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Urban High-Speed Rail Helps Australia's Megacity Sustainability
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ABSTRACT

Reducing transport emissions is a key challenge for United Nation's Resolution A/RES/70/1 Goal 11 (United Nations, 2015, pp. 21-22), sustainable cities and communities.

Urban high-speed rail requires much less energy per passenger-km than conventional transport modes (AECOM, 2013; Chester & Horvath, 2012; Davies & Thompson, 2009; Krishnan et al., 2015; Moran et al., 2014; Miyoshi & Givoni, 2012; Robertson, 2013). Being electric, renewable supplies offer further opportunities for greenhouse gas emission (GHG) reductions. This abstract proposes that high-speed rail within a sprawling large city would win market share from other transport modes.

The purpose of this paper is to stimulate innovation and encourage discussion about extending the strategic thinking about congestion and emissions to include high-speed rail systems that connect metropolitan and inner regional locations—rather than restricting the technology's potential to intercity and interstate travel.

A four-step transport model indicates that savings in travel time and oil-based fuel expenses can overcome modest rail fares and so win modal shift, especially for longer commuter journeys. These benefits are greater for lower-density megacities, which suffer more urban sprawl.

Preliminary train-timetable analysis suggests that the proposed capacity is adequate for the growing population**.** Brief commuter times can be sustained for decades.

Desktop modelling of GHG emissions from vehicle operation, assuming today's mix of electricity generation technology, shows that energy consumption drops sharply and that GHG emissions are comparable or considerably less than competing transport modes. Further reductions in GHG emissions could be achieved using renewable electricity generation.

Economic modelling suggests that the fare revenue alone recovers all operating costs and over half of capital costs.

The conclusion suggests there is enough upside or realistic promise in urban high-speed rail to include it as a serious strategy to reduce Australia's transport emissions and congestions issues over the coming century.

Australia is the world leader in urban sprawl. She is well placed to pioneer urban high-speed rail.

INTRODUCTION

This paper proposes the world-first application of high-speed rail (HSR) within an urban environment, to resolve many of the problems of urban sprawl, traffic congestion and future population growth.

Passenger rail networks are key components for the improvement in liveability of many large, growing cities. Experience of implementation of high-speed railway (HSR) around the world shows that the technology has the potential to significantly grow the economy and reduce environmental impact. HSR is defined by the speed it can attain. Typically, new railway lines that allow for 250km/hr travel, or existing railway lines that allow for 200km/hr travel, can be considered HSRs (International Union of Railways 2019).

When the Australian Government released its plan for the development of an East Coast High Speed Rail line in April 2013 (AECOM 2013), it was based on an Intercity Model. The focus was on express services to the capital cities—Melbourne, Canberra, Sydney, and Brisbane—with secondary consideration given to regional cities. The economic focus was on the displacement of aviation services. Commuter services were not proposed as they would "not positively contribute to the economic performance of high-speed rail" (AECOM 2013, p. 6). Indeed, although peripheral stations were proposed at the outer perimeters of Melbourne, Sydney and Brisbane, those stations would only pick up passengers on the outbound leg and drop passengers off on the inbound leg.

The Intercity Model is the predominant HSR model used internationally. China had about 25,000km of HSR lines in service at the end of 2018. Each city on the network has a single city station that connects to other HSR lines, and relies on connections with the metropolitan network to distribute and collect passengers. The three largest cities in China are Shanghai (26.3 million), Beijing (20.1 million) and Guangzhou (13.0 million). Shanghai-Hongquao station has 16 platforms and 30 tracks, Beijing station has 13 platforms and 32 tracks, and Guangzhou South station has 18 platforms and 32 tracks. China is the world's most populous country and has an average population density of 142.3 persons/square hectare.

By contrast, Australia has a population of 25 million and an average population density of 3.14 people/square hectare. The cities on the Intercity plan are Melbourne (5 million), Canberra (0.4 million), Sydney (5.5 million), and Brisbane (2.5 million). With the Melbourne to Canberra leg being 597km and estimated to cost $26.9 billion, Canberra to Sydney being 280km and $23.0 billion, and Sydney to Brisbane being 797km and $54.2 billion (AECOM 2013, p. 17), the Intercity Model makes HSR difficult to justify in Australia. The long distances and long construction timeframes before revenue-generating services can commence are economic disincentives.

Since the 1940s, Australia's transport development has been based on the private automobile. Freeways have been the principal infrastructure development, with established heavy rail lines being run down and light rail (with the notable exception of light rail in Melbourne) being removed to make way for the car. Sprawling suburban growth has been low density, facilitated by personal mobility and suburban activity centres that have historically (but recently less so) been connected with heavy rail lines. Dependence on the private car has seen demand for road-space outstrip supply with resultant traffic congestion. The annual cost of congestion in the major Australian cities (Bureau of Infrastructure, Transport and Regional Economics 2015) is estimated at $19 billion: $6.86 billion for Sydney, $5.81 billion for Melbourne, $2.76 billion for Brisbane, $2.31 billion for Perth, and $1.25 billion for Adelaide. By 2030, these costs are expected to increase to $36.4 billion: respectively $12.6 billion, $10.19 billion, $5.64 billion, $5.69 billion, and $2.25 billion.

Driven by the cry of sprawling Australian capital cities for new capacity along their principal transport corridors and considering the longer-term prospect of intercity HSR, a new Intracity HSR Model was developed. The Model follows a staged development approach:

1. Initial commuter HSR services in major cities
2. Extend into regional hinterland for regional development and population growth
3. Connect respective city services for intercity express services.

With this approach, Melbourne would require east-west, commuter HSR while Sydney, Brisbane, Adelaide, and Perth would require north-south. Canberra has too small a population to include peripheral stations for commuter services.

The aim of this paper is to stimulate innovation and encourage discussion about extending the strategic thinking about commuter HSR that connects metropolitan and regional urban centres. To do so, this paper presents a preliminary case for an intracity commuter HSR system, proposed by MegaRail Australia, across the greater Melbourne region. The next sections present the context, the proposed line, and the technology. The subsequent sections demonstrate the service's feasibility, including its potential to meet the service frequency and passenger demand, to operate with lower energy consumption and greenhouse gas (GHG) emissions than traditional passenger trains and cars, to be economically viable, and to generate broad economic benefits. The final section concludes by summarising findings and recommendations, and suggesting future work.

MELBOURNE CASE STUDY

The contiguous built form of greater Melbourne extends from Werribee in the west to Pakenham in the east, a distance of 90km by road or rail. Only 72km to the west of Melbourne, is Geelong (0.2 million), Victoria's second largest city. The V/Line regional rail service between Geelong and Melbourne central business district (CBD) is estimated to reach up to 140% capacity during peak hour (Jacks 2018). As such, MegaRail include Geelong in the commuter HSR service. Such a service aligns with the Australian Government's commitment to explore the opportunities for HSR in Australia's populous regions (Department of Infrastructure and Regional Development, 2017). Also, midway between Geelong and Werribee is Avalon Airport, which provides domestic aviation services through JetStar Airways and has recently been accredited for international services, including a daily service from Kuala Lumpur with AirAsia. Avalon Airport's strategic plan is to relocate the airport terminal onto the main railway line. Therefore, MegaRail also include Avalon as a stop in the service. The west of Melbourne HSR is shown in Figure 1.

Figure 1. High-speed rail alignment from Geelong to Southern Cross Station in Melbourne.

On the east side of Melbourne, about 30km from Melbourne and midway to the Pakenham extremity, is the major transport hub of Dandenong. Dandenong is adjacent to the Eastern Freeway, at the junction of the Pakenham and Cranbourne electrified railway lines, and the hub for numerous local bus services. It would be an excellent modal interchange point for a commuter HSR service. While Pakenham would be the logical end point for an eastern commuter HSR service, MegaRail selected Dandenong as the first-stage terminal for economic reasons. The infrastructure cost for Geelong–Dandenong has been estimated at $15 billion. The east of Melbourne commuter HSR alignment is shown in Figure 2 following.

Figure 2. High-speed rail alignment from Southern Cross Station in Melbourne to Dandenong.

SERVICE TYPE

The technology selected for the commuter HSR service is consistent with the proposed Australian national HSR system (AECOM 2013, pp. 116-117). The commuter HSR service adopts an operating speed of 350km/h to allow for integration into a national HSR network; a track design speed of 400km/h; and wheel-on-rail technology rather than magnetic levitation (maglev) technology.

To achieve 350km/h operating speed, a minimum 25km is required between stations. Distances from Geelong are 22km to Avalon, 46km to Werribee, 70km to Melbourne, and 100km to Dandenong. Therefore, only the Geelong–Melbourne and Melbourne–Dandenong services achieve full operating speed. The Geelong–Avalon, Avalon–Werribee and Werribee–Melbourne services each achieve 300km/h. For these estimates, a uniform average acceleration of 0.3m/s^2 and deceleration of 0.5m/s^2 (Connor 2014) is assumed. For track geometry a maximum centripetal acceleration of 1.0m/s^2 is adopted, requiring minimum curve radii of 9.4km at cruising speed.

For the Geelong to Newport section, the existing rail reserve is generally straight and conducive to 350km/h running. Existing tracks could be slewed to accommodate a central HSR track pair. In built-up areas, a double stacked cut-and-cover tunnel could be implemented, as shown in Figure 3.

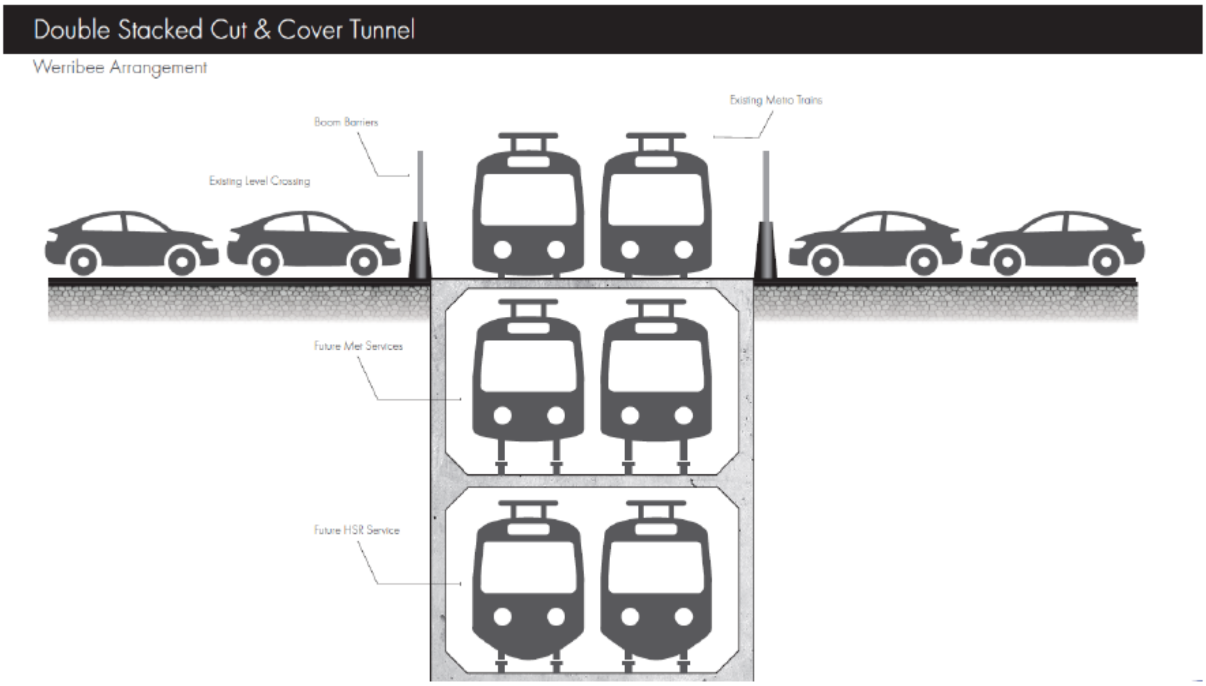

Figure 3. Double stacked cut-and-cover tunnel.

Twin bored tunnels are anticipated between Newport and Oakleigh to avoid the tortuous existing rail alignment. The Oakleigh to Dandenong rail section is also relatively straight but recently elevated by Skyrail. Options could be to widen Skyrail, continue the twin bored tunnels, or develop a new cut-and-cover alignment under the adjacent Princes Highway (the preferred option).

Maglev, the alternative to wheel-on-rail technology, is in the early stages of development for long lines. The Japanese Government has commenced construction of the 286km Chūō Shinkansen maglev line from Tokyo to Nagoya. This ¥5.52 trillion ($73 billion) project will deliver travel speeds of 505km/h and is scheduled for completion in 2027 (Railway Technology 2019). In 2018, the Australian Government Faster Rail program commissioned Consolidated Land and Rail Australia (CLARA) to undertake a study of HSR between Melbourne and Shepparton. The leading choice of train sets for CLARA appears to be the Chuo Shinkansen (CLARA 2019). The acceleration and deceleration of maglevs is superior to wheel-on rail and variously quoted as between $0.5 m/s^2$ to $1.0 m/s^2$. Assuming acceleration and deceleration of $0.64 m/s^2$ (Transrapid 2006), a distance of 30.2km between stops is required for 500km/h speed development. The minimum curve radius for maglev at cruising speed is 19.3km.

Maglev, however, was specifically rejected for the Australian HSR network for the following reasons (AECOM 2013, pp. 118):

- Cost: expected costs are about double that of conventional wheel-on-rail systems
- Construction: the longest existing maglev route is only 30.5km
- Maintenance: long-term maintenance issues are largely unknown
- Operations: cannot share tracks at multi-platform stations

SERVICE PLAN

To maximise the revenue from HSR, the service must meet the passenger demand (Vuchic, 2007, Ceder 2016). As such, the capacity, both from the track point of view (trains/hour) and the train point of view (passengers/train) are important (Vuchic 2007; Ceder 2016).

For commuter HSR services to achieve maximum patronage, stations need to be located at major transport network nodes. Geelong Station is at the transport centre of Victoria's second city, with heavy rail access via V/Line regional services, an extensive bus network, and main road access via Latrobe Terrace. Avalon Station is connected to Avalon Airport with good access to the Princes Freeway. Werribee Station is at the end of the electrified Melbourne Metro Werribee Line and has an extensive bus network and reasonable access to the Princes Freeway. While the station used to be serviced by V/Line, these services were deviated around Werribee on the Tarneit Line in 2016. Access to V/Line services could be restored by extending electrification to Wyndham Vale station. Southern Cross Station is at the centre of Melbourne's transport network—with Metro trains, V/Line regional trains, trams, regional buses, and the Melbourne Airport Skybus. While Dandenong was at the end of the electrified Metro Dandenong line, electrification was extended to Pakenham in 1975 and Cranbourne in 1995. As well as metro services, the station accommodates all V/Line Gippsland regional services, has an extensive bus network; and has good access to the Princes Highway East, Mulgrave Freeway, and Eastlink.

The service plan developed for the 100km MegaRail Geelong–Dandenong HSR service has sought to provide maximum advantage for passengers between Victoria's first and second cities, Melbourne and Geelong, by providing dedicated express services. To maintain a reasonable service at Werribee, the service includes short-start services, which start immediately after the passage of Geelong expresses. To round out the offering, the service includes an all-stops option. The three service types are Geelong–Melbourne expresses, Werribee–Dandenong shuttles, and Geelong–Dandenong all-stops services. Table 1 shows the estimated travel times. Station dwell times are 2 minutes, where required.

Service type	Geelong	Avalon	Werribee	Melbourne	Dandenong
Express	17 (13 for maglev)				10
Shuttle	-		9		10
All stops	8	8	9		10

Table 1. Travel times (minutes) between stops for the three types of service.

Figure 4 presents a concept train graph for the morning peak, showing how the services interact. Only ten high speed trains would be required to provide this service.

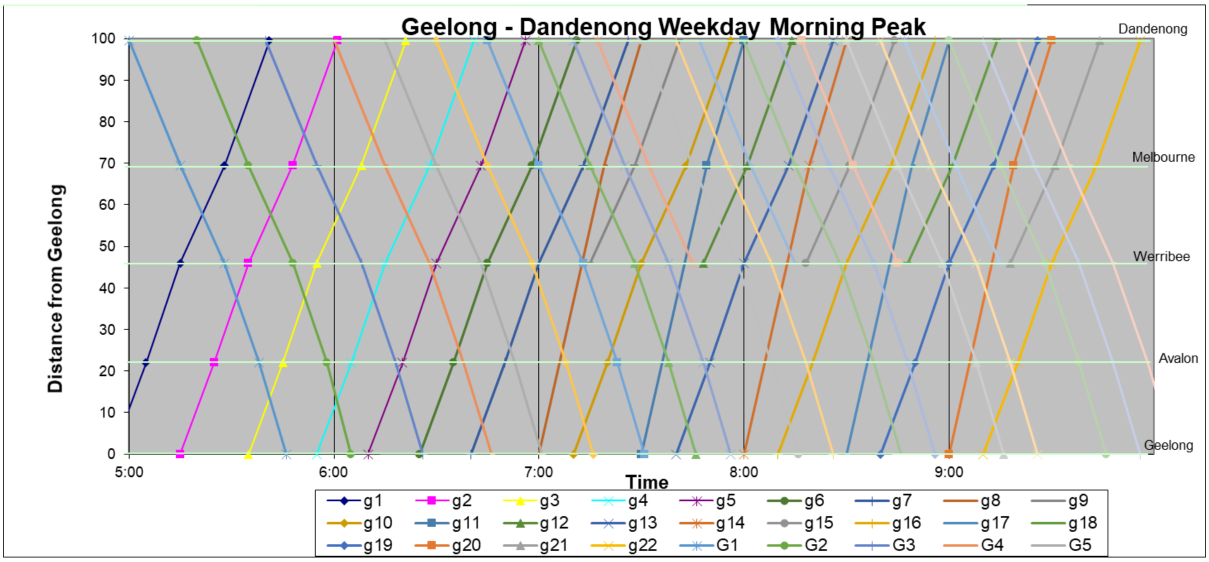

Figure 4. Geelong–Dandenong high speed rail concept service plan, morning peak, 5:00am-10:00am.

PATRONAGE ESTIMATION

Although a detailed estimate of patronage for the commuter HSR service between Geelong and Dandenong has not as yet been completed, a 2013 study of commuter HSR services on the eastern leg, Melbourne–Dandenong has provided significant insight into the impacts of the service on Melbourne's transport network. The study, undertaken for the Gippsland Local Government Network (GLGN) by AWTY Transport Consulting, used a four-step transport model to consider a 350km/h rail service from Melbourne to Traralgon with stops at Dandenong, Pakenham, and Warragul. Travel times of 13m, 12m, 15m, and 18m respectively were used with existing public transport fares. Existing heavy-rail user characteristics were used, with the model being unconstrained by existing network capacity. Modelling was undertaken for the 2021 census year with expected network developments included. Notably, the East-West Link and Melbourne Metro were excluded from the network. The results were that:

- commuter HSR services will attract two-way weekday patronage of 113,000 trips (136,000 for maglev).
- morning peak hour services out of Dandenong running at ten-minute intervals will have loads of 2,000 people per train. This volume is equivalent to removing 12,000 trips per hour (the vehicle-capacity equivalent of six freeway lanes) from the currently congested eastern transport corridor.
- commuter HSR services will increase public transport trips by 29,000 per day, with 25,000 per day coming from displaced car trips.
- commuter HSR services will provide one-way, travel-time savings for commuters of 30 minutes for Dandenong, 40 minutes for Pakenham, 70 minutes for Warragul, and 100 minutes for Traralgon.

The clear implications of the study are that:

- the huge travel-time savings afforded by commuter HSR services drive massive mode shift, substantially affecting future network development.
- the heavy throughputs at HSR stations require special consideration of transport network and land-use development.

From the 2013 study, it has been assumed that mirroring the development in the west to Geelong will double patronage. That is, the commuter HSR service could serve 200,000 passengers per day and 24,000 passengers per hour in the peaks. Because a modest increase in the fare price might deter some passengers, however, the overall patronage is assumed to be 160,000 passengers per day.

ENERGY CONSUMPTION AND GREENHOUSE GAS (GHG) EMISSIONS ANALYSIS

The analysis presented in this section is based on a model that estimates the electricity consumption of HSR train operation, the diesel consumption of traditional train operation, the petrol consumption of petrol car operation, the electricity consumption of electric car operation, and the resulting GHG emissions of each transport mode. A traditional train is compared because the existing V/Line service currently carries commuters between Geelong and Melbourne. Cars are compared because they currently carry the largest portion of travellers on the route sections. Although traditional trains and cars carry many commuters to and from Melbourne, only HSR services would be practical for most commuters over the whole Geelong–Dandenong route. In the model, the HSR train is a Bombardier 16-car V300 ZEFIRO, the traditional train is a 3-car V/Line VLocity, the petrol car is the average petrol-combustion car in Victoria, and the electric car is a pure electric car with a range of 500-600km. Each vehicle makes the all-stops, return trip of Geelong–Avalon–Werribee–Melbourne–Dandenong–Melbourne–Werribee–Avalon–Geelong. The HSR train also makes an express, return trip of Geelong–Melbourne–Dandenong–Melbourne–Geelong.

HSR train electricity consumption is dominated by train acceleration, aerodynamic drag, rolling resistance, climbing resistance. Therefore, the model uses engineering calculations to estimate the electricity consumptions of these tasks. It allows the train to accelerate while the total power requirements for those tasks remain below the estimated maximum power at the rail. The model assumes typical values for the energy conversion efficiencies of the powertrain, electrical infrastructure, and regenerative braking, as well as for the electricity consumptions of auxiliary services. The model assumes that the electricity consumption for climbing is zero when the train is on a decline and for braking is zero when the train is accelerating. For simplicity, the model assumes that the route's sections are straight and that the only speed limit is the train's maximum speed. Electricity consumption for the train is calculated using the below formulae, adapted from Robert Bosch GmbH (2004), with each symbol defined in Table A1 in the Appendix.

$E_{HSR} = ((1/\eta_t) (E_{DRAG} + E_{ROLL} + E_{ACCELLERATE} + E_{CLIMB} + E_{BRAKE}) + E_{AUXILIARY}) (1/ \eta_e)$

where,

$E_{DRAG} = \rho\ c_d\ A_{HSR} / v^3\ \Delta t / 2$

$E_{ROLL} = m\ c_r\ g \cos(\alpha)\ v\ \Delta t$

$E_{ACCELLERATE} = m\ a_a\ v\ \Delta t$

$E_{CLIMB} = m\ g \sin(\alpha)\ v\ \Delta t$

$E_{BRAKE} = m\ a_d\ v\ \eta_r\ \Delta t$

$E_{AUXILIARY} = P_{AUXILIARY}\ \Delta t$

In Australia, electricity is generated predominantly by the combustion of fossil fuels, leading to GHG emissions that contribute to climate change. The model uses its own estimates of the HSR train electricity consumption, converted to units of kWh. It assumes current values for the electricity GHG intensity the car petrol consumption, both of which might decline in the future with increasing deployment of renewable-energy and vehicle-electrification technology. The model estimates the energy consumption and GHG emissions for each trip, each vehicle-km, and each passenger-km. GHG emissions for the vehicles are calculated using the below formulae, with each symbol defined in Table A3 in the Appendix.

$G_{HSR} = E_{HSR}\ F_{ELECTRICITY}$

$G_{TRADITIONAL} = C_{TRADITIONAL}\ s\ F_{DIESEL}$

$G_{P\text{-}CAR} = C_{P\text{-}CAR}\ s\ F_{PETROL}$

$G_{E\text{-}CAR} = C_{E\text{-}CAR}\ s\ F_{ELECTRICITY}$

The model estimates that the electricity consumption of the 16-car HSR train for an all-stops, return trip is 13.1MWh or 0.055kWh/passenger/km; and for an express, return trip is 8.8MWh or 0.037kWh/passenger/km. The per-passenger-km consumptions are within the range reported in the literature (AECOM 2013; Davies & Thompson 2009; Chester & Horvath 2012; Gonzalez-Franco & Garcia-Alvarez 2012; Krishnan et al. 2015; Miyoshi & Givoni 2014; Robertson 2013; Westin and Kågeson 2012). The model estimates that, for a return trip, the diesel consumption of the traditional train is 906 litres or 9.7MWh, the petrol consumption of the petrol car is 20.8 litres or 198kWh, and the electricity consumption of the electric car is 36kWh. In the model, the petrol and electricity consumptions of the cars leads to GHG emission rates per vehicle-km that are within the range reported by GreenVehicleGuide (2019).

Table 2 summarises the energy consumptions and GHG emissions per passenger-km given a range of vehicle occupancies, ignoring the standing room available on trains (which would increase passengers, decrease energy consumption, and decrease GHG emissions). It shows results assuming the 2018 Victorian electricity generation mix [76% brown coal, 17% renewable (Department of the Environment and Energy 2019)] to align with the case study; the 2018 average Australian electricity generation mix [46% balck coal, 19% renewable (Department of the Environment and Energy 2019)] to reflect the wider adoption of intracity HSR in other cities; and near-100% renewable electricity generation to reflect a likely future.

In Victoria, the fully-loaded diesel traditional train has around four times the energy consumption of the fully-loaded HSR train but similar GHG emissions because electricity generation in Victoria is far more GHG-intensive than diesel combustion (Department of the Environment and Energy 2018b). The HSR train has lower GHG emissions on the express trip than on the all-stops trip because it undergoes less total acceleration throughout the trip. Further analysis shows that an 8-car HSR train carrying at least 174 passengers would have lower per-passenger emissions than a petrol car occupied by the current average of 1.1 persons (0.224kg CO_2-e/passenger/km), and with at least 222 passengers, would have lower per-passenger emissions than an electric car occupied by the current average of 1.1 persons (0.175kg CO_2-e/passenger/km). Vehicle operation powered by renewable electricity sources has near-zero GHG emissions.

Commuter HSR and existing V/Line services can operate with nearly full trains because they can add or remove seats (carriages) to match demand. Cars lack such flexibility. Therefore, the GHG emissions of an HSR train are, at worst, comparable to those of a traditional train—but considerably lower if assuming renewable electricity use—and about 20% of those for a single-occupancy petrol car.

Vehicle	Passengers	Energy consumption (kWh/passenger/km)	Greenhouse gas emissions (kg CO_2-e/passenger/km)		
			Victoria (2018)	Australia (2018)	100% renewable
HSR train (8-car, all stops)	600	0.061	0.065	0.049	Near zero
HSR train (16-car, all stops)	1200	0.055	0.058	0.044	Near zero
HSR train (8-car, express)	600	0.044	0.047	0.035	Near zero
HSR train (16-car, express)	1200	0.037	0.039	0.029	Near zero
Traditional train	100	0.486	0.123		
Traditional train	222	0.219	0.056		
Petrol car	1	0.99	0.246		
Petrol car	2	0.49	0.123		
Petrol car	5	0.20	0.049		
Electric car	1	0.18	0.193	0.144	Near zero
Electric car	2	0.09	0.096	0.072	Near zero
Electric car	5	0.036	0.039	0.029	Near zero

Table 2. Energy consumption and greenhouse gas emissions of vehicle operation.

ECONOMIC (FINANCIAL) ANALYSIS

HSR addresses Melbourne's $10 billion p.a. congestion costs

The demand for peak-hour east-west transport services across greater Melbourne is currently high and expected to grow. Melbourne's infrastructure under construction is intended to serve a population of 5 million persons by 2051 (Eddington 2008). The city's population, however, has already reached that size and is now projected to grow to up to 9.8 million persons by 2051 (Australian Bureau of Statistics 2018). Therefore, without further intervention, Melbourne's infrastructure will be drastically under capacity. The commuter HSR service contributes significantly to meeting the demand by maximising the capacity utilisation of scarce east-west corridor space.

A recent Infrastructure Australia (2019a, p. 265) audit found that, despite over $200 billion of programmed investment in new transport infrastructure across Australia, Melbourne, Sydney, and other major urban regions will suffer increasing congestion, with the national annual cost of lost productivity due to gridlock set to grow from $18.9 billion in 2016 to $38.8 billion in 2031. The annual cost of congestion across Melbourne and Geelong would rise from $5.5 billion to $10.4 billion annually (Infrastructure Australia 2019b, pp. 7, 63).

Of the worst driver commutes identified in Australia, by far the two most congested are those specifically addressed by the MegaRail proposal: Geelong to the CBD via the Princes and Westgate Freeways, with a predicted 120-minute daily delay due to congestion (over an uncongested run time) in 2031; and Pakenham to the CBD via the Princes Freeway, with a 114-minute daily delay in 2031 (Infrastructure Australia 2019b, pp. 20, 65, 68).

Cash flows to cover operating and most capital costs

The analysis summarised in this section is based on a preliminary cash-flow model that estimates that the fare revenue alone recovers all operating outflow and over half of capital outflow. The precise fares are commercial-in-confidence. The model makes the following assumptions:

- Fares are within the ranges reported by AECOM (2013) and Sanchez-Borras et al. (2010), and are modest compared to international benchmarks. They are slightly higher than the existing V/Line service fares, which passengers pay twice per day. They are also considerably lower than those for existing HSR services, which, being based on the Intercity Model, compete with airlines.
- Fares are applied to the 160,000 passengers per day reported in 'Patronage estimation' and by MegaRail Australia (2019), which summarises the outcomes of MegaRail seminar at RMIT Univeristy in which participants broadly agreed that the estimated patronage represented the conservative lower end, or floor, of the wide range possible.
- Non-energy operating costs are unit costs taken from AECOM (2013). Operating labour is the largest cost centre, followed by ticketing and net advertising, rolling stock maintenance, insurance, infrastructure maintenance, and staff recruitment-training.
- Electricity consumption is as estimated in 'Energy consumption and greenhouse gas emissions analysis', and electricity prices are professionally estimated through collaboration with authoritative industry experts.
- Capital expenditure on infrastructure is spread over three years at $5 billion per annum. The rolling stock is estimated at $1 billion.

BROADER BENEFITS

Commuter HSR, demonstrated in this paper by MegaRail's proposed project, offers a range of benefits. Benefits to passengers are as follows:

- Fast travel times, as shown in Table 1: Travel time is the primary criterion that many commuters consider when selecting their transport mode. A 2005 survey of Sydney households found that 48% of commuters chose to travel by car because it was faster (Corpuz 2007). Another study concluded that travel time was the most important consideration when passengers select their preferred public transport mode (Fearnley et al. 2018).
- Frequent services, as shown in Figure 4: HSR services are reliable, perform in any weather conditions, and are unaffected by road congestion.
- High-quality service: HSR trains provide adequate seat capacity, a comfortable passenger cabin, and a space to work. HSR services have an excellent safety record.
- Reasonably-priced fares, as presented in the 'Economic (financial) analysis': Fares may be set at a level that are competitive with those of alternative transport modes while, with other revenue plus value capture, still enabling cost recovery and minimising government subsidies.
- Lower household transport costs: Expenditure on taxed fuels and compulsory road charges constitute more than 4% of the average household's income and around 8% of the poorest (bottom income quintile) households' income (Australian Bureau of Statistics 2004 cited in Moving People 2030 Taskforce 2013). To make the Geelong–Melbourne–Geelong trip by car, commuters would typically pay for the car purchase; car maintenance; and energy, which the energy consumption model shows is 9.4 litres of petrol or 16.2kWh of electricity. The HSR fare is lower or competitive with these car costs under a wide range of scenarios.
- Improved wellbeing: The effects on wellbeing of fast, comfortable commutes on HSR seem to starkly contrast those of long, congested commutes in cars or crowded public transport. In a survey that asked 900 Texan women to rank their enjoyment of various activities, commuting came in last, being described as by the authors as "particularly unpleasant" (Kahneman & Krueger 2006). A Swedish study found that couples are 40% more likely to separate if one partner has a one-way commute of more than 45 minutes per day. Furthermore, long, congested commutes, such as those in cars or crowded public transport, can lead to obesity, chronic pain, loneliness, stress and insomnia; and reduce time for social, leisure and physical activities.

Benefits to operators and the electricity market are as follows:

- Less exposure to the electricity market and GHG taxes: The HSR train could be powered by renewable electricity sources, including those directly owned by the HSR operator. Some of the capital costs would be traded-off against the additional investment otherwise required to upgrade the existing mains electrical infrastructure. Thereafter, the electricity supply costs would be considerably lower than purchasing mains electricity. Solar photovoltaic (PV) systems could meet much of the demand because the train services occur largely during daylight hours. PV electricity generation requires a relatively large area, most of which could be met by PV farms on undeveloped areas along the route; the train roof and infrastructure roof have the area to provide only a few kilowatts of power. Batteries could store excess charge for consumption by the morning and evening train services. Wind power systems could also contribute to meeting the demand, given that the western portion of the route is near a region concentrated by existing wind farms (Geoscience Australia 2019). Hydrogen fuel cells could contribute while the train is cruising, when power demand is relatively low. Restricting the technology to this specific application helps to keep the system size and capital costs relatively low.

Benefits to governments and society are as follows:

- Higher network redundancy: The commuter HSR service, being a high-capacity alternative to the existing competing modes, provides network redundancy (Stone 2019). The redundancy accommodates a shift by passengers in the events of episodic interruptions or the pending systemic undercapacity. Thus, capital expenditure to augment capacity on traditional train or road can be deferred or avoided. Furthermore, in the event of a catastrophic breakdown in the service of a competing mode, such as the collapse or closure of the West Gate Bridge, the HSR service can provide enough east-west capacity to prevent social bifurcation of greater Melbourne by the Maribyrnong River. It is noted that currently planned HSR capacity could be tripled by reducing headways (train frequency intervals) from 10 minutes to 3 minutes.
- Improved road utility for other users: Grade-separated transit reduces delays on parallel roadways (Litman 2007). Initial modelling suggests that HSR will displace 50,000 car trips per day. Thus, roadway utility improves for other users, especially freight operators.
- Solution to urban sprawl: HSR will restructure cities by encouraging multi-centric, high-density, mixed-use development around stations. These transit-oriented developments (TODs) are compact, walkable urban villages where residents tend to own fewer cars and drive less than residents of other neighbourhoods (Litman 2007).
- Productive technology, education, medical, and industry clusters: HSR encourages and enables the development of technology and industry clusters, with fast, easy access between locations. Professionals can work in several different locations in a single day. The State Government of Victoria has targeted seven National Employment and Innovation Clusters for Melbourne—including Werribee and Dandenong (Department of Environment, Land, Water and Planning 2017).
- Economic growth and employment: HSR fosters economic development in second-tier cities along train routes. It also links cities to create integrated regions that function as single, stronger economies, broadening labour markets and offering workers a wider industry network (US High Speed Rail Association 2018) with multiple employment locations. In a German study (Ahlfeldt & Feddersen 2010), economists found "compelling evidence" that towns connected to a new HSR line saw their GDP increase by up to 2.7% compared to neighbours not on the route. Further, increased market access through HSR has a direct correlation with GDP–for each 1.0% increase in market access, there is a 0.27% rise in GDP. In another study (Zheng & Kahn 2013), the authors found that Chinese HSR drove rising real estate prices, especially in nearby secondary cities—improving quality of life, reducing air pollution and traffic congestion, and providing a "safety valve" for crowded cities. HSR also improves market access, expands labour markets, and enhances spatial agglomeration. Introduction of the HSR accounted for 59% of the average connected city's increase in market potential[1], a parameter for which each 10% increase is associated with a 4.5% increase in average house price. House prices were estimated to increase

[1] 'Market potential' is a variable incorporating a city's population growth and quality of life factors such as green space, hospital beds per 10,000 persons, and pupil-teacher ratios. 'Housing price' is based on housing sales price data in the four connected cities in the study.

by an average of 4.3% per billion passenger kilometres travelled.

- Increased tourism: HSR also expands visitor markets and tourism, particularly in regional areas, while increasing visitor spending (US High Speed Rail Association 2018).

Commuter HSR is a good fit for greater Melbourne and Geelong. The Department of Transport (2019) states that over 40% of Melbourne's population growth in the next 15 years is expected in new developments in the north, west and south-east. Melbourne's west, in particular, is growing twice as fast as elsewhere in the city. This growth is the reason for the alternative crossing to the West Gate Bridge and the major upgrades to the region's arterials, but more infrastructure will be needed.

The proposed commuter HSR service is the optimal engineering solution to these priority issues, linking the four fastest-growing local government areas (LGAs) in Australia–Wyndham (Werribee), Cranbourne (Dandenong), Melbourne, and Cardinia (Dandenong), which have an average population growth of 5.2% per annum. The service provides a long-term solution to the city's east-west traffic flows, noting that Melbourne's population is already at the 2051 levels predicted in the landmark transport study by Eddington (2008).

Despite the commuter service being a new approach to HSR by primarily servicing commuters, it has already generated significant, behind-the-scenes support from multiple stakeholders. With congestion at critical levels and transport infrastructure now established as a critical election consideration at all levels of government, the time is right to focus on innovative proposals that offer genuine, long-term solutions. In addition, public transport patronage growth rates in Melbourne since 2000 are among the highest in Australasia (Moving People 2030 Taskforce 2013), suggesting a likely rapid take-up for a new transport mode that delivers a high quality, cost-effective service with significant, and tangible, economic and non-economic benefits.

CONCLUSIONS & RECOMMENDATIONS

This paper presented preliminary analyses that demonstrate the feasibility of MegaRail's commuter HSR service in greater Melbourne. The results provide a basis for ongoing discussion and progress towards HSR in Australia. They demonstrate the feasibility of the Intracity Model—the service can meet the expected patronage with high frequency and fast travel times, and it does so with fewer GHG emissions than competing modes. The results also demonstrate the economic advantages of an Intracity Model over an Intercity Model—the cash flow from fares alone will be sufficient to cover full operational costs and the majority of capital costs. Among the broader benefits, the service would aid resolution of urban sprawl and traffic congestion, while the addition of significant capacity on the east-west transport corridor, in particular, would help overcome limitations of competing transport modes, including already capacity-constrained new infrastructure.

Future work is to develop and broaden the analyses into pre-feasibility studies that support a complete cost-benefit analysis. Such an analysis would assist in exploring and resolving debates about the feasibility and practicality of HSR for Australia, particularly within an urban and regional context.

Australia is the world leader in urban sprawl. She is well placed to pioneer commuter HSR services.

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APPENDIX

Symbol	Description	Unit	Value	Comment
E	Electricity consumption	J		Calculated by the model for each vehicle.
η_t	Drivetrain efficiency		0.6	Taken from Feng et al. (2014).
η_e	Electrical infrastructure efficiency		0.9	Assumed typical efficiency.
ρ	Air density	kg/m^3	1.225	Assumed ambient temperature of 15°C.
c_d	Drag coefficient		0.4	Assumed a base value of 0.5 based on Yang et al. (2017), who use 0.316-0.354 for a 3-car train. Reduce to 0.4 based on the estimate of 25% less drag by Bombardier Transportation (2010).
A_{HSR}	Frontal area	m^2	11.9	Approximated as the rectangular area based on the vehicle height and width reported by Bombardier Transportation (nd).
v	Speed	m/s	0-300	Calculated by the model up to the assumed maximum for the application.
Δt	Duration	s	Variable for each segment	
m	Mass	kg	16-car: 1,004,000 8-car: 502,000	Estimated from the 17t axle load for 16 cars reported by Bombardier Transportation (2015) and the assumed 80kg load for each of the 1200 passengers.
c_r	Rolling resistance coefficient		0.001	Assumed for railroad steel wheels on steel rails.
g	Gravitational acceleration	m/s^2	9.81	Assumed at sea level.
α	Angle of ascent	Radians	See Table A2	Estimated assuming a triangular section with a hypotenuse reported by Google Maps (nd) and a height reported by Victorian Government (nd).
a_a	Acceleration	m/s^2	0.18	Assumed based on 25% of a starting acceleration of 0.7 m/s^2 reported by Bombardier Transportation (2015).
a_d	Deceleration	m/s^2	-0.67	Estimated based on linear interpolation between decelerations of -0.6 for v>200km/h and -0.8 f v>200km/h reported by Bombardier Transportation (nd).
η_r	Regenerative braking		0.28	Taken from Gonzalez-Franco & Garcia-Alvarez (2012).

	efficiency			
$P_{AUXILIARY}$	Auxiliary power	W	150,000	Estimated based on the 0.8kWh/km reported by Gonzalez-Franco & Garcia-Alvarez (2012) and 10% of traction power reported by AECOM (2013, Appendix 4C, p.3).
P_{MAX}	Maximum power at rail	W	19,600,000	Estimated as double the power for the 8-car train of 9.8MW @ 300 km/h reported by Bombardier Transportation (2015).

Table A1. Parameters and values for calculations of train electricity consumption.

Location	Cumulative distance (km)	Elevation (m)	Angle of ascent to location (radians)
Geelong	0	15	-
Avalon Airport	22	20	0.00020
Little River	31	40	0.00333
Werribee	46	22	-0.00120
Laverton	57	8	-0.00127
Melbourne	70	10	0.00015
Huntingdale	88	65	0.00306
Dandenong	100	20	-0.00375

Table A2. Cumulative distances, elevations, and angle of ascents for each stop and each intermediate location [distances estimated from Google Maps (nd); elevations estimated from Victorian Government (nd)].

Symbol	Description	Unit	Value	Comment
G	Greenhouse gas emission	kg CO_2-e		Calculated by the model for each transport mode.
E_{HSR}	HSR train electricity consumption	kWh		Estimated by the model.
$F_{ELECTRICITY}$	Electricity GHG intensity	kg CO_2-e/kWh	Victoria: 1.07 Australia: 0.8 100% renewable: 0.0	Values for Victoria and Australia reported by Department of the Environment and Energy (2018b). Assume that renewable electricity generation has zero GHG emissions.
	HSR train trips	1/day	58	Assume 50 trips during 5am-12am (midnight).
	HSR train seats occupied	Seats	8-car: 600 16-car: 1200	Maximum of 600 (8-car) or 1200 (16-car) seats reported by Bombardier Transportation (2015).
F_{DIESEL}	Diesel GHG intensity	kg CO_2-e/MJ	0.071	Calculated from Department of the Environment and Energy (2018b).
$C_{TRADITIONAL}$	Traditional train energy consumption	MJ/passenger/km	0.787	Estimated based on the 0.8391MJ/passenger/km energy consumption and 93.86% contribution by train operations reported by V/Line (2018).
	Traditional train seats occupied	Seats	100, 222	Assume maximum of 222 seats.
F_{PETROL}	Petrol GHG intensity	kg CO_2-e/litre	2.37	Calculated from Department of the Environment and Energy (2018b).
$C_{P\text{-}CAR}$	Car petrol consumption	litre/km	0.104	Assumed to be the average petrol consumption of Victorian petrol passenger cars reported by Australian Bureau of Statistics (2019).
$C_{E\text{-}CAR}$	Car electricity consumption	kWh/km	0.18	Assumed to be the rated electricity consumption of Tesla Model 3 Standard reported by GreenVehicleGuide (2019).
s	Distance	m	See Table A2	Estimated based on distances reported by Google Maps (nd).
	Car seats occupied	Seats	1,2,5	Maximum of 5 seats assumed for a typical sedan.

Table A3. Parameters and values for calculations of greenhouse gas emissions