/bus technology.

2.3 High Speed Tilting Passenger Trains

1973	The 381 series tilting trains operated by JNR (Japan National Railways) begin commercial services on the Chuo Main Line connecting Nagoya and Nagano (Japan)
1976	Fiat's ETR401 tilting trains operated by the Italian State Railways begin commercial services on the Rome-Ancona line (later extended to Rimini) (Italy)
1978	The Spanish tilting trains Talgo operated by RENFE (The Spanish National Railway) begin commercial operations (Spain)

2.3.1 Definition, Development, and Use

High-speed tilting passenger trains operate at speed of about 200 km/h on upgraded and around 250 km/h or faster on newly built tracks defined by the EU (European Union) thanks to their fully operational tilting mechanisms. This mechanism can be disabled after moving onto high-speed tracks and reaching the speed of 250 km/h. Such an advantage makes these trains highly interoperable in rail networks consisting of conventional, upgraded, and completely new (high speed) lines (http://en.wikipedia.org/wiki/Tilting_train). Some tilting trains operating on upgraded tracks at speeds of about 200 km/h include: Virgin Trains' Class 390 Pendolino operating along the West Coast Main Line in the United Kingdom (UK), the Talgo 350 train operating on the Spanish AVE high-speed lines, the Italian Pendolino 2 tilting train ETR600, the Swedish X2 tilting train, and the E5 Series Shinkansen

train operating in Japan. One high-speed tilting train operating on new tracks at speeds of 250 km/h or higher is the most advanced Japanese tilting train—the N700 Series Shinkansen. This train tilts up to one degree and maintains a speed of about 270 km/h as compared to its previous speed of 255 km/h while passing through curves of a radius of 2,500 m on the Tōkaidō Shinkansen line.

2.3.2 Analyzing and Modeling Performances

2.3.2.1 Background

High-speed tilting passenger trains are characterized by their infrastructural, technical/technological, operational, economic, environmental, social, and policy performances, which all influence each other. In general, these trains are designed to primarily operate along conventional tracks at higher speeds than those of conventional passenger trains. In such cases, the tracks do not require any particular modifications. Operation at the higher speeds as the main distinguishing feature of these trains compared to their conventional counterparts is possible under given conditions thanks to the tilting capabilities.

2.3.2.2 Infrastructural Performances

The infrastructural performances of high speed tilting trains relate to the characteristics of the track design and the related standards that these trains can use.

Track design

In order to fully exploit the technical and operating speeds of high-speed tilting passenger trains, conventional tracks need to be upgraded and/or completely rebuilt anyway. The former implies partial reconstruction/redesign of the existing lines by leveling off high grades (horizontal and longitudinal slopes), increasing the radii of curved segments, and partially reconstructing tunnels, bridges, crossings, and platforms at particular stations. The latter implies building completely new lines. Both should be carried out according to the specified standards for designing rail tracks.

The main elements of rail track design relevant to understanding the operation of high-speed tilting passenger trains are as follows (Persson 2007):

- *The track gauge* as the distance between the inner faces of the rail heads of the track is measured 14 mm below the top of the rail on the inner face. The standard track gauge is approximately 1,435 mm. The track gauge has an impact on the lateral behavior of the vehicle which may lead to unstable running. In addition, it impacts the lateral behavior of the vehicle, which in turn impacts lateral ride comfort.

- *The circular horizontal curve* is a curve in the horizontal plane with a constant radius. This curve is characterized by its radius R related to the track center line and/or curvature as an inverse to the radius. The reduced radius of the circular horizontal curve increases the lateral track forces, which increases the derailment ratio. In addition, it has no impact on ride comfort.
- *The transition curve* is used to connect the straight track to the circular horizontal curve or to connect two circular horizontal curves. The transition curve is characterized by its curvature as a function of its longitudinal position. The most common transition curves have linear variation of the curvature and do not affect safety. The reduced length of the transition curve increases the rate of change of the cant deficiency and thereby also the lateral jerk perceived by passengers. It also increases the roll velocity of tilting trains, which is believed to contribute to motion sickness.
- *The track cant (or super elevation)* is the amount at which one running rail is raised above the other running rail (in the curve). The track cant is positive when the outer rail is raised above the inner rail. The UIC has proved that a cant of 180 mm is widely acceptable and safe. The track cant does not influence ride comfort.
- *The cant transitions (or super elevation ramps)* connect two different track cants. In most cases, the cant transition has the same longitudinal position as the transition curve. The cant gradient is characterized by its longitudinal distance to raise one unit (normally expressed as 1 in X, where X is the longitudinal distance in units). The ERRI (European Rail Research Institute) has showed that a cant gradient of 1/400 m/m is acceptable. The most common cant transition has a constant rate of cant change. Steep cant transitions may cause diagonal wheel unloading, which in turn may lead to derailment due to flange climbing. In addition, cant transitions do not impact ride comfort.
- *The rate of cant change* is the rate at which the cant is increased or decreased at a defined speed. The rate of cant change is characterized by the cant change per time unit. This does not impact safety.
- *Cant deficiency* arises when the installed cant is lower than the cant of equilibrium. Cant deficiency is characterized by additional cant needed to ensure equilibrium. High cant deficiency may lead to high lateral track forces. High cant deficiency also increases the risk of over-turning.
- *The rate of change of cant deficiency* is the rate at which the cant deficiency increases or decreases at a defined speed. This rate is characterized by the cant deficiency change per unit of time. The most common transition curve/cant transition has a constant rate of change of the cant deficiency, which does not affect safety. However, an increased rate of change of the cant deficiency increases the lateral jerk perceived by passengers. It also increases the roll velocity of the tilting vehicles, which is found to contribute to motion sickness while onboard the tilting vehicles.
- *The track gradient* connects tracks at different altitudes. The gradient, which affects both safety and ride comfort, is characterized as a change in altitude per unit of distance (%). In certain countries, it is represented as the longitudinal

Table 2.10 Infrastructural performances for the high-speed tilting trains in Europe—infrastructure standards (CEN 2006)

Element	Value
Cant (mm)	180
Rate of cant change (mm/s)	75
Cant deficiency (mm)	306
Rate of change of cant deficiency (mm/s)	150

distance to raise for one unit (it is expressed as 1 in X , where X is the longitudinal distance in units).

- *The vertical curve* not affecting safety and the ride comfort connects two different track gradients and is characterized by its radii.

Design standards (Europe)

The CEN (Comité Européen de Normalisation) provides guidance and standards for particular elements of geometric design of conventional rail vehicles (CEN 2002). This guidance and standards are revised latter on in order to be also convenient for high speed tilting train vehicles (CEN 2006). For high-speed tilting trains, some standards are given in Table 2.10.

In addition, CEN standards categorize the rail tracks, i.e., the rail traffic lines, based on the categories of services they accommodate, as follows:

- Mixed traffic lines for passenger trains traveling at speeds from 80 to 120 km/h;
- Mixed traffic lines for passenger trains traveling at speeds greater than 120 km/h and up to 200 km/h;
- Mixed traffic lines for passenger trains traveling at speeds higher than 200 km/h;
- Mixed traffic lines for passenger trains incorporating special technical design characteristics; and
- Dedicated passenger lines for passenger trains traveling at speeds greater than 250 km/h.

High-speed tilting passenger trains operate on lines (b), (c), and (d).

2.3.2.3 Technical/Technological Performances

The technical/technological performances of high-speed tilting passenger trains relate to tilting principles and tilting technology/mechanism, the vehicle/train technical specifications, signaling system, and energy consumption.

Tilting principle

When trains pass the horizontal curves along the line(s), both the vehicles themselves and passengers onboard are exposed to centrifugal force. This can be reduced by roll inwards, thus enabling trains to pass through curves at higher speeds while still maintaining passenger ride comfort. In general, this inward roll may be achieved by the track cant and/or by tilting the train. Trains composed of coaches with tilting capabilities are called tilting trains, which can generally be

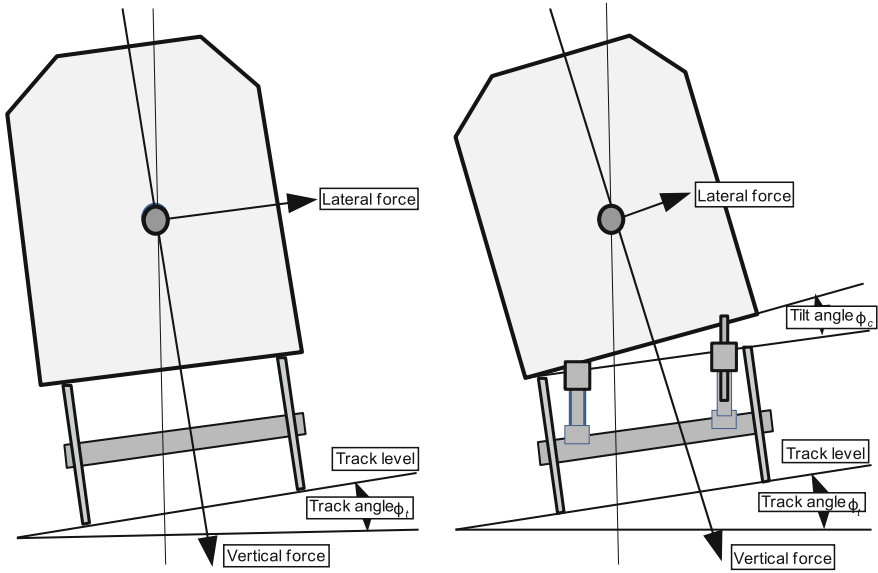


Fig. 2.12 Scheme of tilting principle of high-speed tilting passenger train(s) (Persson 2007)

categorized into two categories: (i) passively natural tilted trains (for example in Japan), and (ii) actively tilted trains (in the rest of the world including Europe). Passive tilt trains rely on the natural laws with a tilt center located above the center of gravity of the coach. Along a curve, under the influence of centrifugal force, the lower part of the coach swings outwards. Conversely, active tilt trains are based on active technology controlled by a controller and executed by an actuator. The main principle of tilting trains is rolling the coaches inwards the curve as schematically shown in Fig. 2.12 in order to reduce the lateral force affecting passengers.

Despite the higher track plane acceleration for the tilting train (right), the lateral force in the car-body is lower. When a coach/train is running along a horizontal curve, horizontal acceleration emerges. It can be expressed as follows:

$$a_h = v^2/R \quad (2.11a)$$

where

v is the operating speed (m/s); and

R is radius of the curve (m).

The acceleration in the track plane can be reduced compared to horizontal acceleration by arranging the track cant D . The angle between the horizontal plane and the track plane is a function of the track cant and the distance $2b_0$ between the two contact points of the wheel-set, as follows:

$$\phi_t = \arctan(D/2b_0) \quad (2.11b)$$

The acceleration experienced by passengers can further be reduced compared with the track plane acceleration by arranging the tilting angle of a coach ϕ_c . Acceleration in the coach is called lateral acceleration a_c , which can be determined as follows:

$$a_c = (v^2/R) \sin(\phi_t + \phi_c) - g \sin(\phi_t + \phi_c) \quad (2.11c)$$

Acceleration in the perpendicular direction is called vertical acceleration a_v , which can be determined as follows:

$$a_v = (v^2/R) \sin(\phi_t + \phi_c) - g \cos(\phi_t + \phi_c) \quad (2.11d)$$

Reducing the lateral acceleration by increasing the track cant or tilt of a coach correlates with a slightly increased vertical acceleration. Some typical values for the lateral and vertical acceleration are $a_c = 0.98 \text{ m/s}^2$ and $a_v = 0.44 \text{ m/s}^2$ for a train operating at speeds of about: $v = 200 \text{ km/h}$, along a track curve with a radius: $R = 1,000 \text{ m}$, track cant: $D = 150 \text{ mm}$, and tilting angle: $\phi_c = 6.5^\circ$.

Tilting technology/mechanism

As mentioned above, the tilting technologies/mechanisms are based on two principles. The first is passive or natural tilting (in Japan), while the other is active tilting (the rest of the world and Europe). Passive tilting uses natural laws with a tilt center located well above the center of gravity of the car-body. On a curve, under the influence of centrifugal force, the lower part of the car-body swings outwards. Active tilting uses tilting mechanisms based on pneumatic systems, where air is shifted from one side to the other of the air suspension. In addition, rollers and pendulums as technological innovations carry the car-body load and provide movement. Then, movement may be controlled by an actuator, which does not need to carry the car-body load, thus resulting in much lower energy consumption.

Actively tilted trains need some kind of control system. Contemporary systems include body feedback with an accelerometer placed in the car-body as a transducer. This can use different information sources. The obvious one is lateral acceleration, but also the roll and yaw velocity can be used. Most tilting trains use more than one source as the basis for their control. Consequently, they can be differentiated in light of the type of tilting mechanism/technology they use as follows: (i) trains tilting by inertial forces; (ii) trains with active tilting based on sensory information provided by an accelerometer; (iii) trains with tilting controlled by a computer; and (iv) the trains with tilting provided by active suspension (http://en.wikipedia.org/wiki/Tilting_train).

Tilting by inertial forces

Some trains tilting by inertial forces include: Talgo (Spain), UAC TurboTrain (US, Canada), and JNR 381 series (Japan). Talgo trains can achieve maximum speeds of 175–200 km/h, a tilting angle of 3–3.5°, and DC traction, while Japanese trains operate at maximum speeds of 120–160 km/h, a tilting angle of 5°, and AC and DC traction systems (DC—Direct Current; AC—Alternating Current).

Tilting actively by sensory information obtained from accelerometers

Some such trains include Light-Rapid Comfortable (LRC) trains built by Bombardier (Canada, US). Depending on the version, these trains operate at maximum speeds of 155–240 km/h, a tilting angle of 6–10°, and AC and DC traction.

Tilting actively controlled by a computer

Currently, this is the most numerous category of high speed tilting trains. Some of them are Acela Express (US), a Bombardier high-speed tilting train operating between Boston and Washington D.C.; British Rail Class 390 “Pendolino” (UK), a high-speed train run by Virgin Trains from London Euston to Liverpool/Manchester/Glasgow/Birmingham and Wolverhampton; Alfa Pendular (Portugal), ElettroTreno (Italy), ICE-T, also called ICT Technologies (Germany), a tilting version of the German high-speed ICE; ICN (Switzerland), a new generation of tilting trains operated by Swiss Rail, a Bombardier-built high-speed tilting train operating between Zurich and Geneva; JetTrain (North America), Bombardier’s experimental non-electric high-speed train; NSB Class 73 (Norway); SŽ series 310 (InterCitySlovenija), a high-speed tilting train operating among Ljubljana, Maribor, and Koper; RegioSwinger (Germany and Croatia), a diesel regional tilting train; Pendolino (Italy, Finland, the UK, and the Czech Republic), built by Alstom (formerly Fiat); Virgin Train Super Voyager, a Bombardier-built high-speed tilting train operating between London and Holyhead/Wrexham/Chester and Birmingham to Edinburgh or Glasgow; Taroko Express (Taiwan), based on the JR Kyūshū 885 Series; Tilt Train by QR, diesel and electric tilting Traveltrains (Australia) operating between Brisbane and Cairns (the Electric Tilt Train is based on the JR Shikoku 8000 series, X2 (Sweden), with tilting mechanism made by ABB; it is also used in China under the name Xinshísù); the JR Shikoku 2000 series (Japan 1989), the first tilting DMU in the world used on many limited express services in Shikoku, including Ashizuri, Ishizuchi, Nanpū, Shimanto, Shiokaze, Uwaka, and Uzushio (the upgraded N2000 Series was introduced from 1995), the JR Hokkaido KiHa 281 series (Japan 1992), branded Heat 281 or Furico 281, and used for Super Hokuto limited express service; the JR Shikoku 8000 series (Japan 1992) is used for the limited express service on the Yosano Line, namely Ishizuchi and Shiokaze; the JE Fast E351 series (Japan 1993) is used for Super Azusa; the Chizu Express HOT7000 series (Japan 1994) is used for Super Hakuto; JR Central 383 series (Japan 1994) is used for Wide View Shinano; JR Kyushu 883 series (Japan 1994) is used for Sonic; the JR Hokkaido KiHa 283 series (Japan 1995), branded as Furico 283 is used for the Super Hokuto, Super Ōzora, and Super Tokachi limited express services. The JR West 283 series (Japan 1996) is used for Ocean Arrow; the JR Kyushu 885 series (Japan 1999) is used for Kamome and Sonic; the JR West KiHa 187 series (Japan 2001) is used for Super Inaba, Super Kunibiki, and Super Oki (these trains operate at maximum speeds of 170–250 km/h, a tilting angle of 8–10°, and AC and DC traction systems).

Tilting by active suspension

Some of these trains are: the JR Hokkaido KiHa 201 series (Japan 1996) used for rapid trains around Sapporo; the JR Hokkaido KiHa 261 series (Japan 1999), branded Tilt 261, used for Super Sōya; the Meitetsu 1600 series (Japan 1999), branded Panorama Super, mainly used for the Meitetsu Nishio Line; the Meitetsu 2000 series (Japan 2004), branded μ -Sky, used to connect Nagoya and Chūbu Centrair International Airport; the Odakyu 50000 series VSE (Japan 2005) used for Romancecar; the N700 Series Shinkansen (except N700-7000/8000 series) (Japan 2007) introduced by JR Central and JR West, used for the Tōkaidō and Sanyō Shinkansen lines; the E5 Series Shinkansen (Japan 2011) introduced by JR East, used for Tōhoku Shinkansen lines. These trains operate at maximum speeds of 120–160 km/h and a tilting angle of 5°.

Vehicles/trains

Most of high-speed tilting trains use electric energy from different voltage and current systems; such flexibility represents an important component of their interoperability. For example, in Europe, depending on the country, these are 1.5 kV and 3 kV DC, 15 kV/16.7 Hz AC and 25 kV 50 Hz AC systems. In the U.S., newly built rail lines are equipped with the 25 kV 60 Hz system. In Europe, one of the largest fleets (52 train sets) of high speed tilting trains is operated by Virgin Trains along the West Coast Main Line in the UK. The technical specifications of these trains are summarized in Table 2.11.

Signaling system

High-speed tilting passenger trains operate using the cab signaling system, which communicates the track status information to the driver's cab. In general, the system transmits information through the rails as electrical signals, which are picked up by antennas placed under the train, then processed by computers and displayed in the cab. The cab signaling system enables controlling the speed of these trains while passing through the curves along a given line in order to maintain it below or at most at the level of PS (Permissible Speed) or EPS (Enhanced Permissible Speed). The latter is slightly under the speed at which these trains can overturn. In general, the speed limits can be different for different types of tilting trains passing through the same curve but usually only one is displayed in order not to confuse the driver. In order to additionally prevent the confusion of driver, the signs for tilting train speeds must be distinctive from those of conventional trains. In addition, the total number of different speeds indicated at any given location along the line(s) must not be greater than three—one for EPS and two for conventional passenger and freight trains. Furthermore, changes in EPS on a route must be signed implying application of the continuous route signing, the positions of signs for any change in PS and EPS must be coincident, and signs for EPS must not be positioned in isolation (i.e., where provided, they must always

Table 2.11 Technical/technological performances of a selected high-speed tilting train—technical specifications (Persson 2007)

Specification	Systems
Type	Pendolino, British Class 390
Owner	Angel Trains (subsidiary of Babcock and Brown)
Operator/Franchise (until 2011)	Virgin Trains
Operations area	West coast route in UK
Number of units and configuration	Fifty two 9-car sets (468 cars) (one was lost in the accident in Grayrigg in 2007);
Delivered to use (year)	Four new 11-car train sets added over the period 2010—2012; 31 older sets received with 2 new cars, with an option for the 21 remaining units.
Configuration	Driving trailer + 7 trailers + driving trailer 1A'A1' + 1A'A1' + 2'2' + 1A'A1' + 2'2' + 1A'A1 + 2'2' + 1A'A1 + 1A'A1; After upgrade: driving trailer + 9 trailers + driving trailer
Length of the train (m)	217.4 (9-car set); 265 (11-car set)
Maximum weight (tons)	439
Capacity (seats/passengers)	439 (145 first class; 294 standard class)
Power (MW/hp)	5.1/6840(12 × 425 kW) (in Pendolino the power is distributed throughout the train set; regenerative braking system);
Single current versions	25 kV 50 Hz overhead
Maximum technical speed (km/h)	230

have an accompanying sign for conventional trains). High-speed tilting passenger trains are permitted to operate at EPS through curves only if the speed limit information and speed supervision and control are provided by the above-mentioned cab signaling and automatic train protection system. The cab signaling system continuously displays information on the speed limit, which is consistent with EPS (where applicable), and the speed restrictions on the given line(s).

In addition to the signals along the track, the cab signaling system enables the allowable speed and information about the tracks ahead to be displayed. Furthermore, the automatic train protection system added on the top of the cab signaling system warns the driver of dangerous conditions ahead including the automatic activation of brakes able to decelerate and/or bring the train to a stop, but exclusively in cases when the driver misjudges a dangerous condition.

2.3.2.4 Operational Performances

The operational performances of high-speed tilting passenger trains include interoperability, speed, turnaround time, required fleet, technical productivity, and influence on the rail line capacity.

Interoperability

As mentioned above, the AEIF (European Association for Railway Interoperability) also provides the TSI (Technical Specifications of Interoperability) for Trans-European High-Speed Rail Infrastructure including guidance on the cant and the cant deficiency for non-tilting vehicles (AEIF 2002). However, analogous specifications and guidance for high-speed tilting passenger trains/vehicles have been left to the owners/operators/managers of the corresponding infrastructure. Under such circumstances, interoperability of high-speed tilting passenger trains can be defined as their flexibility to:

- Operate along the above-mentioned (b), (c), and (d) category of railway lines at operating speeds that are usually higher than the speeds of their conventional counterparts; and
- Use different power (electricity) supply systems (1.5, 3, and/or 25 kV; kV—kilovolt).

Both criteria have already been achieved thanks to tilting mechanism/technologies, multi-system locomotives (power units of the train sets), and particularly in Europe, thanks to the forthcoming advanced train signaling and control system developed as components of the ERTMS (European Rail Traffic Management System) (EC 2010).

Speed

As applies to the other categories, the technical speed, operational speed, and commercial speed of high-speed tilting trains can be distinguished.

Technical speed is defined as the maximum speed that a given high train can achieve under given conditions (category of rail line and power supply system). Usually, this speed is specified through the train design.

Operational speed is the maximum speed at which a given train commonly operates on the given rail line. This speed is lower than or at most equal to the technical speed.

Commercial speed is the travel speed of a given train along the given rail line including acceleration, deceleration, intermediate stops, and other maneuvers influencing the operating speed. This speed is lower than the operating speed. In addition to the length of the line, it crucially influences the turnaround time of the given train set(s).

Turnaround time

The turnaround time of a given train scheduled to operate along a given rail line is defined as the total time the train spends between its stations, i.e., from the origin to the destination station, and back. This time also includes the train's stop time at intermediate stations, which mainly depends on the pattern and volume of passenger demand to be served in both directions. In addition, the turnaround time includes the train's acceleration and deceleration time to/from the operating/cruising speed. Thus, the train line can be considered as a route consisting of

several segments. If the stops are the same in both directions, the turnaround time of a given train can be estimated as follows:

$$t_{tr} = t_0 + 2 \left[\sum_{i=1}^N t_i + \sum_{k=1}^K t_k \right] + t_d \quad (2.12a)$$

where

t_o, t_d is the train's stop time at the origin and destination station (terminus), respectively (min);

t_i is the train's running time along the (i)-th segment of the given route (min);

t_k is the train's stopping time at the (k)-th intermediate station along the given route (min);

N is the number of segments of the given route; and

K is the number of stations along the given route where the train stops ($K = N - 1$).

The train's running time along the (i)-th segment of the route in Eq. 2.15a can be estimated as follows:

$$t_i = v_i/a_i + s_i/v_i \quad (2.12b)$$

where

v_i is the train's operating/cruising speed along the (i)-th segment of the route (km/h);

a_i is the train's acceleration/deceleration rate at the beginning and the end of the (i)-th segment of the route (m/s^2); and

s_i is the length of the (i)-th segment of the route (km).

In addition, the length of the route in one direction can be estimated as follows:

$$d = \sum_{i=1}^N s_i \quad (2.12c)$$

Furthermore, the commercial speed of the train along a given route based on Eq. 2.15c can be estimated as follows:

$$v_c(d) = d/t_{tr} \quad (2.12d)$$

where all symbols are as in the previous equations.

Fleet size

The fleet size of the high-speed tilting trains scheduled to operate on the route of length d during the time period T can be determined, based on Eq. 2.12a, as follows:

$$N[d, f(T, d)] = f(T, d) * t_{tr} \quad (2.13a)$$

where

$f(T, d)$ is the frequency of train services along the route d during time T .

The frequency $f(T, d)$ in Eq. 2.13a can be determined as follows:

$$f(T, d) = Q(T, d) / [\lambda(T, D) * N(d)] \quad (2.13b)$$

where

$Q(T, d)$ is the passenger demand on the route of length d during the time interval T (passengers);

$\lambda(T, d)$ is the average load factor of a given train service scheduled along the route of length d during time T ; and

$N(d)$ is the seating capacity of a given train operating along the route d (seats).

The other symbols are analogous to those in the previous equations.

Technical productivity

The technical productivity of a high speed tilting train can be determined as the product of its seating capacity and its technical, operational, and/or commercial speed. In particular, the latter depends on the route length d . Thus it follows:

$$TP[v(d), N(d)] = v(d) * C(d) \quad (2.14a)$$

In addition, the technical productivity of a given route operated by high-speed tilting trains can be estimated as the product of the total number of seats supplied during a given period of time and the average speed of train services as follows:

$$TP[f(T, d), v(d), N(d)] = f(T, d) * v(d) * C(d) \quad (2.14b)$$

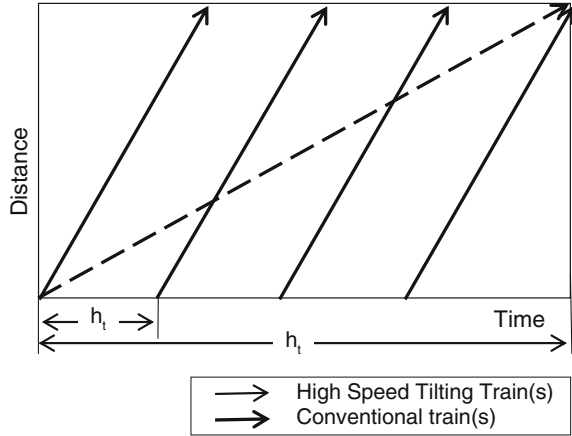
Obviously, the service frequency $f(T)$ in Eq. 2.14b is an integer as a reciprocal of the time interval(s) between scheduling the train services. Depending on the pattern of passenger demand, these intervals can typically be 1 h ($h(d) = 1$ h), half an hour ($h(d) = 1/2$ h), etc. during the day. Consequently, the technical productivity of the train services along a given line of length d can be expressed as the volume of passenger-km produced during the period T under given conditions.

Effects on the rail line capacity

High speed tilting trains can contribute to increasing the utilization of the available capacity of a given train line. This happens when they replace their conventional counterparts. Let's assume that high-speed tilting and conventional trains are scheduled exclusively along the given line of length d at constant intervals h_t and h_c , respectively, during the time T . In such case, the following conditions need to be satisfied:

$$(n_t - 1)h_t + t_{tr/t} = T \quad (2.15a)$$

Fig. 2.13 Time-space diagram of possible replacing conventional with high-speed tilting trains on a given (rail) line



$$(n_c - 1)h_c + t_{tr/c} = T \quad (2.15b)$$

where

n_t, n_c is the number of high-speed tilting and conventional trains, respectively, scheduled on the line during the time period T .

The other symbols are as in the previous equations. From Eqs. 2.15a, b, the number of additional high-speed tilting trains as compared to the number of conventional trains that can be scheduled on the line d under given conditions can be estimated as follows:

$$n_t = (n_c - 1) * (h_t/h_c) + (t_{tr/c} - t_{tr/t}) + 1 \quad (2.15c)$$

where all symbols are as in the previous equations. A simplified scheme of the time-distance diagram is shown in Fig. 2.13.

Let the length of the line be $d = 500$ km. Both categories of trains are exclusively scheduled along the line with nine intermediate stops, each taking about 2 min. The stop time at the origin and destination station takes about 20 min. The average operating speed of a high-speed tilting train is about 190 km/h and that of a conventional train about 100 km/h. From Eq. 2.15a, the turnaround time of both categories of trains is estimated to be $t_{tr/t} = 5.3$ h and $t_{tr/c} = 10$ h. Both categories of trains are scheduled along the line in constant intervals of $h_t = h_c = 1$ h. From Eqs. 2.15a, b, the number of high-speed tilting trains that can be scheduled along the line is determined as: $n_t = n_c + 5$. In addition, inclusion of the seat capacity of both categories of trains can indicate the real extent of the contribution of high-speed tilting trains to increasing utilization of the capacity of a given rail line. However, we should always be aware that scheduling of any of these trains is based on the characteristics of demand along a given line, i.e., its volume(s) and time pattern(s).

2.3.2.5 Economic Performances

The economic performances of high-speed tilting passenger trains mainly imply their operational costs. In general, after the infrastructure has been upgraded according to the above-mentioned standards, these costs consist of two components: infrastructure operational costs related to its exploitation and maintenance, and train operational costs, i.e., the costs of provision of transport services using the infrastructure. In many, particularly European countries, the operation and maintenance of rail infrastructure are managed by agencies/companies independent of those providing services. Consequently, many rail service providers/operators can access and use the same infrastructure, thus competing with each other. Under such circumstances, they are charged for using the infrastructure at rates that at least enable the given infrastructure managing company to cover the maintenance costs.

Infrastructure maintenance and operating costs

Infrastructure maintenance and operating costs generally include the costs of the labor, energy and other material consumed for day-to-day maintenance and operations of the rail lines/tracks, terminals, stations, energy supplying and signaling systems, as well as the traffic management and safety systems. These costs consist of fixed and variable parts. The former depends on the volumes of operations routinely performed in accordance to technical and safety standards, while the latter depends on the intensity of traffic on the given line generating the need for different kinds of interventions. Some figures provided by UIC indicate that the labor shares the largest part of the total infrastructure maintenance costs as follows: 55 % for maintenance of electric traction installations, 45 % for maintenance of tracks, and 50 % for maintenance of equipment. For example, the average cost of maintaining new and upgraded high speed rail lines in Europe ranges from 28 to 33 thousand euros (2000) per kilometer of a single track (De Rus 2009).

Train operating costs

The operating costs of high-speed tilting passenger trains can be divided into four main categories: (i) shunting and train operations (mainly, labor costs); (ii) maintenance of the trains/rolling stock and other equipment; (iii) energy; and (iv) sales and administration. The latter vary across different rail operators depending on the expected level of traffic, since they mainly include labor costs related to ticket sales and providing information at the stations/stops. The other three components vary widely depending on the technology/type of the high-speed tilting train, and the local operating and economic conditions. For example, the average operating costs of the ETR480 high-speed tilting train operating in Italy since 1997 is about: $c = 0.1756$ €/seat-km (This does not include the costs of acquiring the train and the costs of energy consumption). The former cost appears to be rather negligible after it is spread over the annual volume of kilometers travelled (about 150–200 thousands/train) and the train's amortization period of about 30–40 years. The latter cost mainly depends on the above-mentioned factors

influencing the energy consumption and the prices of electricity. The latter are often conditioned by local agreements between the suppliers and consumers (rail operator) (the ETR480 train set has a length of 296.6 m, weight of 400 tons, power 6 MW (8,000 Hp), maximum technical speed of 250 km/h, and 480 seats). In addition, the average operating costs of the ICE-T high-speed tilting train that began services in Germany in 1999 amount to about: $c = 0.1346$ €/seat-km, again excluding the costs of acquiring the train set and the costs of energy consumption (De Rus 2009) (Depending on the configuration (5 or 7 cars), the train's length is 133–185 m, its weight 270–368 tons, its engine power 3–4 MW, and seat capacity of 250–357 seats (RTR 2005)).

2.3.2.6 Environmental Performances

The environmental performances of high-speed tilting passenger trains include energy consumption and related emissions of greenhouse gases, and land use/take.

Energy consumption

High-speed tilting passenger trains consume electricity, which, in general, can be generated by electricity power plants using different primary sources. The proportion of particular sources is always region- and country-specific. For example, at present, in the EU27 (European Union) countries, these proportions are as follows: coal/lignite 28.4 %, oil 4.2 %, gas 21.0 %, nuclear 30.2 %, renewable 14.0 %, and others 2.2 % (EEA 2007; Kemp 2007).

Different factors influence the energy consumption of high-speed tilting trains. The most important are design and size of the train influencing the air and rolling resistance, the operating speed, the number of stops, and regenerative braking.

Train/vehicle design

The energy consumption of a given high-speed tilting train is directly proportional to its size. This implies that in order to lower this consumption per train seat (and/or passenger), the size of the train needs to be reduced. However, instead, particular design parameters could be adjusted during designing a new train set. The options are as follows: car body width (e.g., 5 instead of 3–4 seats per row) and bi-level cars (up to 50 % more seats per meter of the train); the mass per unit of the train length has been reduced up to about 2 tons/meter, etc. For example, the average weight across almost all existing high speed tilting trains is just above 2 tons/m. The Class 390 Pendolino is about 6 % below this average and about 30 % above the best in the class—the Shinkansen 700 high-speed tilting train (Henri et al. 1991).

Air and rolling resistance

The air resistance of high-speed tilting trains can be estimated as follows:

$$F_D = (1/2) * \rho * v^2 * A * C_d \quad (2.16a)$$

where

ρ is air density (kg/m^3);
 V is operating speed (m/s);
 A is reference area (m^2); and
 C_d is drag coefficient.

This implies that a lower reference area at a given speed will enable lower energy consumption. However, the intention is to reduce this consumption per seat-km or passenger-km, which requires just the opposite, namely widening the train's reference area. The compromise is found in the above-mentioned design of high speed tilting trains in combination with reducing the drag coefficient from about 1.8–2.0 (ordinary trains) to 0.11 (Shinkansen 300).

Rolling resistance represents the resultant force that must be overcome by the tractive power of the locomotive to move a given train set at a constant speed along a level tangent track in still air. This force includes air resistance, train dynamic forces, bearing resistance, and rolling friction between the wheels and the track. Consequently, it appears obvious that, in order to overcome a larger resultant force, a larger quantity of energy needs to be consumed by high-speed tilting train(s).

Operating speed

The operating speed influences the energy consumption of a high speed tilting train through the energy required for acceleration and increased air resistance. In general, kinetic energy and aerodynamic resistance represent the largest part of a train's energy consumption. For example, for the selected single-deck European high-speed tilting trains, the specific energy consumption depending on the operating speed is estimated as follows:

$$E(v) = 0.00018v; (R^2 = 0.787; N = 11) \quad (2.16b)$$

where

$E(v)$ is the energy consumption (kWh/seat-km); and
 V is the train operating speed (km/h).

In general, a substantial amount of energy is consumed when trains decelerate before passing through the curve segments of the line(s). However, in addition to the tilting mechanisms, the above-mentioned track cants contribute to reducing the need for substantial deceleration in the curves. Thus, the energy consumption of high-speed tilting trains remains dependent mainly on (higher) operating speed(s).

The number of stops

Stops along the route prolong the journey duration of high-speed tilting trains. Additional energy is consumed during each stop due to the train's acceleration after the stop.

Regenerative braking

High speed tilting trains are equipped with technology to convert parts of the kinetic energy back into electric energy during the deceleration and braking phase of the trip. The portion of energy that can be regained mainly depends on the braking rate and the grid. The most recent capacitor technology (ultra-caps) enables storing this energy for subsequent use, providing faster acceleration after stopping. For example, some measurements of Pendolino 390 trains operating on the West Coast Main Line (UK) have indicated that the returned energy over the period of 24 h amounts to 16–18 % of the total energy taken from the grid. This total energy includes all the electricity drawn from the overhead grid including that during train preparation and stops at intermediate stations.

Examples

An example for the energy consumption of high speed tilting trains is the above-mentioned Pendolino 390 (Table 2.11). Measurements have shown that, under different operating conditions along the West Coast Main Line (the UK), the average energy consumption has been $E = 0.040$ kWh/seat-km for a 9-car train set and $E = 0.035$ kWh/seat-km for a 11-car train set, both operated at the maximum speed of $v = 220$ km/h (The average for Pendolino trains operating in Europe is $E = 0.033$ kWh/p-km). Another example is the Swedish X2000 high-speed tilting passenger train in a 5-car configuration with 270 seats and weighing 340 tons, which consumes $E = 0.042$ kWh/seat-km. Its 6-car version, with a capacity of 310 seats and weighing 366 tons, consumes on average $E = 0.0377$ kWh/seat-km. Both trains operate at the speed of 200 km/h (Persson 2007).

Emissions of GHG

Emissions of GHG (Greenhouse Gases) depend on the energy consumption and emissions from the primary sources used to produce the electricity in question. As already mentioned, the composition of these primary sources is region/country-specific. In general, the energy consumption $E(v)$ and emissions of GHG $E_e(v)$ of the high speed tilting trains are interrelated as follows:

$$E_e(v) = e_{em} * E(v) \quad (2.17)$$

where

e_{em} is the emission rate from producing the electricity in a given region (country) (kgCO_{2e}/kWh).

For example, if the emission rate of GHG is $e_{em} = 0.455$ kgCO_{2e}/kWh (UK), the emissions of GHG by a Pendolino 390 train operating at the speed of: $v = 200$ km/h, will be, based on Eqs. 2.16b and 2.17, equal to $E_{em}(v) = 0.455 \times 0.036 = 0.0164$ kgCO_{2e}/seat-km. By multiplying this amount with the number of seats per train and the running distance, the total emissions of GHG by a given train service can be obtained. Similar estimates of the energy

consumption and related emissions of GHG by high-speed tilting trains operating in the other regions (countries) can be made.

Land use

High-speed tilting passenger trains can be considered as “neutral” in terms of using additional land for building new and/or upgrading existing infrastructure. This is mainly due to them operating on upgraded existing/conventional lines. In some cases, the upgrading can require additional land, but usually on a negligible scale as compared to when completely new rail lines are built.

2.3.2.7 Social/Policy Performances

The social/policy performances of high-speed tilting passenger trains relate to their noise, congestion, and traffic incidents/accidents (safety).

Noise

Noise from high-speed tilting trains is an important and sensitive issue, as the rail lines often pass close to or even through densely populated areas, as well as through areas where the ambient noise used to be very low. Recently, this noise was considered as a parameter of the trains’ “interoperability” causing their speed to be limited in the TSI (Technical Specification for Interoperability) regulative document. The aim is to limit noise by all passing trains in Europe (EC 2002).

The main source of noise of high-speed tilting trains is rolling noise and aerodynamic noise. At a given speed, the former depends on the quality of wheels, and the number of axis. The latter is mainly dependent on the train’s aerodynamic characteristics. The train noise is usually expressed in dB(A), i.e., equivalent sound pressure *levels*— $LA_{eq,tp}$.

The lateral distance and height of the point of measurement and the source(s) of noise, i.e., passing train(s), is standardized to 25 and 3 m, respectively. Measurements throughout Europe indicate that the noise by passing conventional, high-speed tilting, and high-speed trains increases in line with their speed according to the “30 log (v)” regression rule, with dominating rolling noise, as follows (Poisson et al. 2008)

$$LA_{eq,tp}(v) = 30.465 \log(v/v_0) + 19.909; (R^2 = 0.935; N = 25) \quad (2.18a)$$

where

v is the train operating speed (km/h); and

v_0 is the reference train speed ($v_0 = 1$)

The index (tp) in Eq. 2.18a denotes a train passing by the noise measurement location. As mentioned above, the value of 30 is commonly used in the regression equation for predicting the rolling noise of conventional trains. This confirms the fact that the contribution of the rolling noise, which is the main noise source of

conventional trains, remains the same (dominating) source of noise of high-speed tilting trains, both comfortably complying with the TSI limits.

Some measurements have indicated that the ETR480 and ETR500 tilting trains generate noise of 90.5 and 88.0 dB(A) while passing at speeds of 250 km/h. This is well below the TSI limits of 92 and 94 dB(A) at speeds of 300 and 320 km/h, respectively (EC 2002; Poisson et al. 2008).

It should be mentioned that the noise from passing high-speed tilting trains experienced by the local population is always lower than that predicted by the above-mentioned regression equation. This is due to noise protecting barriers (walls) near noise sensitive areas as well as the distances of these areas from the rail line(s), which are usually greater than 25 m.

Congestion

High-speed tilting passenger trains do not cause congestion along the lines they exclusively operate. However, on lines with mixed traffic, they can cause congestion and delays of the lower prioritized conventional passenger and freight trains. Furthermore, if these trains cause a road to rail modal shift, they can contribute to mitigating local road congestion. For example, a single tilting train with a seat capacity of 440 seats and load factor of 0.5 can replace about 110 passenger cars occupied on average by two persons.

Safety

Safe operations of high-speed tilting passenger trains is provided through their scheduling and by respecting their operational constraints, particularly those concerning the maximum allowable speed along particular segments of the line(s) (along curves). Scheduling, in addition to satisfying passenger demand and the operators' perspective, also inherently implies specifying the minimum distance between any two trains moving in the same direction. This is the distance at which the running trains must stay apart in any case in order to prevent back collisions in cases of immediate and/or unpredictable braking. This safe distance mainly depends on the breaking characteristics of the trains and their operating speed as follows:

$$d_{\min} = v_{\max}^2 / 2b + v_{\max} / \Delta \quad (2.18b)$$

where

- $v_{\max}$ is the maximum operating speed (m/s);
- b is the maximum deceleration rate (m/s^2); and
- Δ is the minimum time between activating and staring braking.

For example, for a high-speed tilting train operating at the speed of $v_{\max} = 200$ km/h, with a deceleration rate $b = 0.65 \text{ m/s}^2$, and the braking system reaction time $\Delta = 5$ s, the minimum breaking distance will be $d_{\min} = 2,652$ m.

Respecting the maximum allowable speed(s) along the curves and other parts of the rail line(s) prevents derailments of the high-speed tilting trains and related

damaging (incidental/accidental) events. However, except reports and descriptions of individual accidents/incidents, additional aggregate statistical figures on these events and their consequences are currently unavailable. Therefore, at this moment, judgment about the overall safety of these trains can only be made indirectly by considering the aggregate statistics for the passenger railways in the given region. For example, the number of fatalities and injuries in passenger traffic in EU27 Member States has been continuously decreasing over time (the 1997–2008 period) and reached about 3.5 fatalities per billion passenger-km in the year 2009, of which only 1 % was caused by derailments including those of high-speed tilting passenger trains (EC 2009). This suggests that high-speed tilting passenger trains in Europe have been overall very safe.

2.3.3 Evaluation

High-speed tilting passenger trains possess both advantages (Strengths and Opportunities) and disadvantages (Weaknesses and Threats).

Advantages

- Operating as the exclusive HS (High Speed) rail alternative in some regions/countries;
- Operating as an intermediate phase from conventional to the full HS trains;
- Decreasing investments and maintenance costs for building rail infrastructure as compared to that of full HS rails;
- Increasing utilization of the capacity of given rail lines;
- Enabling higher commercial speeds and thus shortening passenger journey time, which in combination with improved riding comfort makes traveling by rail more attractive for existing and prospective users/passengers;
- Stimulating internal and external modal shift; the former from conventional rail services and the latter mainly from individual passenger cars; and
- Mitigating the environmental and social impacts as compared to those of conventional trains after modal shift occurs.

Disadvantages

- Affecting interoperability at border crossings due to the diversity of standards related to the geometry of infrastructure/tracks and train sets, which are mostly country/manufacturer/rail line specific; and
- Exposing users/passengers to the inherent risk of motion sickness during tilting at high speeds through the curves.

Finally, can high-speed tilting passenger trains be considered as an advanced transport system? The answer is “yes,” particularly as compared to their conventional passenger train counterparts.

2.4 Advanced Subsonic Commercial Aircraft

1935	The first flight of the piston engine-powered Douglas DC3 aircraft is carried out (U.S.)
1951	The first commercial jet engine-powered aircraft (Comet I) is launched (UK)
1957	The first flight of the first commercially successful jet engine-powered Boeing B707 aircraft is carried out (U.S.)
1969	The first commercial wide-body Boeing B747 aircraft is launched (U.S.)
2012	The Boeing B787-8 aircraft begins commercial operation

2.4.1 Definition, Development, and Use

The main priorities in aircraft design over the past 30 years for both manufacturers and operators—airlines have been improving safety while reducing operating costs. The latter indicates that technology has also been strongly driven by commercial/market driving forces. But, what about the future? Most research to date states that the same priorities will continue in the medium- to long-term future, i.e., for about 10 to 30 years ahead, without significant and revolutionary changes in technology. This implies that changes will be mostly evolutionary with the advancements likely following the current lines of development:

- In the aerodynamic design, reducing drag by about 10 % as compared to the design(s) in the 2001;
- In the operating empty weight, reduction by about 15 % thanks to the increased use of composite materials in aircraft construction (airframe, engines, and the other systems); and
- In propulsion, increasing the overall efficiency by about 8 % through improved thermal efficiency—by increasing the overall pressure ratio and turbine inlet temperature on the one hand, and improving combustion technology on the other; this should result in reducing fuel consumption by about 30 % and the related emissions of NO_x (Nitrogen Oxides) by about 8 % (ICAO CAEP/6 NO_x limits) and further by 11–19 % (the proposed EPA Tier 8 NO_x limits depending on the engine pressure ratio) as compared to aircraft/engine technologies in 2001 (EPA 2011).

Consequently, aircraft manufacturers have undertaken to design commercial aircraft that will be able to reach the above-mentioned targets. In particular, the U.S. aircraft manufacturer Boeing, using the technology previously developed for the Sonic Cruiser aircraft, announced at the end of January 2003 design of the conventional configuration, the B7E7 aircraft, which later became the B787-8. Furthermore, in July 2006, the European aircraft manufacturer Airbus began development of the advanced A350 XWB (Xtra Wide Body) aircraft family as a direct competitor to the above-mentioned Boeing B787-8 and existing B777 aircraft family. Commercial flights of these aircraft with a seating capacity of

270–350 passengers (depending on the version: A350-800, -900, -1000) are expected to begin in 2014. Because the B787-8 aircraft is already in commercial service, it is elaborated in more detail. The A350XWB aircraft is still under development and therefore it is only mentioned for comparison where reasonable.

2.4.2 Analyzing and Modeling Performances

2.4.2.1 Background

The main idea behind the design of B787 aircraft was to emphasize the convenience of smaller mid-size twin-jet compared to the large Airbus A380- and Boeing B747-400/8 aircraft, which could also drive a stronger shift from hub-and-spoke to point-to-point airline air route networks. After being postponed several times, the B787-8 aircraft began commercial operations in October 2012 (Boeing 2012).

The B787-8 aircraft is characterized by its infrastructural, technical/technological, operational, economic, environmental, social, and policy performances.

2.4.2.2 Infrastructural Performances

The infrastructural performances of B787-8 aircraft relate to its airport operations. Some of indicators and measures of these performances are given in Table 2.12. As mentioned above, those for the A350-800 aircraft are given for comparative purposes.

As far as airport operations are concerned, the Boeing 787-8 is categorized as a medium-sized twin-engine long-range aircraft. Respecting the wing span, the aircraft belongs to the E group according to the ICAO (International Civil Aviation Organization) and the V group according to the US FAA (Federal Aviation Administration) classification. Respecting the overall length, the aircraft belongs to the ICAO's RFF category 8 and FAA's ARFF Index D (Boeing 2012a). In addition, with its final approach speed of about 140 kts (kts=knots), the B787-8 belongs to the FAA category IV. The A350-800 aircraft is categorized similarly (Airbus 2012; Boeing 2012a; Horonjeff and Mckelvey 1994).

Since the B787-8 aircraft is designed to perform nonstop flights of and longer than 9,000 nm (nm—nautical mile: 1 nm = 1.852 km), the take-off runway need to be no shorter than 3,400 m (11,000 ft) (ft—feet: 1 ft = 0.305 m).

Regarding airport maneuverability, the B787-8 is more advanced than its closest counterparts, for example, the B767-300ER aircraft. Namely, the geometry of maneuvering an aircraft at the airport is characterized by its turning radii, which are a function of the nose steering angle. In principle, the larger the steering angle, the smaller the radii, and consequently the greater the maneuverability. From the standpoint of maneuvering close to buildings and other aircraft, the largest turning

Table 2.12 Infrastructural performances of the B787-8 and A350-800 aircraft—airport operations (Boeing 2012, Airbus 2012)

Specification	Aircraft type	
	B787-8	A350-800 ^d
Length (m)	56.7	60.6
Wingspan (m)	60.1	64.0
Wing area (m ²)	325	443
Wing sweepback (°)	32.2	31.9
Height (m)	16.9	17.0
Fuselage constant diameter (m)	5.75	5.32
Maximum Take-Off Weight (MTOW) (t)	219.5	248
Maximum Landing Weight (MLW) (t)	168	193
Maximum payload (t)	44.5	35.7
Take-off field length (m) ^a	3,100	751
Landing field length (m) ^b	1,600–1,800	1,525
Maximum pavement width (m)	42	–
Effective steering angle (°)	65	–
Aircraft Classification Number (ACN) ^c	57–101	65–105
	(flexible pavement)	(flexible pavement)
	57–91	59–93
	(rigid pavement)	(rigid pavement)

^a MTOW Maximum Take-off Weight, Sea level pressure altitude, standard day +15 °C temperature, dry runway; ^b MLW Maximum Landing Weight, sea level pressure altitude, dry runway; m meter; t ton; ^c ACN is the ratio between the pavement thickness required for a given aircraft and that required for the standard aircraft single wheel load; ^d Preliminary data

radius is the most critical (Horonjeff and McKelvey 1994). The minimum turning radius corresponds to the maximum nose steering angle, which is, for example, 65° for the B787-8 aircraft. This enables it to turn on a path (runway, taxiway, apron) 42 m wide, which is about 2 m narrower than that of the B767-300ER aircraft with the maximum steering angle of 61° (44 m). Consequently, the radius of the taxiway centerline for B787-8 is 32.9 m as compared to that of B767-300ER of 33.8 m (AT 20).

In addition, the size of parking stands at the apron gate complex depends mainly on the aircraft's overall size, the required buffer space between the aircraft and the permanent fixtures (buildings), temporarily static objects (other aircraft and traffic at the airport), and the type of parking scheme (nose-in, parallel, angled) (Horonjeff and McKelvey 1994). Respecting its dimensions in Table 2.12, the size of parking stand of a nose in parked B787-8 aircraft is approximately 5,385 m² (this includes the aircraft footprint and a buffer space of 7.5 m around it). For comparison, the size of the parking stand of nose in a parked B767-300ER aircraft is approximately 4,376 m², which is about 23 % lower than that of the B787-8 aircraft whose scheme of airport/ground servicing is shown in Fig. 2.14.

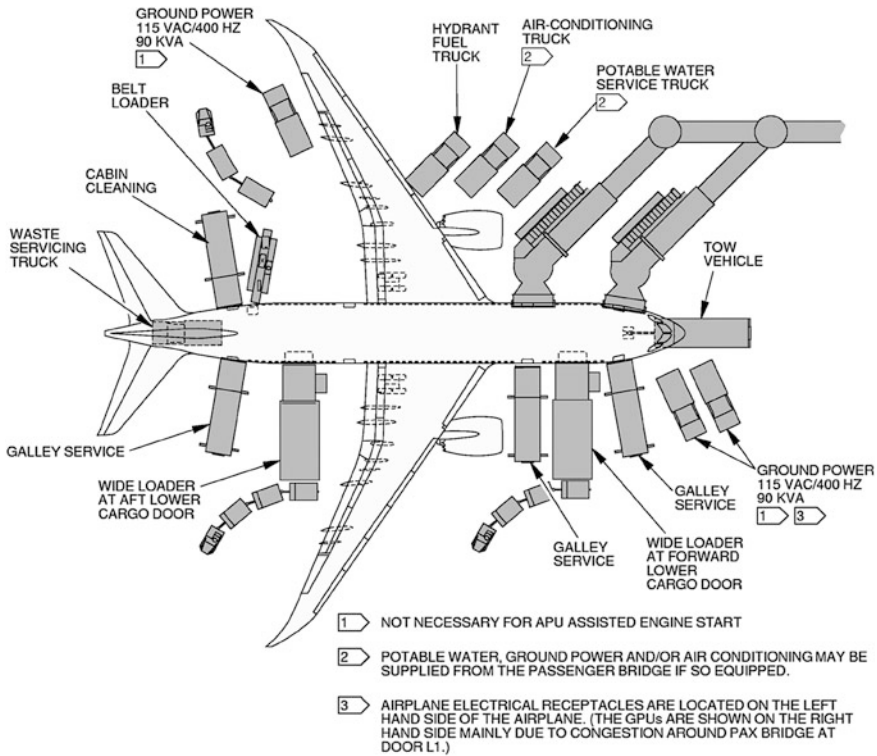


Fig. 2.14 Scheme of ground servicing of the B787-8 aircraft—regular conditions when *APU* Auxiliary Power Unit is used (Boeing 2012a)

A can be seen, the facilities and equipment for the airport/ground servicing of B787-8 are similar to those of B777 aircraft. The maximum turnaround time of the aircraft at the apron gate stand is specified to be 41 min and the through time 28 min (Boeing 2012a).

2.4.2.3 Technical/Technological Performances

The technical/technological performances of B787-8 aircraft relate to its aerodynamic design and materials used for its construction, engines, and aircraft systems.

Aerodynamics and materials

Aerodynamic

The aerodynamic design of the Boeing 787-8 aircraft is “advanced” due to the following reasons:

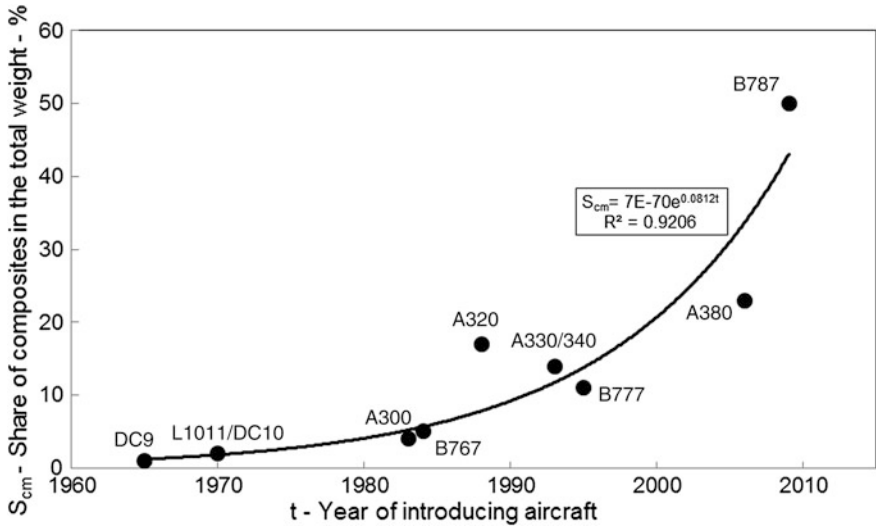


Fig. 2.15 Share of composite materials in the commercial aircraft over time (GAO 2011)

- Optimal combination of the aircraft weight, drag, and engine performance;
- Advanced transonic wing design for improved speed and lift (raked wingtips optimal for long-haul flights);
- High performance, but mechanically simplified high lift system of high reliability and reduced maintenance costs;
- Tightly integrated packaging of systems to reduce the size of aerodynamic fairings for reduced weight and drag; and
- Final nose configuration (four windows, fewer posts, pilot vision similar as in a B777 aircraft, non-opening windows, crew escape door, vertically stowed wipers, etc.).

Materials

The structures of commercial aircraft have been continuously upgraded with an increased use of composite materials as shown in Fig. 2.15.

As can be seen, the share of composites in the total weight is the greatest in the latest B787 aircraft. In addition, Table 2.13 shows shares of different materials in the weight of Boeing 787-8 and its current and forthcoming counterparts.

The share of composite materials in the B787-8 is the second greatest—after that of the forthcoming A350-800 aircraft. In terms of volume, composite materials account for about 80 % of the B787/8 aircraft total. One of the main reasons to use substantial amounts of these materials is to reduce the aircraft weight while retaining the required strength of the construction. In turn, this improves the aircraft efficiency primarily in terms of reduced fuel consumption and simpler maintenance, thus reducing both corresponding costs. Specifically, in the B787-8 aircraft, composites (carbon laminate, carbon sandwich, and fiberglass) are mainly

Table 2.13 Share of particular materials in the weight of selected aircraft (%) (Boeing 2012; Airbus 2012)

Material	Aircraft type			
	B777	A330-200	B787-8	A350-800 ^c
Composites ^a	11	10	50	53
Steel	11	19	10	10
Titanium	7	8	15	14
Aluminum/Al-Li ^b	70	58	20	19
Others	1	2	5	8

^a Carbon laminate, Carbon sandwich, fiberglass (Fiberglass = Carbon fiber); ^b Alloys of Aluminum and Lithium; ^c Preliminary data

used for the largest part of the fuselage, wings, horizontal, and vertical part of the tail. Aluminum is used on the wing and tail leading edges. Titanium is used mainly on the engines and fasteners, while steel is used in various places.

In order to illustrate the possible effects of substituting different materials in aircraft construction, let p_i be the current share of the material (i) with a specific gravity of g_i (g/cm^3) to be partially substituted by material (j) with the current share p_j and a specific gravity of g_j (g/cm^3). The proportion of material (i) to be substituted by material (j) is assumed to be q_{ji} . Consequently, the relative change of aircraft weight due to changing the shares of these two materials on account of each other can be estimated as follows:

$$\Delta w_{ji} = 1 - [(p_i - q_{ji})g_i + (p_j + q_{ji})g_j] / (p_i g_i + p_j g_j) \quad (2.19a)$$

The value Δw_{ji} in Eq. 2.19a can take positive and negative values. The former implies a decrease and the latter an increase in the aircraft weight in relative terms by the given substitution of materials. For example, if the current share of composite materials of $p_j = 50\%$ with a specific gravity of $g_j = 2.1 \text{ g/cm}^3$ was further increased in the construction of B787 by about $q_{ji} = 5\%$ on the account of aluminum with a current share of $p_i = 20\%$ and a specific gravity of $g_i = 2.7 \text{ g/cm}^3$, the aircraft weight would be reduced by about 4.5%. If steel (specific gravity $g_i = 7.83 \text{ g/cm}^3$), with a current share of 10% was reduced by about 5% on account of composites whose share was increased to 55%, the aircraft weight would be further reduced by about 16%.

Engines

General

The most important performances of contemporary turbofan jet engines are thrust, fuel efficiency, and SFC (Specific Fuel Consumption).

- *Thrust* (T) is generally derived from the change in momentum of the air through the engine and the thrust that occurs due to the static pressure ratio across the final (exhaust) nozzle. Analytically, it can be expressed as (Jenkinson et al. 1999):

$$T = m(v_1 - v_0)/g + (p - p_0)/A \quad (2.19b)$$

where

- m is the air flow through the engine (kg/s);
- v_1 is the velocity of exhaust jet (m/s);
- v_0 is the velocity of air entering the engine (m/s);
- g is gravitational acceleration (m/s²);
- p, p_0 is the pressure at the intake and the exhaust station, respectively, (N/m); and
- A is the nozzle cross sectional area (m²).

The thrust T in Eq. 2.19b is usually expressed in kN (kiloNewton) (SI units) or Libras (lb) (British units).

- *Efficiency* (η_e) directly expresses the rationale of the engine fuel consumption, i.e, higher efficiency implies lower fuel consumption per unit of the engine thrust, and vice versa.
- *SFC* (*Specific Fuel Consumption*) expresses the ratio of fuel burned per hour per ton of net thrust (Janic 2007). It is expressed in kg of fuel per kg of thrust/h. The SFC and engine efficiency η_e are interrelated as follows:

$$SFC = M/4 * \eta_e \quad (2.19c)$$

where

M is the Mach number.

Engines with higher bypass ratios usually have lower SFC. For most contemporary aircraft turbofan jet engines, this amounts about 0.25–0.30 kg of fuel/kg of thrust/h. In addition, SFC relates to the jet engine bypass ratio (BR). The nature of this relationship is illustrated using the data for the cruising phase of the flight of 20 different engines produced by different airspace manufacturers. The regression relationship in which the bypass ratio BR is considered as the independent and SFC as the dependent variable is as follows (Janic 2007):

$$SFC = 0.3435BR^{-0.1624}; (R^2 = 0.425; N = 20) \quad (2.19d)$$

The B787-8 aircraft is powered either by RR (Rolls Royce) TRENT 1000 or by General Electric GENx1B engines.

RR (Rolls Royce) TRENT 1000 engine

The RR (Rolls Royce) TRENT 1000 engine is considered an advanced turbofan jet engine as compared to its counterparts due to the following features: no-engine-bleed systems, higher bypass ratio and higher pressure ratio compressor, high-flow slower-speed fan, advanced materials and coatings, architecture, low-noise nacelles with chevrons, and interchangeability at wing/pylon interface. Table 2.14 gives some important performances of the RR TRENT 1000 engine.

Table 2.14 Characteristics of the RR (Rolls-Royce) Trent 1000 aircraft engine (RR 2011)

Parameter	Value
Type	Three-shaft high bypass ratio turbofan engine
<i>Dimension/weight</i>	
Length (m)	4.769
Fan diameter (m)	2.85
Dry weight (tons)	6.018
<i>Performances</i>	
Maximum thrust (kN)	307–330
OPR (Overall Pressure Ratio)	33
SFC (Specific Fuel Consumption) ^a (kg-fuel/kg-thrust/h)	0.224
BR (Bypass Ratio)	10.0–11.0
Thrust-to-weight ratio (kN/ton)	51.01–54.84

^a Based on the performance of the RR Trent 800 engine (reduction for about 15 %); t ton

The no-engine-bleed systems of the RR Trent 1000 engine and its tiled engine combustor suit the need for more electricity in Boeing 787-8 s, and thus enable reduction in the overall aircraft weight, and consequently fuel consumption. In addition, the RR Trent 1000 engine has a bypass ratio of about 10.0–11.0, which gives an average efficiency rate of about $\eta_e = 0.908$ during the cruising phase of flight at the speed of: $M = 0.85$. For example, for the BR (Bypass Ratio) = 11, the SFC (Specific Fuel Consumption) will be $SPC = 0.224$ kg-fuel/kg-thrust/h (cruise).

Aircraft systems

The systems of the B787-8 aircraft include: (i) Efficiency Systems; (ii) Highly Integrated Avionics, and (iii) e-Enabled Airplane Systems (Nelson 2005; Boeing 2012a).

Efficiency Systems

Efficiency systems aim at generating, distributing, and consuming energy efficiently and effectively. They include the following subcomponents: Advanced Energy Management (The More Electric Aircraft), and Flight Controls (Variable Camber Trailing Edge and Drooped Spoilers).

Highly Integrated Avionics

Highly integrated avionics systems enable the efficient and effective navigation during flight. They include the following subcomponents: Common Core Systems open architecture, Integrated Flight Controls Electronics, Integrated Communication/Navigation/Surveillance equipment, and Integrated Aircraft Systems Control.

Table 2.15 Operational performances of the B787-8/9 and A350-800 aircraft (Airbus 2012; Boeing 2012a)

Indicator/measure	Aircraft type		
	787-8	787-9	A350-800 ^a
Cockpit crew	Two	Two	
Seating capacity (seats)	242 (3-class)	250–290 (3-class)	
	264 (2-class)	280 (2-class)	
MTOW (tons)	219.5	251	248
MLW (tons)	168	193	190
MZFW (tons)	156	181	181
OEW (tons)	110	115	105
Cruising speed (Mach/kts)	0.85/490 at 3,5000 ft/10,700 m		0.85/490
			40,000/12,190
Maximum speed (Mach/kts)	0.89/515 knots at 35,000 ft/10,700 m)		0.89/515
			40,000/12,190
Service ceiling (ft/m)	43,000 /13,100		–
Range, fully loaded (nm/km)	5,550/10,280	6,500/12,036	5,000/9,375
Maximum fuel capacity (000 l)	126	139	129
Engines (×2)	RR Trent 1000	RR Trent 1000	Trent XWB
Type			
Thrust (kN)	2 × 307–330	2 × 330	2 × 351

MTOW Maximum Take of Weight; *MLW* Maximum Landing Weight; *MZFW* Maximum Zero Fuel Weight; *OEW* Operating Empty Weight; *l* liter; *ft* foot; *kts* knots; *kN* Kilo Newton; *RR* Rolls Royce

^a Preliminary data

e-Enabled Airplane Systems

e-enabled aircraft systems provide the flight crew with wireless communication both inside and outside the aircraft. They include broadband connectivity within the aircraft and with the ground (Flight Deck, Crew Information System, Onboard Health Maintenance, and Cabin systems).

2.4.2.4 Operational Performances

The main operational performances of the B787-8 aircraft include its payload-range characteristics and technical productivity. They are influenced by the aircraft relevant parameters/indicators given in Table 2.15.

Payload-range characteristics

The payload-range characteristics of the Boeing 787-8 aircraft can be analytically expressed as follows:

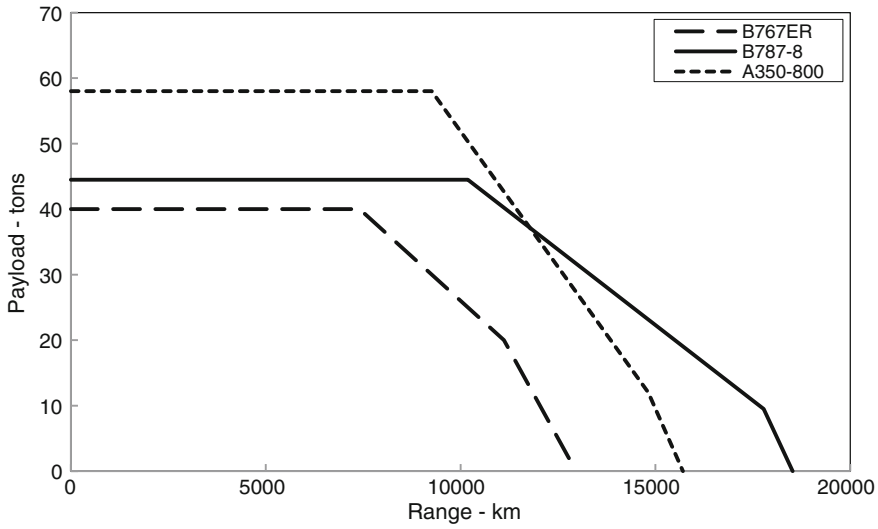


Fig. 2.16 Payload-range characteristics of the selected commercial aircraft (Airbus 2012; Boeing 2012a; http://nl.wikipedia.org/wiki/Airbus_A350)

$$PL(R) = \begin{bmatrix} 44.5, & 0 < R \leq 5550 \\ 44.5 - 0.00864 * (R - 5550), & 5550 < R \leq 9600 \\ 9.5 - 0.023 * (R - 9600), & 9600 < R \leq 10000 \end{bmatrix} \quad (2.20a)$$

where

R is the range (nm); and

$PL(R)$ is the payload (tons).

In addition, the payload-range characteristics for the B787-8, B767-300ER, and A350-800 aircraft are shown in Fig. 2.16.

Evidently, the B787-8 appears superior to its B767-300ER counterpart as it is able to operate along longer nonstop distances with greater payload. The forthcoming A350-800 will at least be comparable to the B787-8 aircraft by carrying seemingly higher payloads on shorter nonstop distances.

Technical productivity

The technical productivity of commercial aircraft including the B787-8 can be estimated as the product of their operational/cruising speed and payload. As mentioned above, the maximum payload of each aircraft changes and depends on the range. Consequently, technical productivity can be calculated as follows:

$$TP[v(R), PL(R)] = v(R) * PL(R) \quad (2.20b)$$

where

$v(R)$ is the aircraft operating/cruising speed depending on the range R (km/h or kts (nm/h)).

The other symbols are analogous to those in previous equations. Thus, for example, if the B787-8 aircraft performs a flight of the length of $R = 9,280$ km at an average cruising speed of $v(R) = 900$ km/h, its technical productivity will be $TP[v(R), PL(R)] = 44.5 \text{ tons} \times 900 \text{ km/h} = 40,050 \text{ ton-km/h}$. In case of longer flights carried out approximately at the same speed, this productivity will decrease in line with decreasing of the payload carried. It would not be reasonable to investigate the influence of the operating/cruising speed on much shorter flights with the maximum payload since this aircraft is just designed to operate long-haul flights within the airline point-to-point network. The similar seems to apply to the forthcoming A350-800 aircraft and the rest of its family.

2.4.2.5 Economic Performances

The main economic performances of the B787-8 aircraft are its costs and revenues, which can also be said for its conventional counterparts.

Costs

Aircraft costs are roughly divided into operating and non-operating cost. In particular, operating cost can be divided into DOC (Direct Operating Cost) and IOC (Indirect Operating Cost) (Janic 2007). The former consist of the costs of aircraft depreciation, insurance, maintenance and overhauling (airframe, engines and avionics), and the cost of flight operations (crew, fuel/oil, airport, and navigation charges). The latter roughly include the costs of aircraft and traffic servicing, promotion and sale, passenger services, general and administrative overheads, and maintenance and depreciation of the ground property and equipment. In general, both DOC and IOC have shown to increase in line with the aircraft size (i.e., seating capacity) and stage length.

The aircraft DOC are usually expressed in average monetary units per flight or per unit of flight output (US\$ or € per ASK (Available Seat-Kilometer) or PKM (Passenger Kilometer) passenger-km). The ATA (Air Transport Association) of American method with the necessary modifications of the values of inputs is still relevant for estimating and comparing aircraft DOC, particularly of aircraft that are just at the beginning of their full commercialization such as the B787-8. An example of application of this method is shown in Fig. 2.17 (AC 2005; Janic 2007).

As can be seen, the average cost per ASK (Available Seat-Kilometer) decreases more than proportionally as the stage length increases, thus indicating economies of distance in the case of the selected aircraft. At the same time, the average costs of the B787 s aircraft are by about 3–11 and 8–11.5 % lower than those of the

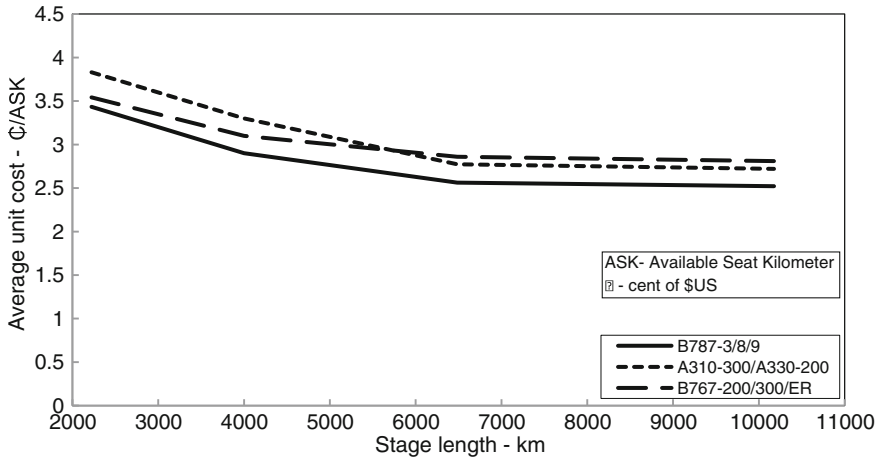


Fig. 2.17 Relationships between the average operating cost and stage length of the selected commercial aircraft (AC 2005)

B767-200/300/ER and A310/330-200 aircraft, respectively (The cost components include aircraft price and interests on bonds, i.e., finance charges, navigational and landing charges, flight attendant and crew costs, and maintenance and fuel cost). The beginning of commercial operations of the B787-8 aircraft has confirmed the above-mentioned expectations mainly thanks to the lower maintenance airframe and engine costs and lower fuel consumption of increasingly expensive fuel. These last two cost components will likely continue to influence the short-term variations of the DOC. For example, let's assume that the share of fuel costs in the total operating cost of a given long-haul flight is about 30 %. Since the B787-8 aircraft is supposed to consume about 20 % less fuel than its counterparts (B767-300ER, A310-300/A330-200/300), the share of its fuel costs in DOC will decrease from 30 % to about 24 %. If the other cost components and their influencing factors remain unchanged, this will decrease the total cost per flight by about 6 %. The savings in DOC from operating the B787-8 aircraft will increase, for example, by about 10 % if the share of fuel costs mainly caused by increasing of the fuel prices rises (for example, from 30 to 50 %).

Revenues

As with other aircraft, revenues from operating B787 aircraft are obtained by charging passengers on the given routes. For example, the average price/airfare covering the cost of a flight in time T can be estimated as follows:

$$p_{ij}(T) \geq \frac{c_{ij}(N_{ij}, d_{ij})}{\lambda_{ij} N_{ij}} \quad (2.21)$$

where

$c_{ij}(N_{ij}, d_{ij})$ is the cost per flight carried out by an aircraft of the seat capacity N_{ij} on the route of length d_{ij} in time T ; and

λ_{ij} is the average load factor of a flight on the route d_{ij} carried out by an aircraft of the seat capacity N_{ij} in time T ($0 < \lambda_{ij} \leq 1$).

As Eq. 2.21 indicates, the average price/airfare depends on the cost and the average load factor of a given flight carried out by any aircraft, including the B787-8 aircraft.

2.4.2.6 Environmental Performances

The environmental performances of the B787-8 aircraft include fuel consumption and related emissions of GHG (Greenhouse Gases), and land use/take.

Fuel consumption and emissions of GHG

Multiplying the SFC with the thrust per engine and the number of engines per aircraft can give an estimation of the aircraft total fuel consumption per unit of time (tons/h). In addition, fuel consumption per seat-kilometer can be relevant for comparison of different aircraft with respect to fuel consumption/efficiency. Some estimates given in Fig. 2.18 indicate that the B787-8 aircraft could be more fuel efficient by about 8, 9, and 18 % than its B767-200ER, B777-200ER, and 777-300ER counterparts, respectively.

The most recent figures obtained by ANA (Air Nippon Airlines, Japan) show that the fuel savings by operating B787-8 powered by RR Trent 1000 engines on short-haul routes are 15–20 % and up to 21 % on long-haul (international) routes as compared to the B767-200/300ER aircraft. Some additional savings of up to about 3 % have been reported by JAL (Japan Airlines) using the B787-8 aircraft powered by GENx 1B engines (AW 2012). In addition, Airbus expects the fuel consumption of the A350-800 to be about 6 % lower than that of B787-8 aircraft as shown in Fig. 2.18.

The related emissions of GHG (Greenhouse Gases) from burning JP1 or JP-A fuel are CO₂ (Carbon), H₂O (Water vapor), NO (Nitric Oxide) and NO₂ (Nitrogen Dioxide) (together called NO_x (Nitric Oxides)), SO_x (Sulfur Oxides), and smoke. The emission rates of CO₂, H₂O, and SO₂ are relatively constant—3.18 and 1.23 kg/kg, and up to 0.84 g/kg of fuel, respectively (Janic 2007). The emission rate of NO_x (Nitrogen Oxides) changes (increases) in line with increasing of the OPR (Overall Pressure Ratio¹) of the given turbofan jet engine. The above-mentioned higher fuel efficiency thanks to the higher engine BR (Bypass Ratio) (11.0) and better combustion makes the related emissions of GHG (particularly CO₂ and NO_x) by the B787-8 aircraft proportionally lower than those of its closest counterparts.

¹ The OPR (Overall Pressure Ratio) is defined as the ratio of the total pressure at the compressor discharge and the pressure at the compressor entry (Hunecke 1997; Janic 2007).

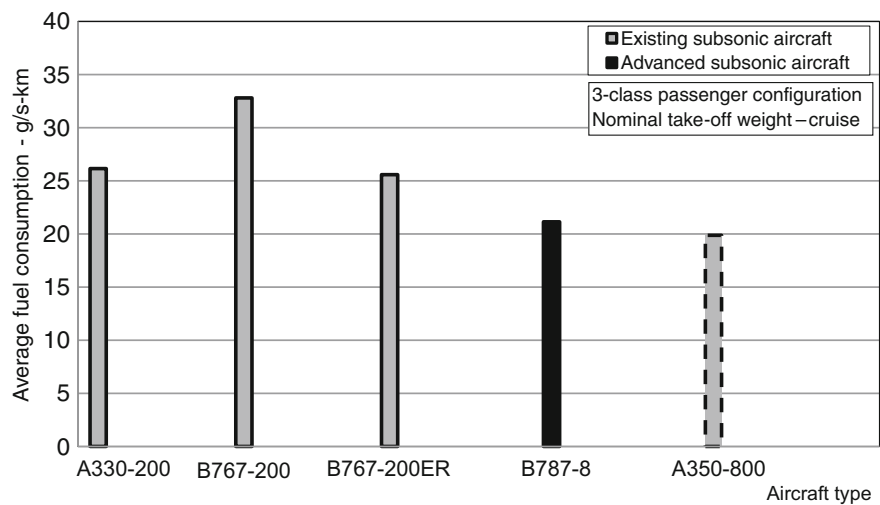


Fig. 2.18 Fuel efficiency of the selected commercial aircraft (<http://www.lissys.demon.co.uk/boeing787.html>)

Land use

Thanks to its advanced maneuverability, accommodating the B787-8 aircraft at certified airports does not require use of additional land. Eventual modifications of taxiways and apron-gate parking stands are to be carried out within the airport area, i.e., over the already taken land. Thus, the B787-8 aircraft can be considered as a land use/take “neutral” aircraft.

2.4.2.7 Social/Policy Performances

The social/policy performances of the B787-8 aircraft relate to noise, congestion, and traffic incidents/accidents (safety).

Noise

Noise primarily comes from the aircraft engines while flying near the ground, i.e., during approach and landing, flyover, and take-off. The noise spreads in front of and behind the aircraft engine(s). The front noise-spreading generators are the engine(s) compressor and fan. The back noise-spreading generators are the turbine, fan, and jet efflux. The aircraft are certified for noise at various noise certification locations around the airport. The maximum noise at these locations must not exceed 108 EPNLdB (this noise is equivalent to about 96 dB (A) measured by A-noise weighted scale) (Huenecke 1997; Horonjeff and McKelvey 1994;

Table 2.16 Social performances of the selected commercial Aircraft—noise (Cohen-Nir 2010; EASA 2011, 2012)

Aircraft type	TOW ^a	Noise level (EPNLdB) ^c		
		Lateral	Flyover	Approach
B767-200	144	95.7	91.5	102.1
B767-200ER	168	97.8	91.1	98.6
B767-300	158	96.0	91.3	98.5
B767-30ER	180	95.7	91.5	99.7
A330-200	230	97.0	94.4	96.8
A330-300	217	97.6	91.6	98.9
B787-8	220	90.5	83.0	96.2
A350-800 ^b	259	89.0	83.0	95.0

^a Typical TOW Take-Off-Weight; ^b Preliminary data; ^c EPNLdB Effective Perceived Noise Level in decibels (typical engines)

Janic 2007). Table 2.16 gives the noise characteristics of selected aircraft at the noise certification locations.

Evidently, the B787-8 aircraft generates about 5–7, 7 and 0.6–6 dB lower certificated noise than its counterparts while taking off, flying over, and approaching, respectively (EASA 2011, 2012). In addition, making a broader judgment concerning mitigation of noise by B787-8 can be made by assuming it replaces the B767-200/200ER aircraft. This implies the gradual increase in the number of replacing aircraft (B787-8) on the account of gradually replaced aircraft (B767-200/200ER). The total number of B767-200/200ER aircraft to be replaced is assumed to be 800 (based on the current orders of B787-8). Regarding operating long-haul flights, each aircraft of both fleets is assumed to perform the same number of flights (2/day). The noise level is considered to be the certified EPNLdB (the case in Europe) (EASA 2011). The total noise exposure by take-off or approach/landing operating fleet of both aircraft during the day can be estimated as follows (Smith 2004):

$$\overline{EPNLdB} = \frac{1}{n} \sum_{i=1}^2 n_i [EPNLdB_i + 10 \log_{10}(n_i * \theta_i)] \quad (2.22)$$

where

- $EPNLdB_i$ is the Effective Perceived Noise Level of the aircraft in decibels (i);
- n_i is the number of aircraft (i) in operation (per day);
- θ_i is the average number of flights per day of aircraft (i); and
- n is the total number of aircraft in operation (per day).

The example is shown in Fig. 2.19.

As can be seen, the total potential noise exposure by the entire replacing and replaced fleet decreases more than proportionally with increasing of the proportion of advanced B787-8 aircraft. By full replacement, this exposure could be reduced by about 3 dB and 6 dB during approach and take-off, respectively. Consequently,

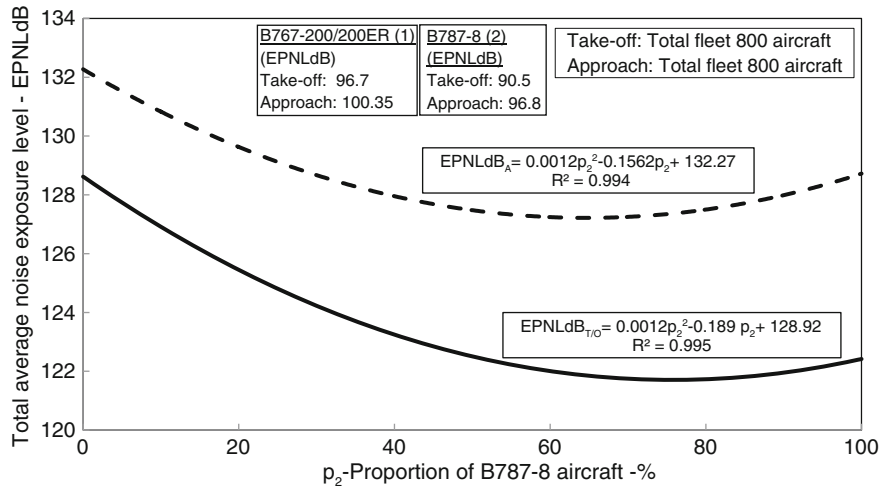


Fig. 2.19 Relationship between the average noise exposure and the proportion of B787-8 aircraft in the fleet

the “noise contour” or “noise footprint” as the area of constant noise generated by B787-8 aircraft around an airport can be by about 60 % smaller than those of its counterparts, thus ensuring that noise above the level of 85 dB certainly does not spread outside the airport boundaries. This is achieved mainly thanks to the improved aerodynamics design on the one hand, and the lower fan speed and low jet velocity of the RR Trent 1000 engines, on the other. The forthcoming A350-800 aircraft is expected to be even quieter (Cohen-Nir 2010).

Congestion

The B787-8 aircraft is categorized as a heavy aircraft. This implies that as being the leading aircraft in the landing sequence, it needs to be separated from A380, other Heavy, Upper and Lower Medium, Small, and Light aircraft by 4, 4, 5, 6, and 7 nm, respectively. Currently, the separation amounts to 10 nm (nautical mile; 1 nm = 1.875 km). As the leader in the take-off sequence, the B787-8 aircraft needs to be separated from all other aircraft by 3 min (FAA 2011). Consequently, like the increased proportion of other heavy aircraft in the airport arrival and departing streams, an increased proportion of B787-8 aircraft can contribute to increased overall separation interval(s), which reduces the runway landing and take-off capacity almost proportionally. Consequently, at saturated capacity-constrained airports, the overall congestion and aircraft delays may increase.

Safety

The B787-8 is an advanced aircraft designed to operate absolutely safely implying its immunity to incidents and accidents due to all previously known reasons. The forthcoming more intensive operations will certainly confirm such expectations since the aircraft is also designed in light of the overall objectives to make the

present and future air transport system safer despite its continuous growth. For example, in the case of an engine failure during the cruising phase of flight, the ETOPS (Extended Range Twin-Engine Operational Performances) capabilities enable B787-8 aircraft to stay in the air for up to 180 min, which is, like its counterparts, sufficient to reach the closest airport and land safely.

2.4.3 Evaluation

The B787-8 aircraft possesses advantages (Strengths and Opportunities) and disadvantages (Weaknesses and Threats) as compared to its closest counterparts—the Boeing B767-300ER and the Airbus A330-200/300.

Advantages

- Advanced aerodynamic design;
- Substantial use of lighter but very strong composites (about 50 and 80 % of the weight and volume, respectively);
- Superior technical productivity over the entire range;
- Advanced navigational systems onboard being a part of the forthcoming NextGen and SESAR research and development initiatives in the USA and Europe, respectively;
- Increased efficiency in terms of fuel consumption and related emissions of GHG (Greenhouse Gases), but still not sufficiently convincible to be in line with the widely advertised 20 % decrease; and
- Seemingly convincible reduction of noise at source—aircraft engines—but again slightly lower than advertised.

Disadvantages

- Relatively high price;
- Rather modest reduction of direct operating costs due to improvements in the fuel efficiency, i.e., lower fuel consumption and share of fuel costs in the total operating costs;
- Contribution to increasing congestion and delays at capacity constrained airports because of reducing the airport runway capacity affected by increased overall separation within the arrival and departure stream(s); and
- An inherent uncertainty in the technical and operational reliability of the innovative technologies and particularly electrical systems and composites during the aircraft life-cycle of about 25–30 years.

Finally, the B-787-8 aircraft is certainly an advanced subsonic commercial aircraft. At present, most of its infrastructural and technical/technological performances are known. However, its remaining operational, economic, environmental, and social/policy performances and consequently further advantages and disadvantages will only be able to be analyzed in more detail after more intensive aircraft use.

References

- AC. (2005). Can the 787 & A350 transform the economics of long-haul services?. *Aircraft Commerce*, No. 39 (February/March), pp. 23–30.
- AEIF. (2002). *Trans-european high-speed rail system, technical specification for interoperability (TSI), infrastructure*. European association for Railway interoperability, international union of Railways. Paris, France.
- Airbus. (2012). *A350XWB sharpening efficiency*. Blagnac Cedex: Airbus Company.
- AUMA. (2007). *Towards a light rail transit program: Analysis and recommendations*. Alberta, California: Alberta Urban Municipalities Association.
- AW. (2012). ANA, JAL boeing 787 fuel burn performance beating expectations. *Aviation week & space technology*, AW&ST.com, (June), pp. 20–22.
- Boeing. (2012a). *787 Airplane characteristics for airport planning*. Seattle, Washington: Boeing Commercial Airplanes.
- Boeing. (2012). *Boeing 787 dreamliner being designed for environmental performance*. Seattle, Washington: Boeing Commercial Airplanes.
- CE. (2008). *Vehicle technology review: City of Edmonton, LRT Projects*. Retrieved from www.edmonton.ca/LRTProjects
- Cebrián, P. (2008). CNG vehicles for urban transport: An available solution for cleaner air in cities. *BESTUFS (Best Urban Freight Solution) II-8th Workshop*, IVECO trucks and commercial vehicles, March, Madrid, Spain.
- CEN. (2002). Track alignment design parameters—track gauges 1435 and wider—part 1: Plain line. *Railway Applications*. EN13803-1, Comité Européen de Normalisation, Brussels, Belgium.
- CEN. (2006). Track alignment design parameters—track gauges 1435 and wider—part 1: Plain line. *Railway Applications*. Enquire Version EN13803-1, Comité Européen de Normalisation, Brussels, Belgium.
- Cohen-Nir, D. (2010). *Airbus Program Update, Presentation*. Airbus America Inc., Airbus SAS. Herndon, Virginia, USA.
- De Rus, C. J. G. (Ed.). (2009). *Economic analysis of high speed rail in Europe*. Bilbao: BBVA Foundation.
- EASA. (2011). *Type certificate data-sheet for noise no. EASA. A004 for Airbus A330, EASA IM.A. 115 for boeing 787-8, B767*. Koln, Germany: European Aviation Safety Agency.
- EASA. (2012). *Type certificate data sheet data sheet for noise no. EASA.IM.A.115 for boeing 787-8*. Koln, Germany: European Aviation Safety Agency.
- EC. (2002). Technical specification for interoperability relating to the rolling stock subsystem of the trans european high-speed rail system, 30/05/2002. *Official Journal of the European Commissions*, No. 12 (September).
- EC. (2009). *EU energy and transport in figures*. Statistical pocket book, directorate general for energy and transport, Brussels, Belgium.
- EC. (2010). *Signal*. The newsletter of the european rail traffic management system ERTMS, No. 21. European Commission, Brussels, Belgium.
- EEA. (2007). *The emission factors: Technical annex*. Copenhagen, Denmark: European Environmental Agency.
- EPA. (2011). *Control of air pollution from aircraft and aircraft engines; proposed emission standards and test procedures*, Part II, 40 CER Part 80 and 1068. Environmental Protection Agency, Federal Register (Vol. 16, No. 144), Washington D.C., USA.
- ERRAC. (2004). *Light rail and metro systems in Europe: Current market perspectives and research implications*. Brussels, Belgium: The European Rail Research Advisory Council.
- FAA. (2011). *Interim procedures for boeing 747-800 and boeing 787 flights*. Notice N JO 7110.542, Federal Aviation Administration, US Department of Transportation, Washington, D.C., USA.

- GAO. (2001). *Mass transit: Bus rapid transit shows promise*. GAO-01-984, Report to Congressional Requesters, United States Government Accountability Office, Washington, D.C., USA.
- GAO. (2011). *Aviation safety: Status of FAA's actions to oversee the safety of composite airplanes*. Report to Congressional Requesters, Government Accountability Office, GAO-11-849, Washington, D.C., USA.
- GAO. (2012). *Bus rapid transit: Projects improve transit service and can contribute to economic development*. GAO-12-811, Report to the Committee on Banking, Housing, and Urban Affairs, United States Government Accountability Office, Washington, D.C., USA.
- Henri, L., Guy, M., & Jürg Z. (1991). Les Structure des Véhicules. *Revue Générale des Chemins de Fer*. No. 7–8 (July/August).
- Horonjeff, R., & McKelvey, F. R. (1994). *Planning and design of airports* (3rd ed.). New York: McGraw-Hill Book Company.
- Hunecke, K. (1997). *Jet engines: Fundamentals of theory, design and operation*. UK: Airline Publications Ltd.
- Janic, M. (2007). *The sustainability of air transportation: Quantitative analysis and assessment*. UK: Ashgate Publishing Company.
- Janic, M. (2011). Light rail rapid transit (LRRT) system for more sustainable ground accessibility of airports. *Transportation Planning and Technology*, 34(6), 569–592.
- Jenkinson, L. R., Simpkin, P., & Rhodes, D. (1999). *Civil jet aircraft design*. London: Arnold Publisher.
- Kemp, R. (2007). *T618: Tracton energy metrics*, No. 2, Rail Safety and Standards Board. London, UK.
- Levinson, S. H., Zimmerman, S., Butherford, G. S., & Glinger, J. (2002). Bus rapid transit: An overview. *Journal of Public Transportation*, 5(2), 1–30.
- Levinson, S. H., Zimmerman, S., Clinger, J., Gast, J., Rutherford, S., Smith, L. R., Cracknell, J., Soberman, R. (2003a). *Bus rapid transit, Volume 1: Case studies in bus rapid transit*, Report, TCRP (Transit Cooperative Research Program), TRB (Transportation Research Board), Washington, D.C., USA.
- Levinson, S. H., Zimmerman, S., Clinger, J., Gast, J., Rutherford, S., Bruhn, E. (2003b). *Bus rapid transit, Volume 2: Implementation Guidelines*, Report, TCRP (Transit Cooperative Research Program), TRB (Transportation Research Board), Washington, D.C., USA.
- Mishra, K. R., Parida, M., & Rangnecar, S. (2010). Evaluation and analysis of traffic noise along bus rapid transit corridor. *International Journal of Environmental Science and Technology*, 7(4), 737–750.
- Nelson, T. (2005). *787 Systems and Performance*, Flight operations engineering. Boeing Commercial Airplanes, Seattle, USA.
- Persson, R. (2007). *Tilting trains: Description and analysis of the present situation, Literature study ISBN 978-91-7178-608-1*. Stockholm: Royal Institute of Technology.
- Poisson, F., Gautier, P.E., Letourneaux, F. (2008). Noise sources for high speed trains: A review of results in the TGV case. In B. Schulte-Werning et al. (Eds.), *Noise and vibration mitigation*. NFM 99, springerlink.com, Springer, Heidelberg, Germany, pp. 71–77.
- Puchalsky, C. M. (2005). Comparison of emissions from light rail transit and bus rapid transit. *Transportation Research Record 1927: Public Transportation*, pp. 31–37.
- RITA. (2012). *Safety and security time series data (2002–2011)*. Research and Innovative Technology Administration, U.S. Department of Transportation, National Transit Database Washington, D.C., USA.
- Ross, C. J., Staiano, A. M. (2007). A comparison of green and conventional diesel bus noise levels. Paper presented at *Noise-CON Conference*, Reno, Nevada, USA, p. 8.
- RR. (2011). *TRENT100 Factsheet: Optimized for B787 Dreamliner Family*. Rolls Royce, COM13797, Issue 9, November 2011, London, England.
- RTR. (2005). High speed and network extension. *Rail technical review*, No. 2. pp. 11–18.
- Saavedra, S. N. (2011). *The evolution of transportation planning in bogota, Report*. Traffic and Transport Research Program, Universidad Nacional de Colombia, Bogota, Columbia.

- Smith, J. T. M. (2004). *Aircraft noise*. Cambridge: Cambridge University Press.
- STSI. (2008). *Light rail vehicles*. Siemens Transportation Systems Inc., Rolling Stock Division, Sacramento, California, USA.
- Tegner, G. (2003). Comparison of costs between Bus, PRT, LRT, and Metro/Rail. In EC project *European Demonstration of Innovative City Transport (EDICT)*. European Commission 5th Framework Program, DG VII, Brussels, Belgium.
- TRB. (2008). *Airport ground access system mode choice models: A synthesis of airport practice*. ACRP Synthesis 5. Washington, D.C., USA: TRB.
- Vincent, W., Jerram, C. L. (2006). The potential for bus rapid transit to reduce related CO₂ emissions. *Journal of Public Transportation*, Special Edition, pp. 219–237.
- VTI. (2004). *Transit bus emissions study: Comparison of emissions from diesel and natural gas buses*. Research Report, Technical Research Center of Finland, Tampere, Finland.
- Vuchic, R. V. (2007). *Urban public transportation systems and technology*. New York: Wiley.
- Wright, L. (2003). *Bus rapid transit-mode 3b*, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Germany: Eschbom.
- Wright, L., & Hook, W. (2007). *Bus rapid transit planning guide* (3rd ed.). New York: Institute for Transportation & Development Policy.

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