CENTRE FOR INFRASTRUCTURE RESEARCH, UNIVERSITY OF AUCKLAND, UNIVERSITY COLLEGE LONDON, VOLTERRA PARTNERS LLP and SYNERGINE

Emerging Technologies for Rapid Transit: Part One
Future-proofing Investment Decisions

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Dr Jim Bentley
Director, Centre for Infrastructure Research
University of Auckland

Professor Brian S. Collins
University College London
Director, Europium Consulting

Paul Buchanan
Partner, Volterra Partners LLP

Professor Nick Tyler
University College London

Jenny McArthur
Consultant, Synergine Group
PhD candidate, University College London

Quality Assurance Statement	
Department of Civil and Environmental Engineering The University of Auckland Private Bag 92019 Auckland 1142 New Zealand	**Project Manager:** Dr Jim Bentley, University of Auckland
	Prepared by: Dr Jim Bentley, University of Auckland Paul Buchanan, Volterra Partners LLP Professor Brian S. Collins, University College London Professor Nick Tyler, University College London Jenny McArthur, Synergine / University College London
	Approved for issue by: Dr Jim Bentley …………………………….

Executive Summary

As new technologies emerge, it is crucial to future-proof investment decisions for urban transit. There is a risk that current investment decisions 'lock in' technologies that may be superseded in coming decades. This report evaluates a technology review produced by Auckland Transport's Technical Advisor, and draws together academic and empirical literature on bus rapid transit (BRT) and light rail transit (LRT) systems, to inform investment decisions. The technology review summarises current and emerging technologies for various dimensions of rapid transit, including vehicle design, power sources and transmission, and control systems. New technologies are improving the vehicle capacity and ride quality for BRT vehicles, speed and accessibility of LRT vehicles. It is anticipated that electric or hybrid vehicles will become standard for BRT in the medium term, reducing air pollution and CO_2 emissions from transit services. The review highlights that there is an apparent convergence in certain dimensions of transit modes, such as ride quality, peak line capacity and energy sources, but concludes that there remain fundamental differences in the nature of transit services provided. Despite some convergence, the advantage offered by LRT in terms of development impacts, operating cost efficiency, peak line capacity and speed are significant. Table 1, overleaf, summarises the relative costs, capacity and performance of different transit technologies. Terminal capacity is a key constraint, and while it depends on the specific design of terminal stations, vehicle size is an important determinant. The maximum capacity of LRT vehicles is significantly higher than that for BRT. Figure 1 shows the trade-offs between spatial requirements, line capacity and flexibility for different options. The apparent advantages of BRT in providing high-capacity, flexible services are traded off against higher spatial requirements. Flexible routes are only available if the BRT system does not have fixed platform infrastructure, reducing potential capacity.

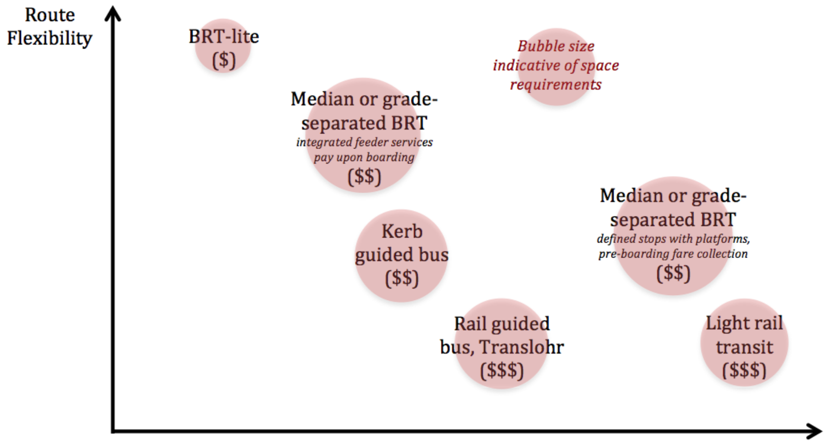

Figure 1 - Trade-offs between flexibility and capacity

The Technology Review does not focus specifically on the system properties of transit. However, to future-proof investment decisions, it is useful to consider the transit network not as an isolated entity but in the context of its wider environment. Transit provision affects local development patterns and travel behaviour. Proximate areas are often redeveloped to higher density commercial and residential uses, and induced shift from other modes to the improved transit service. Despite convergence in some functional dimensions, including peak line capacity and ride quality, the type of accessibility provided by BRT and LRT remain distinct from one another. BRT can meet travel demand across a wide variety of paths. LRT systems are less flexible, however they offer higher capacity once land use impacts are realised and demand paths consolidated to the transit corridor. LRT tends to induce a higher mode shift from private automobile than bus or BRT modes, which should be considered if Auckland's investment priorities include modal shift alongside increasing transit capacity and level of service.

To future-proof investment decisions, a narrow view that focuses only on technological and financial characteristics, omits induced demand and long-term development impacts and may overlook more significant long term planning issues. As case studies in Ottawa, Adelaide, and Brisbane show, the "best case" scenarios for BRT investment often result in subsequent upgrades to LRT or tunneling to separate BRT systems from surface traffic, because BRT technologies do not yet provide equivalent spatial efficiency, terminal capacity, and service quality of LRT.

Table 1: Comparison of transit technologies, adapted from Vuchic et al. (2013), Nelson and Ganning (2015) unless cited otherwise

Mode	Bus	Bus Rapid Transit	Guided Bus Transit	Light Rail Transit
	Mixed traffic	*Median or grade separated*	*Kerb or rail guided*	*Median or grade separated*
Spatial requirements	Low	High	Medium	Medium
Aesthetic amenity	Low	Medium	High	High
Peak line capacity (ppdph)[1]	5,000	7,200-20,000	7,200	12,200-27,000
Vehicle capacity (maximum)	100 (double decker)	230 (Phileas)	255 (Translohr)	420-600 (60-98m vehicle)
Average operating speed[2] (including stops)	15-20km/hr	25-48km/hr	25-35km/hr	25-55km/hr
Capital investment ($NZ/km)	Low	$29-78m/km[3]	$37-42m/km (kerb-guided)[4] $61m/km Translohr[5]	$31-120/km[6]
Operating costs	Efficient below 1,500 ppdph	Efficient between 1,500-2,800 ppdph		Efficient above 2,800 ppdph
Land development impacts	Low	Residential value increase 2.2-10% Commercial value increase 25%		Residential value increase 6.5-17% Commercial value increase 72-120%

[1] Hubbell (2009); Zhang (2008). Figures given as passengers per direction, per hour (ppdph)

[2] Range of BRT operating speeds: *Brisbane South East Busway – 55km/hr, Sydney T-Way – 29km/hr, Ottawa Transitway – 45km/hr, Pittsburgh MLK East Busway – 48.3km/hr, Los Angeles Orange Line – 32km/hr, Bogotà TransMilenio – 26.2km/hr, Curitiba Linha Verde – 25km/hr. Source: brtdata.org*

Range of GLT operating speeds: *Adelaide O-Bahn – 25km/hr (brtdata.org), Paris T5 Translohr – 25km/hr (ratp.fr)*

Range of LRT operating speeds: *Los Angeles Gold Line – 35km/hr (metro.net), Croyden TramLink – 25km/hr (croyden-tramlink.co.uk), Denver Light Rail – 55km/hr (rtd-denver.com)*

[3] Range of BRT capital costs: *Parramatta Transitway - $29m/km, Brisbane Southeast Busway - $78m/km*

[4] Based on Adelaide O-Bahn and Cambridge Busway

[5] Based on Paris T6 Translohr

[6] Range of LRT capital costs: Sacramento LRT - $31m/km, Bordeaux LRT - $120m/km

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1. Scope of report

The emergence of new technologies for light rail transit (LRT) and bus rapid transit (BRT) is changing the performance and functional characteristics of these transport modes, bringing into question the optimal investment decisions to avoid technological lock-in and future-proof the transport network. The Rapid Transit Technology Review produced by Auckland Transport's Technical Advisor is reviewed, alongside evaluation of international case studies for urban rapid transit and the input of experts in both BRT and LRT modes.

Future-proofing considerations are informed by empirical data on the technical attributes, costs, nature and level of service for different transit technologies. The evolution of transit systems in various cities across Europe, North and South America is also evaluated to understand how different modes have been implemented over longer time scales. The conclusions explain the degree to which transit technologies are converging, and how, to inform investment decisions.

2. High capacity rapid transit: Light rail and bus rapid transit

Light rail transit (LRT) and bus rapid transit (BRT) provide shared transport services on partially or fully segregated paths, with priority or full right-of-way at intersections. LRT can operate as single vehicles or trains, allowing passengers to alight at track or car-floor level. The smaller scale of light rail vehicles enables transit services to access high-density urban areas without necessarily requiring subsurface infrastructure. This plays an important role to connect the inner city with outlying districts (De Bruijn and Veeneman, 2009). Figure 2 illustrates the growth in LRT schemes in recent decades.

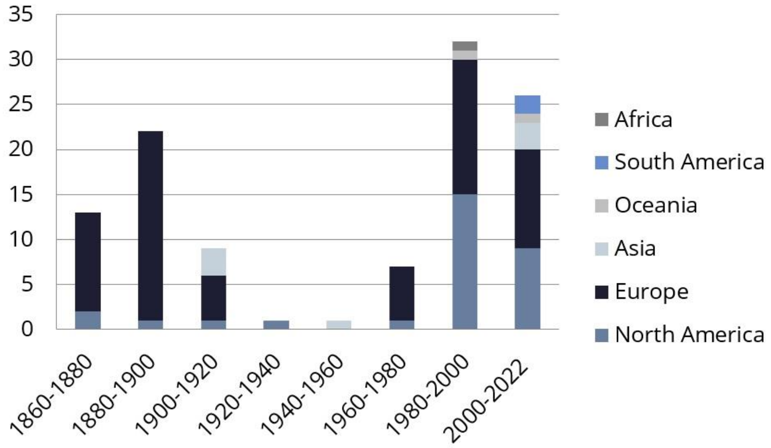


Figure 2: Growth in LRT schemes, by continent (Volterra, 2015)

BRT systems emerged in the 1970s, at which point many cities had developed comprehensive roading infrastructure and bus services were common. By providing separated lanes and partial or full right-of-way for buses, BRT leveraged the capacity of bus transit, and improved travel times. Many cities opted to build BRT systems in favour of rail, as the capital and operating costs were lower, and the use of buses offered more flexibility for service routes. The different options for BRT range from "BRT-lite", which provides partial prioritisation of road space and signal priority for bus transit, to comprehensive systems with median or grade-separated corridors, accessible vehicles and pre-boarding fare collection. Other variations on BRT include rail, kerb, or optically-guided bus systems. Across the range of BRT options, trade-offs emerge between system and/or line capacity and flexibility. For example, rail-guided buses such as the Alstom Translohr provide high line capacity on narrower corridors, but operate on fixed routes and cost similar to an equivalent LRT system. Consideration of investment options must clarify what is meant by “BRT”, to make a meaningful comparison with LRT and other technologies. Table 2 provides a summary of variations of bus rapid transit.

Table 2: Full Service BRT and "BRT-lite" systems, adapted from Cervero (2013)

	Full Service BRT	“BRT-Lite”
Running ways	Exclusive transit-ways; dedicated bus lanes; some grade separation;	Mixed traffic; modest intersection treatments
Stations/stops	Enhance shelters to large temperature-controlled transit centres	Stops, sometimes with shelter, seating, lighting and passenger information
Service design	Frequent services; integrated local and express services; timed transfers	More traditional service designs
Fare collection	Off-vehicle collection; smart cards; multi-door loading	Fares paid upon boarding
Technology	Automated Vehicle Location; traffic signal preferences; vehicle docking/guidance systems	More limited technological applications

In some cases, BRT systems operate on fixed tracks (such as the Cambridge Busway and Adelaide O-Bahn). “Rubber-tired trams” have also been developed, such as the proprietary Translohr model, by Alstom, which operates on a fixed guiderail. Successful BRT systems are in operation in cities such as Bogotá (Figure 3) and Curitiba in South America, Paris (Figure 4), Brisbane and Adelaide (Figure 5) in Australia. Despite the lower financial cost of BRT, LRT remains a common choice for cities such as Newcastle (Figure 6), Canberra, and metropolitan areas in the US including Los Angeles and Houston. Section 5 explores the drivers of transit investment decisions in further detail.

To improve transit travel times, an exclusive right-of-way offers the best level of service for both LRT and BRT systems. Both modes can operate along the median of existing corridors (illustrated by the Bogotá system, Figure 3), or on completely different routes (illustrated by the Adelaide O-Bahn, Figure 5). Grade separation to avoid conflicts at intersections can be costly for both modes, but is an important factor for travel time savings. Where separation requires the construction of bridges or tunnels, guided bus or LRT systems can operate on narrow corridors, which may reduce capital costs.

Figure 3: BRT - Bogotà TransMilenio

Figure 4: BRT - Paris T5 Translohr

Figure 5: BRT - Adelaide O-Bahn

Figure 6: LRT - Newcastle Light Rail (planned)

3. Technical, financial, and systems dimensions of rapid transit

The technical and financial aspects of transit systems are explained in this section, focusing on the nature and level of service, safety and environmental performance, operating and capital costs.

The fundamental nature of transit services provided by BRT and LRT systems differs; BRT offers a high level of system capacity where there is demand for travel over a variety of different paths, whereas LRT provides superior performance for travel demand that is consolidated to a smaller number of routes. As explained further in Section 3.5, LRT tends to induce development patterns that consolidate travel demand along a fixed route.

Investment decisions should carefully consider the desired outcome and associated benefits – whether Auckland aims to develop a system that delivers access to different areas of the city, or a linear transit route linking activities at multiple locations. The long term impacts of investment, and the role of transit investment in supporting growth is also significant.

3.1 Capacity

The capacity of a transit system can be considered in several dimensions:

- Network capacity - accounting for whole journeys made by passengers, the potential for a transit network to provide trips across a number of different routes
- Peak line capacity - the number of passengers passing through a single point on the network at peak hour
- Terminal capacity - the capacity of facilities allowing passengers to alight from transit services

BRT offers superior network capacity where demand is characterised by a variety of different demand paths; and the ability of vehicles to act independently of each other implies that such differences can be continued for longer, with fewer interchanges required. LRT can provide superior capacity once demand paths have been consolidated, but less flexibility if a large variety of paths are required. Adequate feeder services are key to the success of fixed-line services such as LRT, and will become more important to BRT as network design tends towards exclusive rights-of-way and trunk route services. In light of the differing nature of transport services provided by different modes, investment decisions should be guided by a clear goal for the short and long-term performance of the system, and desired impacts on land development patterns.

Terminal capacity can be a significant issue for transit systems feeding to high-density city centres, and networks may be designed to pass through congested areas to avoid a layover in the city centre. Many cities construct underground stations or tunnels to allow transit routes to pass through without conflicting with public spaces, pedestrian movement and other inner-city traffic. A number of successful BRT systems have eventually opted to construct tunnels to enable access to the city centre, include the O-Bahn Busway in Adelaide, Brisbane Busway, and the Metropolitano in Lima. Light rail transit may also be tunnelled in high-density areas, although aesthetic impacts on the immediate surroundings are often less intrusive than those for bus services.

Table 3 summarises the theoretical line capacity for different transit options. While both LRT and BRT systems can operate on exclusive rights-of-way, the potential capacity of BRT varies widely depending on whether BRT systems have double lanes to allow passing at stations, and the number of stops along a route. The capacity of guided systems is similar to that of articulated buses. Since a fixed kerb or rail guideway eliminates the potential for buses to overtake, these options may be limited to single-lane operation. The peak line capacity of BRT can surpass that of light rail, as illustrated by examples from Bogotá and Brisbane, however the spatial requirements are larger to allow double-lanes at bus stops or stations so vehicles can pass one another. The line capacities reached by the Bogotá TransMilenio are very high, and require a level of overcrowding that is likely to be unacceptable for the Auckland context. The typical line capacity of a single-lane bus operation is up to 7,200 passengers/direction/hour, based on an average of one bus per minute, carrying 120 people. The capacity of transit stations, either rail stations or bus stops, is an important factor for line capacity. Specific design considerations around platform size, vehicle capacity, and provision of pre-boarding fare collection infrastructure are key to determine the potential number of passengers that can board or alight from vehicles at peak times.

Exceeding 7,200 passengers/direction/hour on BRT depends on provisions for passing lanes at bus stops, frequencies of buses, and dwell time (dependent on provision for pre-boarding fare collection, bus accessibility for disabled passengers). Specific routes in Auckland, such as Symonds Street, already experience high peak-hour bus volumes of up to 140 buses per hour in mixed traffic. To meet growing demand to access the city centre, given the limited space available in transit corridors, BRT has lower potential than LRT to expand the volume beyond the single-lane capacity of approximately 7,200 passengers/direction/hour.

Table 3: Maximum line capacities of transit notes (Zhang, 2008)

Mode	Vehicle dimensions	Vehicle capacity	Minimum headway	Maximum frequency	Line capacity
	(metres)	*(passengers)*	*(seconds)*	*(vehicles/hour)*	*(passengers/hour/ direction)*
Standard bus	12 x 2.5	75	70-50	51-72	3,800-5,400
Articulated bus	18 x 2.5	120	80-60	45-60	5,400-7,200
High-capacity bus (BRT)	22 x 2.5	160	30-12	120-300	9,000-30,000
LRT (right of way, partially separated)	24 x 2.7	510-560	150-75	24-48	12,200-26,900

3.2 Flexibility

The flexibility of transit services creates both advantages and disadvantages. Flexible routes allow the transport service provided to adapt to demand as a city grows, with potential for phased upgrades in service frequency and coverage. However, the induced impacts on land development (discussed further in Section 3.5) require that property developers have credible long-term assurance that transit routes will remain in place, to lock in the value of proximate property developments.

BRT systems that operate on flexible routes may also face some trade-offs against efficiency; for example, to allow pre-board fare collection and multiple-door boarding, additional investment is required for bus stops and platforms equipped for fare collection, guided docking systems, and segregated access to buses (ITDP, 2007). These additional infrastructural elements require routes to be fixed in place, limiting flexibility of the network.

3.3 Systems approach

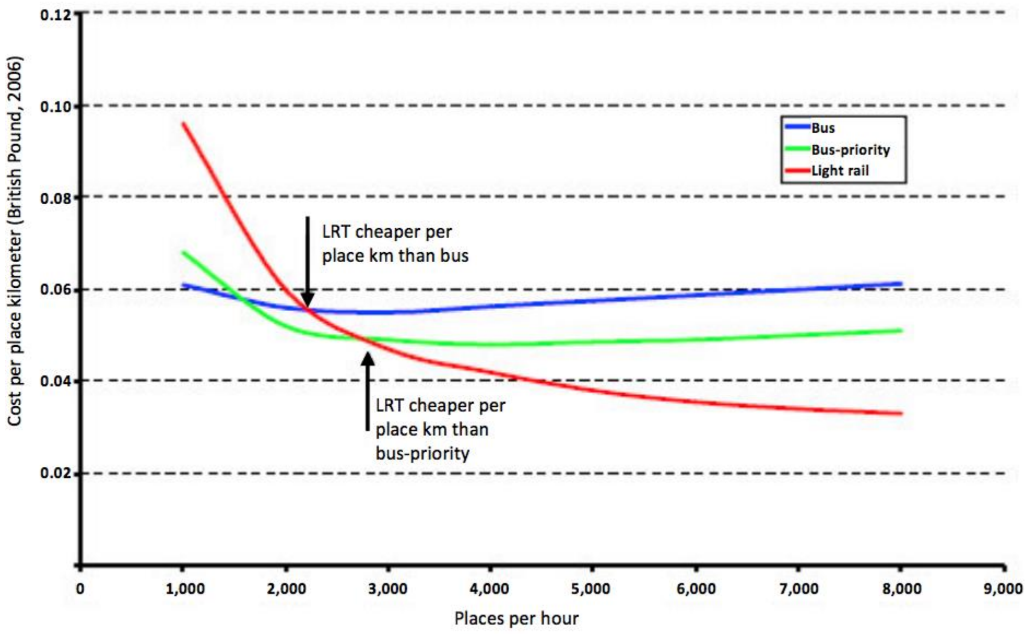
A systems approach considers urban transit as a socio-technical system, where technical capacity, cost, service quality and passenger behaviour are interdependent and interact to determine the broader social and economic value of an investment. While the value can be difficult to quantify in monetary terms, it is reflected in tangible ways through the impact on surrounding land values and patronage levels. Non-technical factors influencing travel demand and patronage should be considered, including the impact of station design on boarding and alighting behaviour, aesthetic quality and comfort, particularly to protect passengers from weather.

There are two dynamics of transit systems which are relevant to future-proofing investment and long term planning. Firstly, transit induces changes in land development and often creates clusters of higher-density development around transit stations and along corridors. This capitalises the accessibility benefits generated, and is important to the long-term viability of the transit system. Secondly, where transit investment improves the quality of services, and level of accessibility across a city, travel demand is induced as riders shift from other modes, or make trips that previously would not have occurred due to the cost or effort of travel. From a planning perspective, transit provision should not discount the potential demand increases induced from additional investment, and anticipate how capacity constraints will be managed in the long term.

Design often aims to make the whole-of-life investment costs as low as possible, while optimising value created. Costs include not only the fixed infrastructure and vehicles, but ongoing operating costs of fuel, staff, and maintenance. Lock-in to specific technologies may be a higher risk for LRT systems, due to inflexible installation methods, however this is balanced by potential risk of on-road BRT systems being affected by other traffic and changes to the road network. Additionally, the likelihood of effective BRT systems inducing high ridership and eventually requiring upgrade to LRT (or BRT tunnels, to separate traffic flow from high-density urban centres) should be carefully considered.

3.4 Operating and capital costs

Operating expenditure for BRT and LRT systems varies with travel demand. Since bus services have a proportionally higher labour cost than rail, BRT tends to be more cost-effective at lower levels of patronage, while LRT becomes more efficient with high patronage levels. Bruun (2005) compared the operating costs of LRT and BRT, based on data and cost structures from the Dallas DART network. For peak services, BRT was 24% more expensive than LRT, while for trunk line capacities below 1,600 passengers per hour, per direction, BRT was more efficient. Figure 7 illustrates the cost curves of bus and rail transit modes, using data from Transport for London. A higher capacity of 2,800 was identified as the capacity where operating costs are lower for light rail over bus or bus rapid transit systems. Adjusting for inflation and exchange rates, the break even operating cost equates to approximately NZ$0.14/place-km at 2,800 passengers per direction, per hour.



Source: TfL

Figure 7: Operating expenditure for bus and rail transit, adapted from Luke (2006)

Figures 8 and 9 show the actual peak volume (often less than the theoretical capacity) and capital cost ($NZ) for a range of BRT and LRT systems.

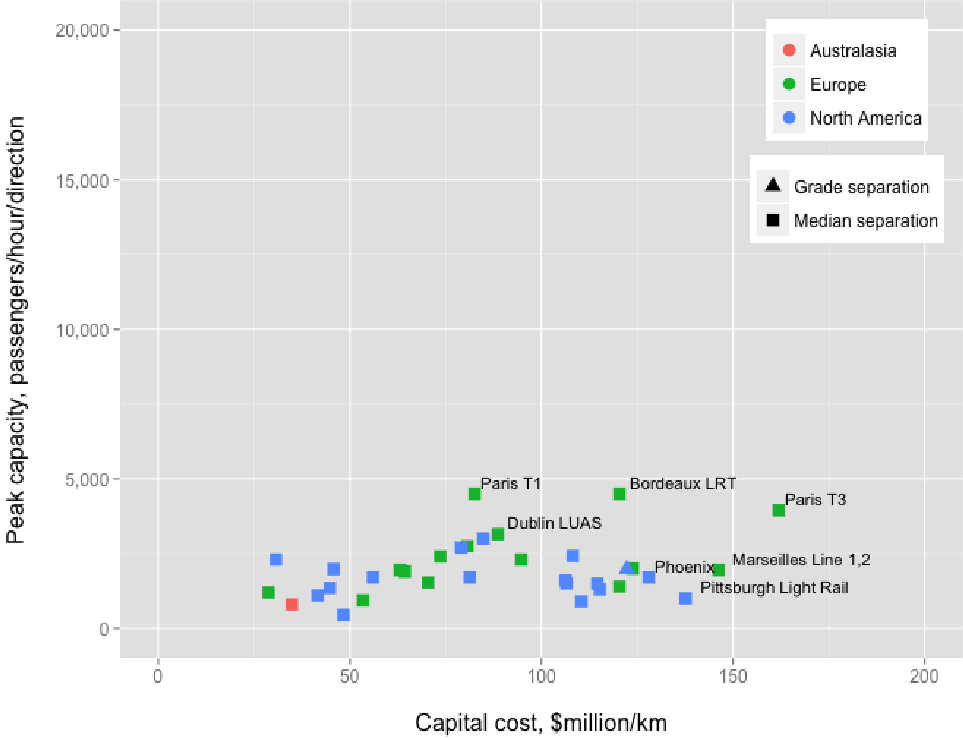


Figure 8: LRT systems, data from Clark (2011)

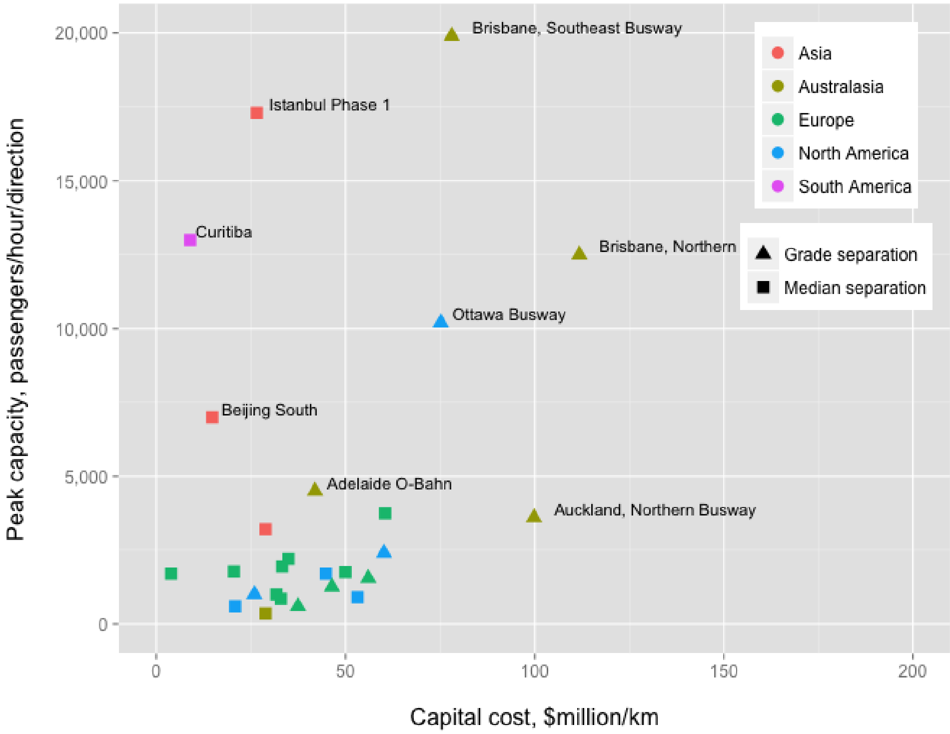


Figure 9: BRT systems, data from Clark (2011)

The variation across transit systems, in terms of the peak capacity, level of capital investment, spatial requirements and level of service is substantial. Between LRT and BRT there is significant overlap in the capital costs and line capacity provided. As explained further in Section 3.7, a high quality of transit service is necessary to induce mode shift away from private automobiles, and so the cost of providing an effective service in the New Zealand context may require higher capital investment than the examples provided in Istanbul, Curitiba and Beijing.

Evaluation of the planning and evolution of the transit systems in international case studies show a tendency for cities with successful BRT systems to upgrade to LRT to increase the peak hour or terminal capacity, as in Ottawa, supplement the BRT system with light rail to ease overcrowding, as in Bogotá, or construct tunnels in the central city section of the transit network so that BRT traffic does not impact negatively on the urban environment, as in Brisbane and Adelaide. Tunneling substantially increases the construction cost of transit systems, potentially counteracting the apparent cost savings of BRT over LRT.

3.5 Development impacts

Long-term development impacts of transit investment are important to ensure that transit investment can lock in accessibility benefits through land development and intensification.

Traditionally, rail services were perceived as producing greater impacts on land development due to the fixed nature of rail infrastructure, improved service quality, and less significant aesthetic impacts on the surrounding environment. Stokenberga (2014) reviewed empirical studies of BRT systems and found that evidence for development impacts was uneven and difficult to quantify. Some BRT systems had a negative impact on surrounding property values, due to poor service or station quality, and inadequate feeder services. Robust evidence for a positive impact could not be identified across the existing systems. Currie (2011) analysed the drivers of BRT ridership across Australia and found little evidence that land development impacts were significant.

Table 4 summarises existing evidence for the impact of transit investment on land values. LRT shows a moderate premium of 6.5-17% for residential land, and 72-120% value uplift for commercial land at close proximity. The benefits of BRT are inconsistent and where there is a premium, it varies from 2.2-10.0% for residential land, and up to 25% for commercial land. The emergence of BRT technologies that use similar vehicles to LRT, such as the Paris T5 Translohr (Figure 4) or Adelaide Guided Busway (Figure 5) substantially reduce the space requirements and provide a better quality urban environment. However the improved amenity benefits come at greater capital cost, and lower peak capacity. Fixed-guideway systems, including Translohr and Phileas, do not allow over-taking and so the capacity is limited to that of a single-lane system.

Table 4: Summary of transit impact on land values and development

Light rail		
Location	Land use	Development impacts
Portland, USA	Residential	6.5-10.6% increase in land values (Al-Mosaind et al., 1993; Chen et al., 1997; Dueker and Bianco, 1999)
Santa Clara County, USA	Commercial	120% premium for land within 400m of a rail station (Cervero and Duncan, 2002)
San Diego, USA	All	17% premium for residential properties, 72-91% premium for commercial properties
Bus Rapid Transit		
Location	Land use	Development impacts
Bogotá, Colombia	Residential	Value premium for middle-income households, average 2.2-2.9% (Munoz-Raskin, 2010). Rental prices decrease 7-9% with each additional five minutes walking distance from stations (Rodriguez and Targa, 2004)
Los Angeles, USA	All	Uneven, positive and negative impacts on residential land values. Negative impact on commercial land values (Cervero, 2002)
Seoul, South Korea	All	Residential premiums up to 10% for properties within 300m of BRT stops, 25% for retail and non-residential uses within 150m (Cervero and Kang, 2011).

3.6 Safety, reliability and environmental performance

The safety of LRT and BRT systems is largely dependent on the network layout. While most issues emerge from the design and geometry of traffic corridors, rather than the specific technology (Goh et al., 2013), differences between bus and rail transit emerge with regard to braking rates and the management of conflict points along the transit corridor (Vuchic, 2007). Buses tend to have a higher braking rate, which reduces the risk of collision with pedestrians, however corollary to this is an increased risk to bus passengers from sudden stops. For the TransMilenio BRT system in Bogotá, sudden braking is responsible for as many injuries as pedestrian collisions, although the severity of injury tends to be lower for bus passengers (Duduta et al., 2015). Management of conflict points also differs between modes. Light rail uses signaling systems, while BRT relies on driver training to manage hazards and avoid collisions. Conflict points emerge for BRT systems at overtaking lanes, where local buses need to enter into the flow of express buses. Collisions have a high risk of serious injury, particularly where express buses operate at high speed. Investigation of the impacts of BRT on serious incidents found that the overall reduction was substantial (60% on Caracas corridor and 48% reduction on Norte-Quito-Sur, relative to a city-wide average reduction of 39%), and closely linked to the induced mode shift from private vehicles or para-transit to BRT. However, there was a notable increase in accidents for specific areas, linked to conflict zones between BRT stations, mixed traffic and pedestrian flows (Vecino-Ortiz and Hyder, 2015).

LRT or BRT on grade-separated schemes tend to be safest as the transit vehicles have right of way and no potential conflict with other traffic (Federal Transit Administration, 2004; Rogers, 2002). Increased separation from traffic enables more reliable operation of transit services (Xu and Zheng, 2012), although fixed systems have a higher potential for delay, as vehicles cannot pass one another. Impacts on air quality and reduced carbon emissions are significant for both LRT and BRT technologies, and closely linked to the induced mode shift away from private automobiles (Federal Transit Administration, 2004; Echeverry et al., 2004; Vincent et al., 2012). Emerging technologies for power systems enable the use of diesel hybrid or fully electric buses, reducing emissions and noise pollution in urban environments. Wireless energy systems, such as that planned for the Canberra Metro Gungahlin tram line, can capture and store kinetic energy from braking in roof-mounted super-capacitors (CAF, 2016).

3.7 User experience and perceptions

Attracting ridership is crucial to the long-term sustainability of transit systems and the realisation of environmental, safety, and broader land development impacts. The qualitative aspects, including the aesthetics, comfort, and user perceptions of transit services are important to induce mode shift, particularly from private vehicles to transit (Deng and Nelson, 2010; Rabinovitch and Hoehn, 1995). These dimensions depend on the choice of technologies, design of transit infrastructure (including stops, stations and complementary “place-making” investments), and management of the system. The mode choice of commuters is not entirely rational, and while travel time and cost are important, they cannot entirely explain the preferences of transit users. Aesthetics, comfort, and the potential productivity of travel time are also important (De Witte et al., 2013). Empirical research, based on both survey data and the actual preferences, suggests that, focusing solely on quantifiable service characteristics such as travel time and cost, there is no emergent passenger preference expressed between BRT and LRT, however when qualitative aspects are accounted for, there is a bias toward rail (Cain and Flynn, 2009; Ben-Akiva and Morikawa, 2002; Axhausen et al., 2001).

Cain and Flynn (2009) characterised riders into four groups: auto-captive, transit-captive, auto-choice and transit-choice. Captive riders, who have no alternative to public transit, will not change their behaviour unless the transit investment provides new services to formerly under-served areas. Investigation found that choice riders, who had the option to either drive or commute by transit, placed a higher value on service quality and comfort to incentivize modal shift. Complementary policies with regard to parking and road tolling also play a strong role in inducing a shift to transit (Kuby et al., 2004; Al-Dubikhi and Mees, 2010).

With the convergence of technologies and BRT systems such as Translohr (rail guided electric battery bus) and optical guided bus, the improved service quality could narrow the differential between BRT and LRT systems. However this comes at additional capital cost, eroding the cost advantage of BRT, and the capacity is limited as vehicles are on fixed guideways and cannot overtake.

4. Review of recent transit investments

Table 5 summarises the transit investments of different cities over the past decade, and the justification for selection of bus or rail transit systems. Those selecting BRT typically cite the lower capital costs, and often do not anticipate patronage to reach levels sufficient to justify LRT.

Table 5: Transit investments and justification for mode choice

City	Rationale
Ottawa, Canada Population: 1,318,000 Mode: LRT Open: 2018	Improved passenger capacity, reliability and speed. Reduced operating costs, air quality impacts. Preserve downtown urban environment, induce development around transit stations (MKI, 2010; Croft, 2011)
Victoria, Canada Population: 345,000 Mode: LRT Open: tbc	Maximising passenger capacity in the long term, improved development impacts (SNC-Lavalin, 2011).
Canberra, Australia Population: 380,000 Mode: LRT Open: 2019	Broader land development outcomes, for the improved amenity of Canberra's city centre and Northbourne Avenue transit corridor (Capital Metro, 2012).
Newcastle, Australia Population: 426,000 Mode: LRT Open: 2017	Contain population growth along transport corridor and retain the city centre's amenity, maximise land use benefits (McKibbin, 2015).
Eugene-Springfield, USA Population: 352,000 Mode: BRT Open: 2007	Lower cost, perceived to have similar service and reliability to rail systems (TCRP, 2002).
Nantes, France Population: 288,000 Mode: BRT Open: 2006	Transit demand not sufficient to justify light rail, lower capital cost option (Conles et al., 2014).
Belfast, Northern Ireland Population: 579,000 Mode: BRT Open: 2017	BRT optimal investment according to cost bene.t analysis, recommended that corridor allows for future LRT upgrade (Northern Ireland Assembly, 2008).
Edinburgh, Scotland Population: 492,000 Mode: LRT Open: 2014	Improved speed, quality, and capacity, Higher modal shift from private cars (City of Edinburgh Council, 2006)

The recent increase in light rail investment has accompanied concerns for the quality of the urban environment and higher demand for rapid transit as cities shift away from automobile dependent transport. Viewing transit as an investment that creates benefits for the broader urban environment, inducing positive development impacts and efficient patterns of residential and commercial development, explains the persistent advantage of LRT.

As illustrated by the city of Nantes, transit investment need not take an either/or approach to bus and rail services, and it is possible to integrate across modes. However, the potential “transfer penalty”, (Cheng and Tseng, 2016; Iseki and Taylor, 2009) may have a significant impact on modal shift. Cities choosing to invest in LRT justified investment based on the need for higher peak-hour capacities, positive impacts on land development, and providing a high-amenity urban environment. In some cases, such as Ottawa, the existing BRT system had already reached capacity and the negative impact of large numbers of buses on the amenity of the central city was substantial. Figure 10, below, shows the current BRT and planned LRT stations in Ottawa. The improved amenity and aesthetic quality of LRT stations are anticipated to induce land development around the station.

Figure 10: Lees Transitway Station - Current station (left) and proposed upgrade (right)

Cities such as Newcastle, Australia, propose LRT as a means to induce land development and contain future growth within the city centre, preserving the quality of the built environment while allowing intensification and growth.

5. Review of Technical Advisor's Report

The review of rapid transit technologies provided by Auckland Transport's Technical Advisor summarises current and emerging technologies to inform future proofing. Technologies reviewed include guided buses, LRT bogie designs, alternative power sources and supply, and control systems. In addition, consideration of ITS technologies may provide further differentiation between BRT and LRT with regard to the quality of service that might be obtained, in terms of resilience and potential productivity of travel time for passengers.

5.1 Current RTN modes

Bus rapid transit modes comprise a broad subset of transit, ranging from what is commonly termed "BRT-lite", with prioritisation of road space for bus services and predetermined stops, to more permanent systems with exclusive right-of-way, high capacity buses, fare collection prior to boarding and platform-like stops at fixed locations. Distinguishing between different forms of BRT is important, since the technical performance of systems can vary according to the exact specifications for the system. Empirical survey of surface BRT systems without exclusive right-of-way at intersections found an average operating speed of around 20km/hour (Hensher and Golob, 2008), highlighting that exclusive lanes of grade separation are essential to achieve travel time improvements for BRT transit. Variation in LRT systems is also emphasised, ranging from on-street tram networks to routes along separated corridors, entirely independent of the street network and conflicts with other traffic. LRT is differentiated from heavy rail or metro rail transit according to the use of low-axle load passenger vehicles operating on rails. Technology development for LRT is primarily focused on increasing capacity, increasing the number of doors, vehicle length, speed, and modularity of designs.

The figures provided for transit vehicle capacity do not reflect the full range across existing BRT and LRT systems. Bus capacity is cited as 150 for articulated buses, 105 for Phileas advanced buses, and 200 for the Translohr guided bus, however in Curitiba, 24m bi-articulated buses can carry up to 270 passengers at crunch load, Istanbul's ATC Phileas buses can carry up to 230 passengers (Cervero, 2013), and a 46m Translohr vehicle can carry up to 255 passengers (NTL, 2016). These passenger loads show that BRT can operate very efficiently, however it is also common to experience over-crowding of vehicles (Federal Transit Administration, 2006), which may cause some passengers to shift back to private transport (Cervero, 2013). Estimated capacities for LRT vehicles appear to be similarly under-estimated, with trams and light rail vehicles ranging from 140-420 passengers for vehicles from 24-60m in length. The anticipated capacity of two-car trains (Alstom Citadis) operating on the Ottawa Confederation Line is 600 passengers for each 98m train (Rideau Transit Group, 2013).

System capacity is measured in terms of passengers per direction per hour (ppdph). BRT capacity is estimated at 18,000 ppdph for a grade-separated system with 24m articulated buses, however the Bogotá TransMilenio can support up to 45,000 ppdph, albeit in overcrowded conditions that have shown to reduce service quality. Light rail systems have also exceeded the maximum quoted figures in the review. Light rail is referenced as carrying 13,500 ppdph; however the Vancouver Expo Line in Canada has a design capacity of 25,000 ppdph (Translink, 2010). As discussed in Section 3.1, there are multiple dimensions to the capacity of a transit system. While line capacity is important for potential bottlenecks or high-volume sections of a transit network, it does not adequately describe how a system meets travel demand across a city, where demand exists over a variety of routes. In terms of emerging technologies, transit's potential to provide accessibility is affected not only by higher vehicle capacity, but the appropriate use of feeder services to fixed trunk routes. BRT systems without fixed guiderails or pre-boarding fare collection may provide a high level of accessibility, with fewer interchanges where bus services can link directly from feeder routes to separated busways.

5.2 Emerging technologies

5.2.1 Vehicle technology

Established vehicle technologies were reviewed, including the O-Bahn Kerb Guided Bus, alongside newer proprietary models such as the Bombardier GLT (Rail Guided Electric Bus), Phileas (Magnetic Guided Electric Battery Bus), Alstom Translohr (Rail Guided Electric Battery Bus), and Siemens Optiguide (Optical Guided Bus).

The key advantage of a guided bus system, over manual operation, is that it enables buses to operate in narrower corridors, with docking and level boarding at stops. Guided buses may offer a smoother ride quality than manually operated buses.

Current and emerging technologies for guided buses offer distinct advantages and limitations. Optical guided buses, including the reviewed Siemens Optiguide, use an optical system which guides the vehicles path using road markings, at speeds up to 40km/hr. Since this requires full visibility of road markings, which may be obscured by snow, heavy rain, fog, dust or leaves, optical guidance is typically restricted to docking only (COWI, 2014). Otherwise, the system may require substantial maintenance costs to keep the roadway clear of obstructions, or face reliability issues during severe weather. The Siemens Optiguide has been implemented for the Rouen Transport Est-Ouest Rouennais (TEOR) in France, and Castellon Trolleybus in Spain. Use of Optiguide technology in Las Vegas encountered difficulties in keeping the road markings clean and visible in the hot and dusty desert environment (James, 2012). The transit agency found that bus drivers were able to manually steer the vehicles to their stops with adequate precision, and the Optiguide system was removed (Kantor et al., 2006). Rail-guided buses are another option, and proprietary models have been produced by Bombardier and Alstom. While the Bombardier Guided Light Transit (GLT) has been withdrawn due to reliability issues, the Alstom Translohr is in operation in a number of systems. As a 'rubber-tyred tram", the Translohr uses overhead electric power, a guide rail, and tram-style vehicles. The key advantage of the Translohr is its ability to handle steep gradients, due to the traction of rubber wheels (Halcrow Group, 2007). As highlighted in the technical review, the economic cost of the Translohr is greater than that for LRT, with slightly lower capacity and low flexibility due to the need for guiderails.

Kerb-guided busways such as the Adelaide O-Bahn have been effective in providing a lower-cost alternative to light rail transit. However, while the system is more efficient on a purely financial basis, the full economic merits are still lower than that offered by LRT (Rogers, 2002). The importance of terminal capacity has emerged as a key issue for Adelaide, and current works to construct a tunnel to enable more reliable access to the city, and reduce conflicts on the inner city ring road (DPTI, 2015). The safety record and operating speeds of the busway suggest that it has performed well as a transit system (Rogers, 2002), however broader impacts to induce land development are uncertain.

Low floor LRT vehicles, offering more accessible and efficient boarding, require bogies to incorporate the motor, braking, and suspension within a narrow space below the vehicle floor. The technology review summarised advanced bogie designs for 70-100% low-floor LRT models. Options are available with a maximum speed of 100km/hour (for 70% low-floor), or 80km/hour (for 100% low-floor), without a significant cost premium. For BRT systems, low-floor vehicles are available, although there is often a trade-off with ease of boarding, and capacity losses of 4-8 seats from wheel wells for 100% low floor designs

Potential for reductions in the weight of LRT vehicles are limited, as standardised steel shells provide robust and repairable units, and the addition of components for battery, super-capacitor or ground-level power supplies increases the unit weight. The primary concern around vehicle weight is the impact on energy consumption, and as new energy sources emerge, the decision on which power source to use will be important to understand the corresponding advantages for lighter vehicles.

5.2.2 Power sources and delivery

Power sources and delivery systems have advanced for both LRT and BRT technology, and there is high potential for electric buses to become standard vehicles for BRT systems. The current cost premium for electric buses, which is approximately twice the capital cost of conventional vehicles, is expected to fall. Technology for hybrid diesel electric buses is established and reliable, however the review suggests that battery electric buses have higher development potential. Newer fuel sources using hydrogen fuel cells have been trialled, however hybrid or electric buses have superseded this technology in most cases. Investment into bus transit may need to consider whether to take on a higher vehicle cost for battery electric buses, against the lower cost and more reliable hybrid technology. The volatility of electricity and diesel fuel prices may also be relevant to understand long-term operating costs.

5.2.3 Control systems

The development of control systems has largely considered autonomous or semi-autonomous systems. These are aimed at reducing the need for driver interventions by increasing the density of vehicles (and hence passenger journeys) per kilometre of road or rail. These are being widely tested and are likely to produce semi-autonomous vehicles within five years. They will focus on crash avoidance, increased vehicle density and interchange management.

In addition, the capability of higher density vehicles, either BRT or LRT, to deliver greater passenger flow will depend not only on technology or information, but the propensity of travellers to board and alight promptly from vehicles, and disperse from stations and termini. Since one of the factors attracting commercial development around stations is the increased number of pedestrians in the area, a complete socio-technical-economic systems analysis is needed to reliably quantify the effects of different technologies.

5.2.4 Convergence

The information gathered from transit manufacturers highlighted vehicle capacity improvements for both BRT and LRT, and a tendency toward international standardisation of vehicle design. While the emergence of “rubber-tyred trams” shifts the physical form and ride quality of bus transit toward that of light rail, the additional cost of vehicles and requirement for fixed guiderails eliminates any cost or flexibility advantage for BRT. While in theory it is possible for buses to take similar form and dimensions to light rail vehicles, current and emerging technologies indicate that this is not yet feasible, at a lower cost than LRT.

Trade-offs between the capacity and speed are evident for guided bus systems, such as the Translohr and Siemens Optical Guided Bus. While these offer better ride quality than traditional buses, the need for a fixed path eliminates the potential for buses to overtake at stations, which is necessary to achieve the very high peak capacities shown in cities such as Bogotá, Brisbane and Ottawa. The overview of various transit systems, provided in Table 1, shows the range of line capacities, however the space required support these volumes varies substantially. High capacity BRT systems (over 10,000 passengers per hour, per direction) require double lanes at stations for buses to pass. Providing space for buses to operate in this arrangement within city centres can impact on the amenity of the surrounding urban environment. The Ottawa and Curitiba BRT stations, illustrated in Figure 11, show the wide corridors needed to support high-capacity BRT.

Figure 11: Ottawa (left) and Curitiba (right) BRT stations

Improved power systems show that both BRT and LRT systems will be able to offer environmentally-sound transit services, with the improvement of battery electric and hybrid buses, and high potential for battery technology in LRT. Convergence in ride quality is evident across BRT and LRT modes, although the capacity and spatial efficiency offered by LRT remains a fundamental advantage. Terminal capacity is often a limiting factor for BRT systems. High-density urban environments have additional needs for streets to cater for pedestrian movement, and this is often hindered by large volumes of buses requiring space to load and unload passengers. The decisions taken by Brisbane, Adelaide and Ottawa to take BRT systems into tunnels to access the city centre, or replace with LRT, reflect this challenge.

6. Conclusions

Review of emerging technologies by the Technical Advisor highlighted that some aspects of BRT and LRT converge, such as vehicle capacity and ride quality. Nonetheless, the differing spatial requirements, and capacity potential for high-density environments imply that BRT and LRT are not likely to converge completely in the time horizon to 2026. Some aspects of the technology review do not explore the full variety of issues around convergence, particularly the systems behavior of transit investments, and the figures quoted for vehicle and line capacity tend to under-estimate those found in service for both LRT and BRT. However, the overall findings are in alignment with the conclusions of this report. To future-proof investment into transit, convergence is not purely an issue of technical performance, but should consider the broader impacts and planning issues. Auckland's specific priorities for transit provision, desired impacts on travel behaviour and long term land use patterns should be considered to ensure that value is optimized in the long term.

Despite some convergence in the physical form and performance of BRT and LRT, the two transit systems cannot be treated as equivalent. BRT provides greater capacity to meet travel demand over a broader range of routes, while LRT has superior capacity once travel routes have been consolidated. Transit investment has significant impacts on land use and development, and long-term effects of induced development are very important for the ongoing viability of transit investments. BRT has the potential to achieve different outcomes to LRT, and the choice of a suitable option may reflect the relative priority of network vs linear capacity, flexibility vs permanence, frequency of access vs in-vehicle capacity. An advantage of BRT is the potential reach of the network to support a high level of accessibility. This advantage may come at the cost of reduced development impacts to induce efficient growth patterns in the long term. For both modes of transit, feeder services are key to enable adequate access to trunk line routes. BRT would enable feeder service of the same mode, potentially reducing interchanges - however in this scenario it is less likely to be an effective pre-cursor to LRT, since it may not induce land development impacts required to ensure that LRT is viable and efficient. While BRT can provide a lower cost option from a purely financial perspective, and in some cases can support equivalent line capacity or ride quality to LRT, trade-offs emerge between capacity, cost, service quality and the impact on the urban environment. The potential for induced land development impacts in the long term is higher and more consistent for LRT. The spatial requirements also vary; BRT systems require double lanes to support passing at stops or stations, as well as pre-boarding fare collection infrastructure to provide a comparable line capacity to LRT.

The review of investment decisions made by various cities, in Table 5, shows the investment rationales provided in different contexts. Investment in BRT is driven by cost considerations in two of the three cases reviewed, and in some cases a perception that the transit services provided were equivalent. Cities opting for LRT systems cited the importance of capacity and speed, preserving the quality of high-density environments, and greater impacts to induce land development. Taking the decision-making processes in other cities with successful BRT systems as examples, it appears that BRT has not provided the combination of service quality, passenger capacity and amenity benefits offered by LRT. Both Brisbane and Adelaide are in the process of constructing tunnels for the BRT systems to avoid travelling through the city centre at ground level. Ottawa is replacing its highly successful BRT system with LRT to improve peak line capacity, and Bogotá is constructing LRT to reduce over-crowding on the BRT system. The Lima Metropolitano BRT system constructed the central city station underground, to avoid conflict with surface-level traffic and public space (World Bank Group, 2015). This illustrates that where BRT is most effective, it is likely that demand may eventually reach a level that can only be provided by LRT. The peak capacity of BRT systems is typically less than that offered by light rail, and in the cases where it is greater, the space required for double-lane, separated busways is substantial and generates negative impacts on the amenity of central city environments.

While some literature proposes BRT as a potential pre-cursor to LRT, the suitability of this approach depends heavily on the rate at which transit ridership increases, costs of construction and disruption over two construction phases, and potentially negative long-term effect on the level of redevelopment induced by the transit investment. The substantial increase in transit ridership in Auckland over the past decade, which suggests there is latent demand for transit (and especially high-quality rail services), a staged approach may not be optimal in the long-run to support the city's growth, efficient land use and high quality of urban development.

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