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Emerging Technologies for Rapid Transit: Part Two
An Evaluation of Specific Technologies

JMAC Report 2016/02

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Executive Summary

To inform current investment decisions for mass transit, this paper, Part Two of a series on Emerging Technologies for Rapid Transit, evaluates several emerging technologies in depth to understand their likely future trajectory, and impacts on the forecast costs and benefits of different investment options. Part One of the series, *Emerging Technologies for Rapid Transit: Future-proofing Investment Decisions* (April 2016), indicated that Bus Rapid Transit (BRT) technologies are converging partially with Light Rail Transit (LRT), however LRT still offers superior performance to support high peak hour capacities, with better ride quality and more spatially-efficient transit through high density areas. A review of current innovations in transit has not identified emerging technologies with strong potential to shift the relative value proposition of LRT and BRT in the coming decades. This paper develops future scenarios to test whether emerging technologies could significantly affect these findings, in the Auckland context. Scenarios are developed to evaluate the potential implications of new technologies on the value proposition for different mass transit modes, and forecast return on investments. Scenarios test whether technological changes could shift the relative value proposition for LRT and BRT modes, or reduce demand for mass transit, and identify the implications for anticipated benefits of current investments. Based on review of emerging technologies, technological advances are not likely to shift the relative value proposition between LRT and BRT: while BRT ride quality may improve, the spatial requirements are greater and impacts on development potentially lower. Demand for mass transit can be partially influenced by the investment decisions of Auckland Transport. Introduction of Connected and Autonomous Vehicles (CAVs) may affect transit demand, however CAVs are unlikely to be widely implemented for several decades, so the impacts on benefits received from current transit investments are likely to be minimal, over the next 30-35 years.

The potential for bus guidance and platooning technologies to produce a transit service equivalent to LRT is evaluated, alongside the cost implications for extra infrastructure required. Guidance technologies are not yet reliable for widespread use, and do not function over the entire bus route. Instead, magnetic or optical guidance enables buses to “dock” at stops only. In the case that BRT and platooning technologies do advance rapidly and provide greater capacity and ride quality, the capital cost structure of BRT implies that these new functions must be provided with only a small cost increase, for BRT to be a more cost-effective option. Currently, the overall capital costs of LRT are greater due to engineering, control systems, track work and vehicles. If BRT technologies progress to the stage where peak capacity and ride quality are equivalent to LRT, due to guidance systems and platooning, the capital cost of the guideway, land acquisition and stations are unlikely to fall. Therefore, to remain at a lower cost than LRT, the cost premium for new BRT facilities, power and control systems, track work and vehicles cannot increase more than 50% than the current cost. The capital cost of these components is relatively low at the present time and it is uncertain whether new technologies could be implemented with only a small increase in costs.

This paper (Part Two) extends the preceding report (Part One) into greater depth, evaluating emerging technologies and testing their implications for the anticipated benefits of current investments. Over the investment timeframe, new technologies are unlikely to shift the relative costs and benefits of LRT and BRT sufficiently to change the conclusions reached in Part One.

Table of Contents

List of Figures

List of Tables

1. Scope of report

This paper (Part Two) focuses on bus rapid transit and light rail modes, building on *Emerging Technologies for Rapid Transit: Part One – Future-proofing Investment Decisions* (April 2016) by evaluating specific technologies in greater detail, and testing potential future scenarios for mass transit investment. Given the ongoing evolution of technologies that affect both demand for transit, and the efficiency and level of service provided by different modes, medium to long-term technological development should be considered in current investment decisions. The transport implications of emerging and future transport technologies have been assessed with respect to Connected and Autonomous Vehicles (*Potential Impacts of Connected and Autonomous Vehicles*, October 2015), and changing preferences for transport and telecommunications accessibility and energy prices (Ministry of Transport, 2014).

Findings from scenario testing address the following questions:

- What is the potential for technological changes to reduce the demand for mass transit, and impact on the long term benefits derived from transit investments?
- What is the potential for future technological change to shift the relative value proposition of light rail and bus rapid transit modes?
- Could guidance technologies for bus vehicles improve the ride quality to match light rail services, and what are the associated cost implications for the required infrastructure?

2. Introduction

Anticipating the future trajectory of transport technologies is necessary to future-proof current investment decisions. Strategic planning must identify a range of potential futures and ensure that investment decisions allow for the impacts of new technologies on the performance of the transport network, and anticipate the time scale of returns for current investments. Recent technological developments have seen some convergence between transport modes. Specifically, the reliability, improved travel times and frequency of bus services on BRT systems provides a service that is similar to light rail in some aspects. New communications technologies also allow transport infrastructure to be used in different ways – for example, mobile apps enable shared use of automobiles, vehicle-vehicle communications can support 'platooning' of vehicles, and provision of real-time information significantly improves the usability and convenience of public transport. Vehicle technologies such as magnetic, optical or rail guidance systems improve the ride quality of buses. Alternative power systems enable vehicles to operate with fewer emissions and using clean energy sources in place of diesel. The safety of transport vehicles and systems has also improved, as sensor systems enable vehicles to detect hazards more effectively and avoid collisions.

The past, present, and future impacts of technology on the nature and evolution of transport provision are significant. Historically, different technologies have superseded one another and dramatically altered the capabilities of different transport modes, related energy requirements, safety and environmental impacts. Often, technology changes the qualitative nature of transport services, with varying effects on speed, capacity, safety, and cost. For example, the introduction of private automobiles and supporting road infrastructure vastly improved mobility and accessibility outcomes, while leading to increased negative environmental impacts, greater costs of infrastructure investment and maintenance, and significantly higher per-passenger spatial requirements than transit modes. Technological improvements can therefore generate trade-offs between different dimensions of system performance. Review of the apparent convergence between LRT and BRT systems found that while BRT was able to compete with LRT in terms of peak road capacity and financial cost, it also has higher spatial requirements and lower ride quality. Although factors such as the ride quality are expected to improve, the spatial requirements for BRT may be a constraint for implementation in high-density urban environments.

This paper reviews potential future scenarios, focusing on variation in the two primary uncertainties; the level of technological development and future travel demand. Current trends suggest that transport provision in the future will be influenced not only by new technologies but the changing nature of transport demand, due to energy prices, environmental impacts, new communications technologies, and social factors. Auckland's projected demographic shifts indicate that the city's future population will likely include a larger proportion of international immigrants, and elderly residents (Muhammad, Jackson, Cain, Peace, & Spoonley, forthcoming). The impacts on travel behaviour imply that transit demand will be greater and that these populations display more diverse travel needs. Recent migrants are more likely to rely on transit services for access to employment and education, and elderly populations depend on the frequency and geographic coverage of transit to provide access to community services and healthcare.

3. Emerging and future transport technologies

New technologies can relate to individual components of a system, such as optical guidance or vehicle-vehicle communications, or entire systems, such as the Alstom *Translohr* or personal mass transit. The preceding paper (*Emerging Technologies for Rapid Transit: Part One - Future-proofing Investment Decisions)* surveyed current and emerging mass transit technologies to evaluate how ongoing technological advancement may affect the viability and performance of transit systems in the future.

This section will evaluate several emerging technologies will be explored in more detail; specifically looking at optical guided buses, vehicle-to-vehicle communications enabling platooning, and 'last mile' micro-transit services.

3.1 Guided buses

Emerging technologies for guided buses utilise optical or magnetic systems to improve the ride quality for BRT services. Guidance systems allow "precision docking" at platforms, improving the accessibility of vehicles by aligning the vehicle floor with the platform.

Magnetic guidance

The Phileas magnetic-guided bus introduced in 2004 in Eindhoven, The Netherlands, initially showed promise to provide an equivalent service to LRT, using magnets installed in the paving surface to guide the bus along fixed routes (Polis, 2006). The system experienced numerous reliability issues for the hybrid power system and "Free Ranging on Grid" navigation technologies, which are not yet robust to operating in the street environment with mixed traffic (Unruh, 2012). Following numerous technical faults, the buses were removed from service in 2014 and the manufacturer has closed down (VDL, 2014). Implementation of the Phileas system in the French town of Douai was also removed in 2014, as the guidance technology did not perform reliably (Dethee, 2014). Magnetic guidance technology has also been developed by the PATH research centre in Berkeley, California, although trials carried out between 2009-11 were not extended for full implementation. Magnetic guidance technologies are included in research focusing on Vehicle Assist and Automation (PATH, 2012).

Optical guidance

The Transport East-Ouest Rouennais (TEOR) was opened in Rouen, France, in 2001. Rouen's wider urban area has a population of 464,000 (2014, UN Data) and the TEOR provides an east-west transport corridor as a complement to the existing north-south Metro network. Optically-guided buses were selected instead of light rail to expand the transit network in Rouen, due to limited funding (Transportation Research Board, 2007). The TEOR lines are integrated with the metro network, and extend over 38km in total (including 15km of dedicated lanes). The average operating speed of buses is 18-20km/hour, and the network provides 12 million trips per annum in addition to the 19.3 million trips on the city's light rail network (Greater Wellington Regional Council, 2012).

Optical guidance sensors are used only for a short distance before and after each stop, to support "precision docking", to improve accessibility for wheelchair users and mobility-impaired passengers. Since optical sensors rely on continuous visibility of the painted guidelines, obstacles such as dust, snow, leaves on the roadway, as well as fog and severe weather, limit the feasibility for buses to be optically-guided for the length of the bus route. A full optical guidance system was installed in Las Vegas, but later removed from service due to the substantial maintenance requirements to keep the pavement markings clean (James, 2012).

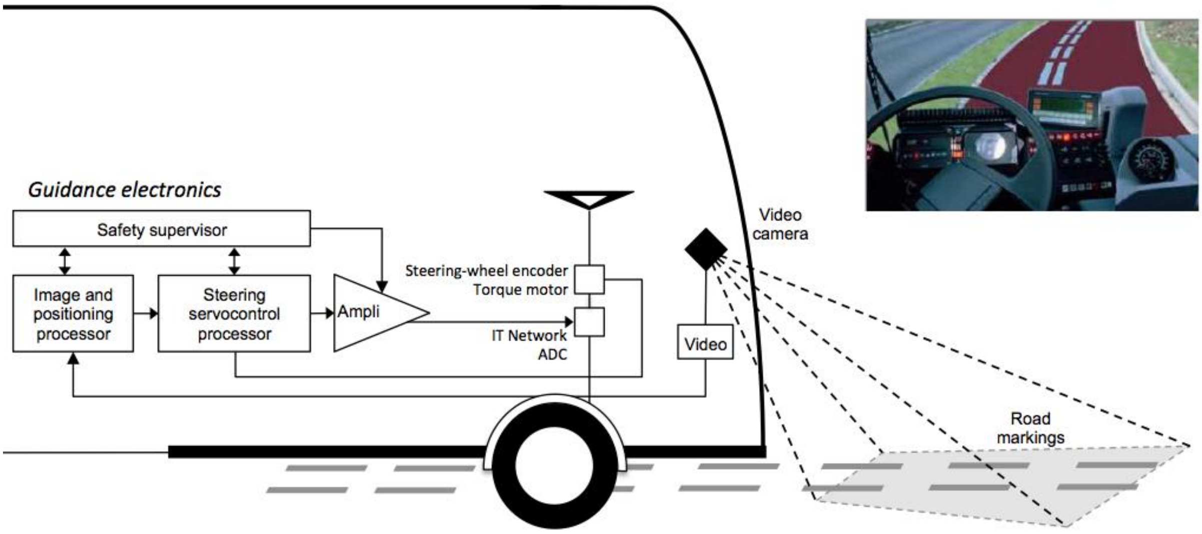

Figure 1 - Optical guidance system (CERTU, 2009)

Figure 1 shows the optical guidance system components. Bus drivers have a special interface to monitor the guidance system and enable switchover from manual to guided operation of the vehicle. The TEOR uses Irisbus *Citelis* and Renault *Agora L* diesel buses, with a maximum vehicle capacity of 111 and 115, respectively. Fare collection and ticket validation can slow the boarding times for buses, however the introduction of contactless payment cards is reducing boarding times to improve the efficiency of bus transit. While significantly slower than light rail, the ride quality of the TEOR system is superior to traditional buses (Shladover, et al., 2007).

The implementation of the TEOR in Rouen to augment the existing rail network enabled the city's transit network to be expanded at a lower cost [than light rail alternatives], however the flexibility of BRT is limited since the system has dedicated lanes, and streets were completely rebuilt to accommodate BRT vehicles. To provide a higher level of service than conventional buses, vehicles must operate on fixed routes. Figure 2 shows the bus-only lanes in the city centre, and Figure 3 shows BRT infrastructure in outlying areas.

Figure 2 - Avenue Alsace-Lorraine: TEOR infrastructure in city centre

Figure 3 - Route de Dieppe: TEOR infrastructure in outlying areas

As an indication of the future potential of optically-guided buses, the Rouen TEOR shows that guided BRT can be an effective complement to LRT, to accommodate the city's transit demand in a cost-effective manner. The slower travel times of the TEOR vehicles indicate that it may be difficult for BRT to provide equivalent peak hour capacity to existing light rail transit. Operation of BRT as a stand-alone transit system or to cater for major transport corridors may face severe capacity constraints, as illustrated in Bogota, Colombia and Ottawa, Canada. The additional space required by BRT vehicles to pass one another significantly increases the spatial requirements, a key concern for city centre areas.

Table 1 - Summary of guided bus systems

	System	Length, System type	Ridership (per day)	Installed	Current status
OPTICAL	TEOR Rouen, France	38km, 15km segregated lanes. Integrated with existing LRT network.	42,000	2001	Guidance used only for docking at stops; maintenance costs to keep roadway free of obstructions are prohibitive.
	Castellón, Spain	2km total, segregated lanes. Integrated with bus network.	3,200	2009	In operation.
	Tango+ T1 Nîmes, France	4.5km total, segregated lanes. Integrated with bus network.	7,700	2012	In operation.
	Metropolitan Area Express Las Vegas, United States	63km total, 30km segregated lanes.	34,200	2004	Removed from service. Optical technology ill-suited to severe weather and dusty conditions.
MAGNETIC	Phileas Eindhoven, Netherlands	15km total. Integrated with bus network.	12,000	2004	Removed from service. Guidance system unreliable, manufacturer has halted development.
	Douai, France	34km total. Integrated with bus network.	1,800	2006	Removed from service, vehicles unreliable. Transit operator took legal action against manufacturer.
	Istanbul, Turkey	52km total, 50km segregated lanes. Integrated with bus and rail network.	750,000	2007	Removed from service, vehicles unreliable. Transit operator took legal action against manufacturer.

Data source: BRTdata.org

3.2 Platooning Vehicles for Automated Bus Rapid Transit

Technologies enabling vehicle-to-vehicle communications can improve the ride quality and efficiency of transit provision. Specifically, platooning functions enable vehicles to travel together, connected by wireless communication. A lead vehicle is operated manually, while a number of follower vehicles are actively co-ordinated to the lead vehicle and follow at close proximity.

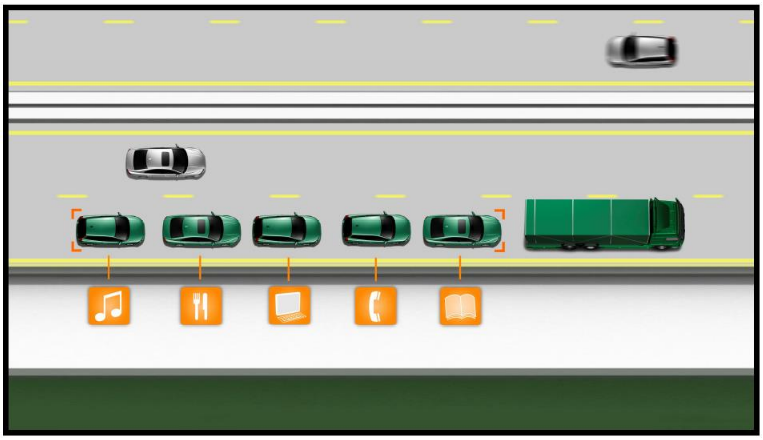

Figure 4 - Platooning technology in highway settings (Davila & Nombela, 2013)

Platooning supports lower fuel consumption for highway travel due to lower aerodynamic drag (Robinson et al., 2010), and improved safety as platooning removes risks of driver error. Technologies for the platooning of bus vehicles have been developed and automated BRT systems were tested by California Partners for Advanced Transportation Technology (PATH) as early as 2003. More recently, trials in Europe saw networked and platooned trucks travel on public roads between Stockholm, Sweden and Rotterdam in Germany. Trials for autonomous platoons of trucks are also planned by the UK Department for Transport (FT, March 2016).

Implementation of platooning technologies for transit is limited, with technological development instead focusing on steering automation systems for transit vehicles. The potential benefits of platooning for freight trucks is deemed to be greater, although there is potential the technologies could be adapted for transit in the future (Shladover, 2012; Nowakowski, 2015). Operating in a mixed traffic environment on urban streets, with additional safety considerations for transit users and pedestrians adds a further layer of complexity to the operation of platooned vehicles.

There is little empirical evidence for the efficiency gains from platooning, in terms of road space occupied by transit vehicles. However, existing BRT systems in South America adopt an informal type of platooning, which is attributed to providing very high peak-hour capacity for certain corridors. Buses travel in platoons of 12-16 vehicles, with one platoon every 96 seconds on average, which is more efficient than equally spaced buses to shift high volumes of passengers (Ardila & Rodriguez, 2000). Individual vehicles can pass one another and often shift between platoons during their journey. The theoretical potential for transit vehicle platooning is significant, although technological development will be driven by perceived market demand.

3.3 Microtransit: Providing for last-mile trips

The 'last mile' problem is a long-standing challenge for urban transit, to provide for the first and last trip within an individuals' commuting journey. If these trips are poorly provided for, it can create significant barriers to transit use. In relation to current investment decisions for Auckland Transport, understanding the potential for different mass transit modes to integrate or provide for last-mile connectivity is important to the overall return on mass transit provision.

New technologies are being implemented in the form of micro-transit, to support this. Complementary modal options to provide for first and last-mile connections include:

- On-demand feeder buses
- Walking and cycling infrastructure
- Bikeshare systems and/or electronic bicycles
- Rideshare apps
- Park and ride infrastructure
- Autonomous vehicles (testing phase).

Figures 5, 6 and 7 illustrate options currently in use. The rideshare, bikeshare, and dynamic transit systems all depend on mobile internet technology to match users to transport services, providing real time information and co-ordinating vehicles.

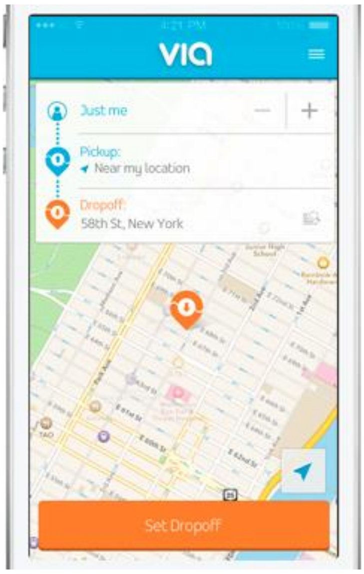

Figure 5 - VIA Rideshare app, New York

Figure 6 - Electric bikeshare scheme, Madrid

Figure 7 - Bridj dynamic transit service, Kansas City

The future viability of mass transit rests on integration of trips connecting from other modes; however there is also potential for micro-transit services to provide competition with mass transit itself. This is particularly pertinent for mechanised modes, including rideshare systems and autonomous vehicles.

Review of the development potential for connected and autonomous vehicles indicates that a 50% fleet transition is not estimated to be reached until 2055[1], suggesting that the benefits of current mass transit investments are not likely to be affected over the next 35-40 years.

The long-term uptake of technologies for microtransit and new forms of shared automobile travel, depends largely on the response of transport regulators and planners to regulate and cater for new forms of transit on the existing networks. The relative prioritisation of mass transit, microtransit, private vehicles and active modes is a key factor for the reliability and travel time of each mode. For efficient operation of the overall transport system, the optimal combination of different modes ensures that modes are matched to commuter flows; high capacity corridors are best served by mass transit, while microtransit has significant potential for last mile trips, and may use the road network less efficiently if providing end-to-end journeys. Since both BRT and LRT are inflexible, due to fixed infrastructure requirements along the transit route, micro-transit provision of last-mile trips will be important for both modes. Design of mass transit networks may consider the complementary role of microtransit to optimise the transit network's effective service coverage.

3.4 Findings to inform scenario development

Recent developments indicate that technologies for guided bus operation, platooning of transit vehicles and integrated micro-transit could enhance the ride quality, efficiency, and level of accessibility provided. At present, technologies for bus guidance and platooning are not sufficiently developed to operate reliably outside a controlled test environment. The future development potential is varied; optical technologies are limited by the sensor systems used, which are easily blocked in adverse weather conditions or by obstructions on the road surface. Magnetic guidance systems have greater potential to operate reliably, although attempted implementation in European cities and towns has been unsuccessful and testing in California in 2008 has not yet progressed to widespread implementation. Platooning technologies are also at an early stage of development. In controlled test settings the technology has performed successfully. Implementation into the street environment with mixed traffic and additional safety considerations adds several layers of complexity for communications and sensor systems.

In addition to the innovations in BRT technology summarised in this section, new technologies are also emerging for LRT systems, and may influence the performance and cost-effectiveness of this option in the future. Ultralight rail (also known as Personal Rapid Transit) offers a lower-cost option to standard rail, with smaller vehicles and passenger loads, and in turn, lower requirements for the supporting rail structure. Vehicles are computer-controlled and can support passenger capacities up to 4,800 passengers, per hour, per direction (Dearien, 2004). Given their low capacity, these systems are typically found in airports or campus facilities (including Heathrow T5, San Francisco Airport's AirTrain, and the Personal Rapid Transit system at the University of West Virginia). Potential use of this technology in the Auckland context may be limited by the capacity constraints, although it could play a complementary role to higher-capacity modes. Newer forms of light rail slab technologies are also being developed to reduce the costs of construction. Current research programmes sponsored by the United Kingdom Department for Transport are developing modular pre-cast track slab and more energy efficient light rail vehicles (Global Rail News, 2015). While these technologies are still in development and testing phases, the ongoing investment into developing light rail technology indicates that the system's potential and cost-effectiveness could improve.

[1] Refer to page 15, *Potential Impacts of Connected and Autonomous Vehicles*

At the present time, the fixed infrastructure costs for surface BRT are lower than LRT, on average, although some BRT investments (such as the Brisbane Busway and Auckland's Northern Busway) had an equivalent per-kilometre capital cost to light rail[2]. This is largely due to a requirement to grade-separate or tunnel underground for BRT, in the central city environment. In coming decades, rapid technological development may shift the relative value proposition for BRT and LRT modes such that a surface BRT option offers equivalent level of service at lower cost, if the aforementioned technologies are fully developed and available for widespread implementation. The slow development and reliability issues experienced in recent years suggest that it may be several decades before technologies are reliable and ready for widespread implementation. Successful implementation of new technologies is important to build credibility in the transport market, and the removal of the Phileas system in Eindhoven and Douai may affect the technology's future potential as transit operators are wary of investing in failed technologies. The limitations of optical guidance technology, which cannot operate along an entire route without significant maintenance costs to keep the roadway clear, cannot be addressed without introducing a different form of sensor. The system has been successful, using guidance for docking at stops, in Rouen, France, however this is in conjunction with an existing Metro network and the BRT lines provide approximately 12.6 million journeys per year, in a city of 464,000. Whether the optically guided BRT option is sufficient to cater for a larger proportion of transit services in a much larger city is uncertain.

The evidence currently available suggests that, for BRT systems to progress to the stage where they can provide an equivalent level of service and reliability to LRT, the technologies would have to advance from testing stage to be ready for full implementation. Given recent setbacks for magnetic guidance and apparent technical limits to optical guidance technologies, and the early stage of development for platooning, the rate of progression does not suggest that there will be a competitive alternative to LRT within the next twenty years. The fixed infrastructure costs associated with guided buses are minimal for optical guidance, since the guidance system is installed on the vehicle and painted lines are added to the existing roadway. However, the TEOR system in Rouen installed a dedicated lane to ensure that the guided buses could have exclusive right of way, at additional cost. Magnetic guidance systems require installation of magnets into the pavement, at an estimated cost of US$22,000 per lane kilometre. The scenarios developed in this paper consider the outcomes of low and high levels of technological development. Potential developments include optical guidance technology, semi-autonomous operation and vehicle-vehicle communications to enable buses to operate with a smoother ride quality and capabilities for platooning, mimicking the kind of service currently provided a tram system. As explained in the preceding paper, 'rubber-tyred' trams exist already in the form of the Alstom *Translohr*, however the cost is currently equivalent to light rail options and the technology is a proprietary system with low inter-operability.

Detailed evaluation of bus platooning and the TEOR system implemented in Rouen illustrated the following issues, relevant to inform scenario development and testing:

- Case studies of the Rouen TEOR guided BRT system and applications of vehicle platooning technology highlight that emerging technologies do not provide transport options that perform better in every respect, but rather introduce trade-offs and different bundles of system attributes. For example, the TEOR provides higher ride quality and reliability than conventional buses, due to optical guidance at platforms and dedicated lanes, however the space required for buses to overtake one another implies that transport corridors must be

[2] Refer to Figure 8 and 9, *Emerging Technologies for Rapid Transit: Future-proofing Investment Decisions*

wider (unless private vehicle lanes are prohibited entirely) and it is not well suited to central city areas.

- The Rouen case illustrates the benefits of integrating different mass transit modes to provide high capacities on primary commuting routes with light rail while extending the network's coverage with feeder services for lower density areas.
- The flexibility of a mass transit system is linked with the requirements for fixed infrastructure. LRT systems are inflexible due to the installation of fixed tracks, however BRT systems such the Rouen TEOR also have limited flexibility, since fixed infrastructure is required along the entire route.
- Platooning technologies may reduce the spatial requirements of buses, however current technological development is oriented around truck fleets and freight transport, as the potential economic payoff is high. Whether this technology can be adapted to enable platooning of buses will depend on the global market demand and adaptability of highway platooning modes to the urban street environment.
- Modal integration to provide for entire transit journeys is a crucial complementary investment to mass transit. Technologies to support this combine both old and new transport technologies, and the real-time communications and navigation provided by mobile internet devices and micro-transit services enable multimodal journeys.

4. Future scenarios

Future scenarios reflect potential outcomes for different levels of transport demand and technological development. At low and high levels of change for each uncertain factor, a future scenario is described, and implications for transit investment decisions are evaluated.

Uncertainty around technological development refers to the difficulty in predicting technological developments. At present, a range of technologies exist at trial stage or with low-level implementation, however it is very difficult to anticipate which of these may develop for widespread use in transit provision and whether other (currently unknown) technologies will emerge in the future. Since technological development is driven by private enterprises catering to global markets, assisted by government investment in research and development, new technologies are likely to be driven by global market demand and Auckland Transport has little influence on the trajectory of development. However, technology should not be viewed as a singular force that will determine the future, regardless of the current policy and investment decisions of Auckland Transport. Strategic investment planning must identify where technology offers benefits and potential threats to the transport network's capability to meet broader accessibility goals. Planning should ensure that the adoption of new technology is appropriately managed to lock in the benefits and safeguard against potentially detrimental effects. Decisions taken by Auckland Transport will impact on future scenarios, specifically those affecting future travel demand for mass transit modes.

Uncertainty around travel demand is shaped by factors both internal and external to transport policy and investment decisions. Shifting modes of consumption, such as the current transition of some goods and services from traditional retailers to the online marketplace and commercial delivery methods, are largely outside the influence of Auckland Transport. Similarly, working arrangements that substitute physical travel for telecommuting are likely to develop independently on the local provision of transport infrastructure, except in extreme cases. However, the relative investment into private and public transport modes and quality of mass transit services is a key driver of future demand for mass transit, and Auckland Transport has influence over these outcomes. The range of factors determining future demand for mass transit services are summarised in Table 2.

Table 2 - Drivers of demand for mass transit

Factors driving low future demand	Factors driving high future demand
• Decreasing rates of urbanisation • Changing modes of consumption and leisure; goods and services provided through the internet and leisure activities carried out using telecommunications in place of physical travel • Changing workplace arrangements; substituting physical travel for telecommuting • Expansion of infrastructure for private transport modes • Dispersed spatial development in urban areas	• Increased urbanisation • Transition away from private transport modes, driven by regulatory or taxation-based measures restricting the use of fossil fuels[3] • Investment in mass transit services, and resulting level of accessibility to employment centres, education and public services, and recreational opportunities • Price of mass transit services

While the development of autonomous and connected vehicles, and mass transit technologies are largely outside the control of scope of influence of Auckland Transport, infrastructure investment and accompanying policy will strongly shape the future viability and operational efficiency of different transport modes in the future. Scenarios characterise the range of futures emerging from different technological trajectories and travel demand for mass transit, and evaluate the implications for current investment decisions.

[3] Regulations to reduce carbon emissions may also drive a shift toward electric vehicles, however the relatively slow fleet turnover rate in New Zealand (Lemon, 2013) and decreasing rates of car use in younger generations (Curran, 2014) suggest that uptake of electric vehicles is unlikely to be rapid.

Table 3 - Scenario development

		Technological development *Cannot be significantly influenced by current investment and planning*	
Future travel demand for mass transit modes *Can be influenced by current investment and planning*		**Low** *Extensive investment in roading infrastructure or technological development of private transport modes supports dispersed urban growth and the predominance of private vehicle travel.*	**High** *Optically guided, semi-autonomous buses with platooning capabilities operate on a bus rapid transit network.*
	Low *Extensive investment in roading infrastructure or technological development of private transport modes supports dispersed urban growth and the predominance of private vehicle travel.*	• At low levels of ridership, bus rapid transit modes offer the flexibility and lower capital costs to mitigate risk of low returns on investment. • Low travel demand implies that the capacity provided by light rail transit may be excess to requirements, and investment may generate low or negative returns.	• Any investment in mass transit will have limited returns where demand is low. Semi-autonomous guided buses are likely to be more cost-effective, however the costs of new technologies will determine whether they generate a significant return. • More flexible options such as bus rapid transit or standard bus services are optimal to limit losses on investments, for services that do not pass through high density central areas, where light rail is likely to be optimal.
	High *Imperatives to address climate change, or manage traffic congestion using road pricing, support an increase in demand for mass transit services.*	• If development or uptake of new technologies is limited, light rail transit remains the optimal solution in terms of providing higher peak capacity, with lower operating costs (at high ridership), improved spatial efficiency and induced impacts on land development along the transit route. • In the case of high demand, investment risk related to the higher capital costs of rail is lower. Bus rapid transit systems can play an important role to augment light rail transit with feeder services, servicing areas outside the city centre with lower population density.	• High demand implies that mass transit must support substantial peak hour passenger loads. In this scenario, light rail systems remain superior to guided, semi-autonomous bus rapid transit in supporting high peak capacities, however bus rapid transit may be important to provide feeder services for lower density areas. • The fixed infrastructure required for both light rail and guided bus require a significant capital cost, however with higher demand, investment risk is lower.

5. Discussion

This section evaluates the capital and operating cost components of different transit options, and discusses the outcomes of scenario testing.

5.1 Comparison of capital and operating costs

The different components of capital and operating costs vary between BRT and LRT systems. Figure 8, below, illustrates the separate capital cost components of BRT and LRT systems, based on data from US projects (Zhang, 2008). While the engineering, power and control systems, track work and vehicle costs are substantially higher for LRT, separating individual cost components shows that the guideway for BRT systems is more costly, on average, and land acquisition costs significantly higher. Review of emerging technologies in earlier sections shows that guidance systems and platooning technologies are improving the ride quality and potential capacity of BRT, although further technological development is needed before systems can operate reliably. In the case that guidance technologies and vehicle-to-vehicle communications enable BRT to provide equivalent ride quality and capacity to that currently provided through LRT, there are implications for the value proposition of the two modes. Figure 8 shows that the two largest cost components for both BRT and LRT are the engineering and management ("soft costs") and guideway.

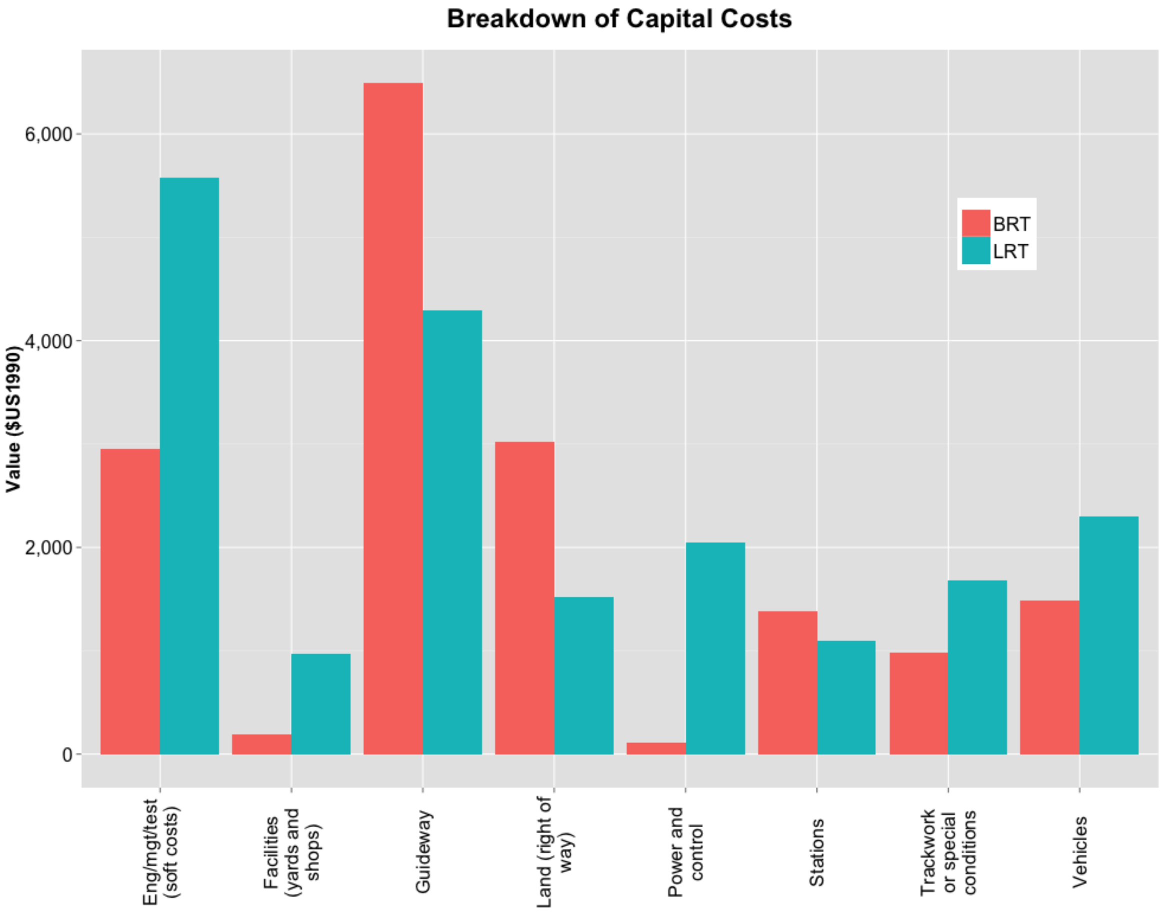

Figure 8 - Capital cost per route mile, by system component (Zhang, 2008)

At present, the capital cost premium for LRT is due to more expensive vehicles, track work, control systems, facilities and engineering costs, as shown in Figure 9. Guidance technologies and platooning do not reduce the land requirements for BRT, and may increase the costs of installing the guideway if installation of magnets or other infrastructure is required. Therefore, holding these costs as fixed, the estimated future cost differential between BRT and LRT depends on the relative costs of track work, power and control systems, facilities, engineering, and vehicles. To remain at a lower cost than LRT, new BRT technologies could not exceed 50% of the value of current capital costs, (equivalent to US$2870 per route mile). Beyond this, the cost advantage of BRT will be eliminated by additional infrastructural requirements.

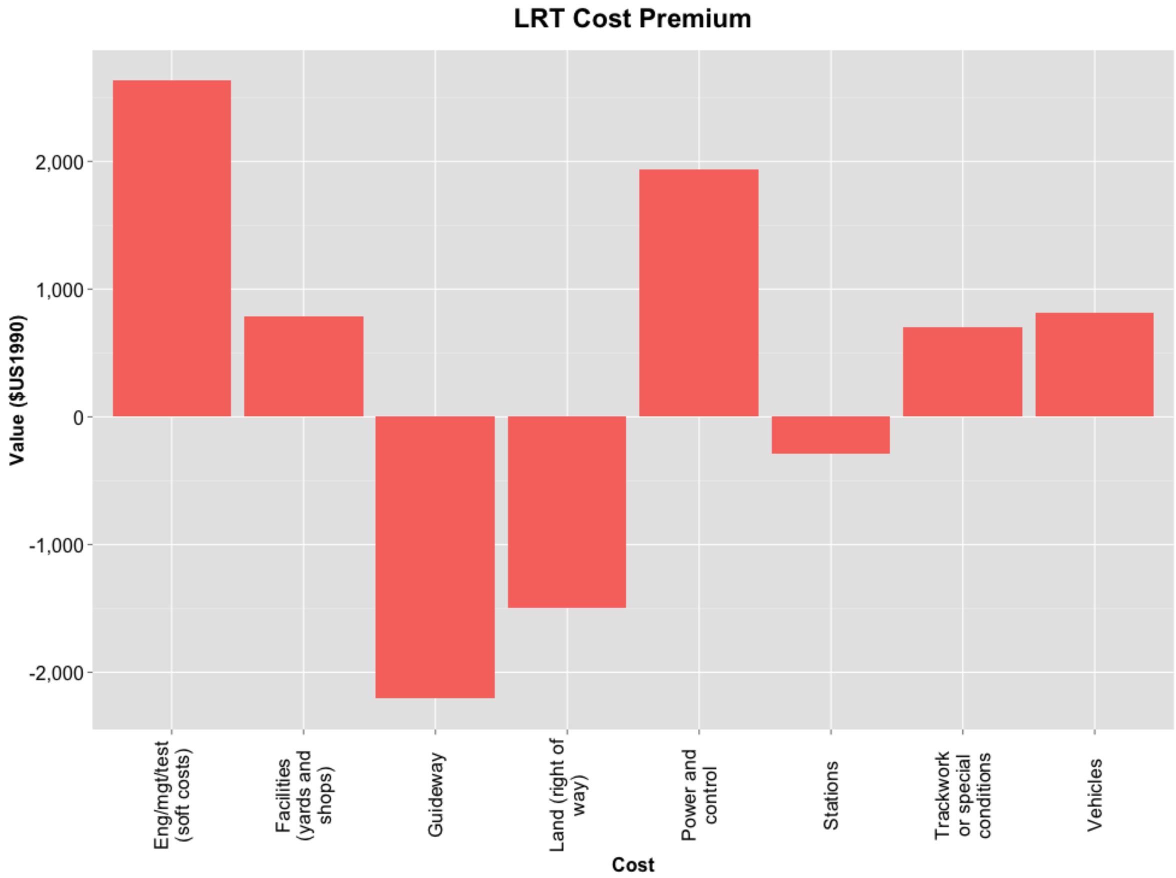

Figure 9 - LRT capital cost premium (relative to BRT) per route mile, by component

Considering that current capital costs for BRT provide relatively simple, low-technology systems, the potential to introduce advanced technologies with less than a 50% capital cost increase is low. Optically-guided buses used by the Nevada Department of Transportation in Las Vegas were approximately US$1.2million per vehicle, in 2005 (Kim, Darido, & Schneck, 2005) and the Rouen TEOR vehicles were US$1.1million per vehicle (Transportation Research Board, 2007). Introducing platooning capabilities to vehicles requires significantly more advanced systems, and developing vehicle-to-vehicle communications that can navigate within the urban street environment, with other vehicles, cyclists, and pedestrians, requires substantial advancement of existing platooning technologies tested for road freight.

The operating cost components also differ substantially between transit modes. Figure 10 illustrates operating and maintenance cost components for BRT and LRT systems, based on data from the US National Transit Database, between 2011-2014 (FTA, 2014). The plot shows the higher vehicle operating costs required for BRT, due to the higher labour requirements for BRT systems to support equivalent passenger volumes to LRT. Non-vehicle maintenance expenditure, related to track maintenance, is much lower for BRT than LRT, and the vehicle maintenance expenditure is approximately equal across both modes. These values represent averages across existing transit systems; as highlighted in the previous report, the level of transit demand also determines operating efficiency. LRT tends to be lower for high levels of demand, while BRT is more cost-effective for lower transit demand.

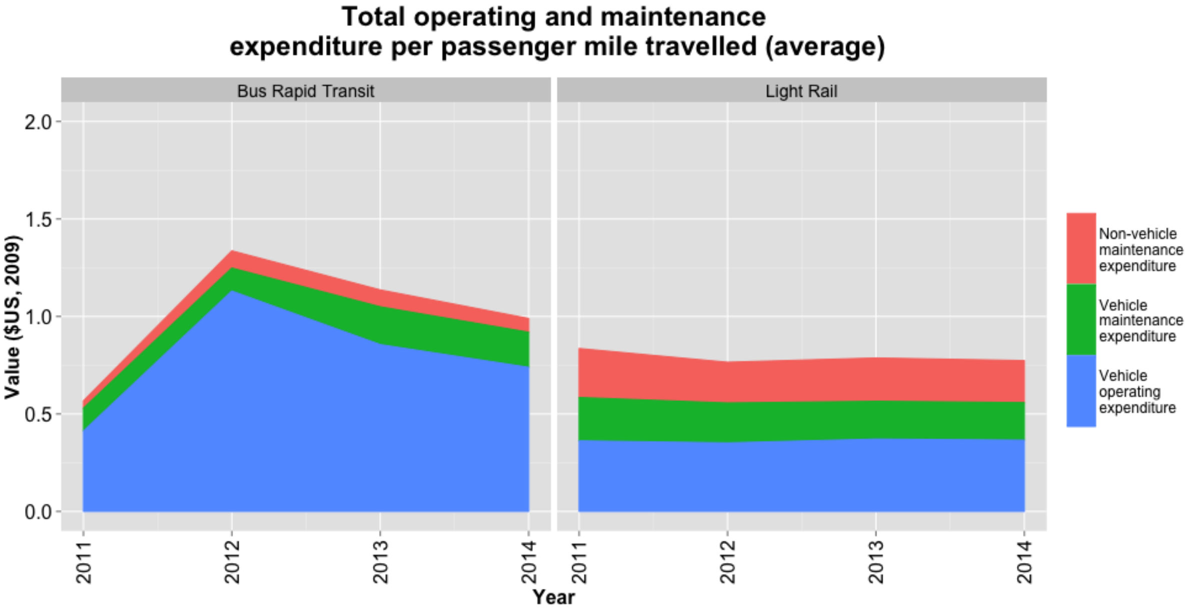

Figure 10 - Operating cost by component, data from FTA (2014)

5.2 Outcomes from scenario testing

Table 3 summarises various future scenarios, according to different levels of mass transit demand and technological development. Scenarios are evaluated with respect to the risk and potential implications for current investment decisions.

Scenario testing illustrates the role of transit demand in ensuring the long-term viability of investments, and therefore the likely timescale across which the expected benefits of investments will be realised. The development potential of Connected and Automated Vehicles (CAV) technologies is not estimated to affect the viability of mass transit modes until 2055; at which point an estimated 50% of the New Zealand vehicle fleet may operate autonomously. The resulting impacts on the net present value of the return on current investments are very low. In terms of comparative benefits of LRT and BRT, there is little substantive evidence that BRT can reliably provide an equivalent level of service and system performance to LRT, or that this may be reached in the near future. Investment decisions should consider the additional spatial requirements of BRT, as BRT routes require passing lanes and terminal capacity to provide equivalent travel times and peak capacity to LRT. For high density urban environments, this could be a constraint to implementing BRT systems, whether transit routes terminate or pass through the city centre.

At low levels of future transit demand, which are closely linked to transport investment decisions across all modes and the relative prioritisation of private transport, active modes and mass transit, any investment in mass transit will be limited in realising forecast benefits. In this scenario, BRT systems may offer a lower risk investment in the case that demand for mass transit is significantly less than services supplied by mass transit networks. In scenarios of both low and high technological development, the lack of demand acts as a limiting factor and a risk-averse perspective suggests that lower cost BRT options are more appropriate, however the ride quality and travel times will be lower than that possible with LRT.

Scenarios of high demand produce very different risks, and selecting the most efficient and high-capacity mass transit modes is preferable to match the high level of transit demand. In the case of low technological development, LRT systems will continue to perform better, with lower operating costs [at high capacity] than BRT and greater peak capacity. The absence of advanced guidance technologies and platooning implies that BRT services will not provide an improved ride quality compared to traditional buses, and the speed and vehicle capacity of buses implies that the peak capacity will not exceed that of LRT in most cases. Unconstrained BRT systems similar to that implemented in Bogota, Colombia, may reach high peak capacities, although ride quality and urban amenity is compromised to achieve this. If technological development is high, the optimal solution may utilise both BRT and LRT, to provide complementary services with a better trade off between capital cost and benefits generated. A number of cities have opted to use both modes, such as Hamburg, Bogota, Rouen and Ottawa. LRT provides a high capacity transit spine, and BRT has been effectively implemented on cross routes, which integrate with light rail. Consideration of both systems is recommended due to the difference in spatial requirements; BRT can operate effectively on routes with broad rights of way and terminal capacity, while LRT provides high capacity on a narrower route, suited to central city locations.

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