Total water requirements of passenger transport modes

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Abstract

With a growing urban population, it is crucial to maintain and develop environmentally friendly transport modes. However, while one of the most important indicators of environmental performance is water use, very few studies have quantified the total water requirements associated with different transport modes.

This study uses input-output analysis to quantify the total water requirements of different passenger-transport modes in Melbourne, Australia, including the direct and indirect water requirements of petrol cars, regional diesel trains and electric metropolitan trains.

Results show that urban electric trains are the least water intensive transport mode (3.4 L/pkm) followed by regional diesel trains (5.2 L/pkm) and petrol cars (6.4 L/pkm). These intensities result in average daily per capita transport-related water use that can be greater than residential water use. Findings also show that occupancy rates greatly affect the water intensity of transport modes and that when occupied by five passengers, cars are the least water intensive transport mode. Finally, this study shows that water use associated with transport depends on a range of factors across the supply chain and that indirect requirements associated with operations, including administration, advertisement, servicing and others, can represent a significant share of the total. Reducing the total water requirements of transport modes is therefore a shared responsibility between all the actors involved and integrated action plans are needed in order to reduce water use associated with transport.

1 Introduction

1.1 The significance of water use in transport

The world's population is expected to grow by 2.7 billion persons in the coming decades and cities will absorb almost all population growth according to current projections (U.N., 2012). This urban growth increases the pressure on transport systems in terms of private transport modes (e.g. cars), public transport modes (e.g. trains) and transport infrastructure (e.g. roads and railways). The good functioning of transport infrastructure systems, both private and public, is essential to the mobility and quality of life of city dwellers (Rogerson, 1999; Ritsema van Eck et al., 2005; Steg and Gifford, 2005; Feng and Hsieh, 2009).

The construction and use of private and public transport systems often results in a number of environmental impacts. For instance, it is well understood that a reliance on cars leads to a significant increase in energy use and greenhouse gas emissions compared to public transport modes (Newman and Kenworthy, 1999; Jenks et al., 2000; van de Coevering and Schwanen, 2006; Karathodorou et al., 2010). This is one of the key drivers for a greater integration of public transport systems in proposals for sustainable city development (Kenworthy, 2006; De Vos and Witlox, 2013) and the consideration of multi-modal transport systems to reduce urban sprawl (Spickermann et al., 2014). However, most studies assessing the environmental impact of transport modes have focused on energy use and greenhouse gas emissions, notably in terms of direct requirements (such as burning fuel in an engine). Only a few studies have investigated both direct and indirect energy requirements and greenhouse gas emissions of transport modes (Lenzen, 1999; Jonson, 2007; Chester and Horvath, 2009). Some other studies have considered other environmental impact categories (such as acidification, ozone depletion and others) using a life cycle assessment (LCA) approach (Spielmann and Scholz, 2005; Chester and Horvath, 2009; Bauer et al., 2015) or combining LCA with a life cycle cost analysis (Banar and Özdemir, 2015). Very few consider water use.

Water is a necessity for all living organisms and is becoming a scarce resource in some geographical areas due to urbanisation and reduced access to water (Bourne and Wouters, 1997). Also, an increasing number of regions across the world are expected to be subject to droughts in the coming decades (IPCC, 2013), increasing water stress (Parish et al., 2012). These regions include Central America, the Mediterranean basin, Southern Africa, South-East Asia, Eastern Australia and

other densely populated areas (Dai, 2011). For all these reasons, water use is and will increasingly become a critical factor to consider in environmental assessment studies. Sustainable transport systems are essential to achieve more sustainable cities (Martos et al., 2016). Including water requirements in the evaluation of the environmental performance of transport systems broadens the assessment beyond energy and greenhouse gas emissions and provides a more comprehensive understanding of transport system environmental effects. This is even more important where water is removed from current or forecasted water-scarce regions.

Water is generally accounted for within the framework of the 'water footprint' (Water Footprint Network, 2013), that estimates the total amount of water associated with a product or service, e.g. a pair of jeans (Chico et al., 2013) or meat products (Gerbens-Leenes et al., 2013). The United Nations have also established a system for water accounting (UNSD, 2012) that relies on input-output analysis (see Section 3.2). Water trade across the economy has also been assessed in different studies (Dietzenbacher and Velázquez, 2007; Lenzen, 2009; Daniels et al., 2011; Cazcarro et al., 2013; Lenzen et al., 2013a) using multi-regional input-output analysis (see Section 3.2).

While some studies advocate for the inclusion of water in the calculation of the environmental performance of transport systems (e.g. Smith *et al.* (2013)), very few studies have assessed water requirements of transport modes (see Section 2.2 for a detailed review of exiting studies). Among these, are studies that have calculated the amount of water associated with producing and using bio-fuels (Gerbens-Leenes and Hoekstra, 2011; Lampert et al., 2016) which are very water intensive. They also assess the water requirements of car manufacture and operation (Schweimer and Levin, 2000; Bras et al., 2012) and the total water requirements of a household (Crawford and Pullen, 2011). A much smaller number of studies have assessed the total water requirements of different transport modes. An example is the study undertaken by Saari *et al.* (2007) on road-based transport modes in Finland. There is therefore a need for a better understanding of the total water requirements of a range of passenger transport modes.

1.2 Aim and scope

The aim of this paper is to quantify the total water requirements of major urban passenger transport modes in order to inform decision-making regarding the environmental performance of urban transport systems.

This paper focuses on water requirements of major passenger transport modes in Melbourne, Australia. In this work, water requirements refer to water use, that is the total gross quantity of water input required. This definition is different from what Bras *et al.* (2012) define as water consumption which refers to the actual quantity of water vaporised or embedded in materials, in other terms, water that is not immediately recoverable after its use. Relying on water use provides a more comprehensive picture and is more suitable for determining total requirements (direct and indirect) as the fate of the water used is not known.

Using input-output analysis, this study captures all the different inputs associated with the annual expenditure of public transport operators, infrastructure management authorities and private car owners. The scope of the study therefore covers all life cycle stages and inputs across the economy, disaggregated according to the level of detail available in the input-output tables used (See Section 3.2). The recovery of embodied water through material recycling at the end-of-life stage is however not taken into account. The allocation of the recycling or recovery value of a material is a controversial issue (Udo de Haes and Heijungs, 2007) since there is no common agreement about how it should be dealt with. Two main schools of thought exist in this regard. The first argues that the energy/water content of recycling should be deducted from the life cycle requirements. The second point of view stresses that the ultimate fate of the material or vehicle is unknown, especially when it has a long service life (like a train or a car), and therefore the benefit should be attributed to the recycled material in the future and not to the present one (Treloar, 2000). While the first perspective can favour the use of recyclable materials the second position results in more conservative values and adopts a more pragmatic perspective. It is therefore adopted by the authors in this study.

Firstly, water requirements of transport are described in Section 2 followed by a review of existing studies in the field. Section 3 describes the method used to quantify the total water requirements for the urban transport system of Melbourne, including data sources used. The total water requirements of the various transport modes are given in Section 4 and Section 5 discusses the results before concluding and proposing future research in Section 6.

2 Water requirements of transport

This section first describes the direct and indirect water requirements of transport modes before presenting the findings of previous studies.

2.1 Direct and indirect water requirements of transport modes

Water is needed for travelling both directly and indirectly, using any transport mode. Direct water requirements include its use in cooling circuits and for vehicle washing. While direct energy requirements of transport have been shown to represent ~55% of the total energy use (Lenzen, 1999; Jonson, 2007), the direct water requirements are typically not as significant. Schweimer and Levin (2000) have shown that direct water requirements can be as low as 8% of total water demand while, Crawford and Pullen (2011) state that it is "*insignificant compared to embodied requirements*" and Stephan and Crawford (2014) show that it can be less than 2% of total water demand. Most water requirements associated with transportation are therefore indirect requirements.

Indirect requirements represent all the water use, across all the supply chains that support the transport mode. For instance, indirect water requirements for car transport are associated with its manufacture, fuel production, insurance, registration, maintenance and repairs, road infrastructure and other aspects. Indirect water requirements for train transport would be associated with its manufacture, electricity generation (or fuel production in case of a diesel train), facilities operation, rail infrastructure, maintenance and other aspects. These examples reveal a very small portion of the extremely long and complex list of processes and services that are associated with the use of various transport modes. In order to provide a comprehensive assessment of water requirements, all processes and services, across the entire supply chain must be taken into account. Quantifying the total water use, across the entire supply chain requires the use of input-output analysis which is described in Section 3.2. Among similar previous studies, very few have considered total water requirements. This is discussed in more detail in the following section.

2.2 Previous studies on the water requirements of passenger transport modes

Only a small number of studies have investigated the water requirements associated with transport modes. Most of these studies have focused on road transport, notably cars.

A significant body of literature has focused on quantifying the embodied water requirements associated with the production of biofuels since these result in a significant water demand for growing crops (inter alia Gerbens-Leenes and Hoekstra, 2011; Scown et al., 2011; Gerbens-Leenes et al., 2012; Lampert et al., 2016). For instance, in their recent study of the life cycle water use associated with fuel production in the United States, Lampert et al. (2016) found that light duty vehicles operating on biodiesel have a water intensity of 434-2 964 L/100 km with an mean value of 657 L/100 km.

Assuming an annual travel distance of 15 000 km, this equates to 99 kL per year associated with water demand, which is very significant. These water intensities are within the same order of magnitude of those found by Scown et al. (2011), who also studied fuel production in the United States. These authors quantified water intensities of 100-1 500 L/100 km for a range of different fuels.

In their report, Schweimer and Levin (2000) established a life cycle inventory of the Volkswagen Golf™ cars. Their inventory included a range of indicators such as energy and water inputs as well as greenhouse gas emissions and solid waste. In their study, they found that a car uses 95 kL of water across its life cycle, including for raw material extraction, material manufacture, processing and transport, assembly, use (10 years) and end-of-life. This is less than the annual water demand associated with the fuel production of a biodiesel vehicle (Lampert et al., 2016). The water use quantified by Schweimer and Levin (2000) was distributed among electric power generation (48%), fuel production (24%), material production (11%), car washing (8%) and other factors (9%). Their life cycle inventory was based on a 'process analysis' technique which maps the supply chain of a product or process and lists all associated the inputs and outputs. While this technique utilises highly specific data from production plants (in this case Volkswagen), it suffers from the 'truncation error' which can result in the omission of more than 50% of the total resource requirements (Lenzen, 2000) and sometimes up to 87% (Crawford, 2008).

Bras *et al.* (2012) rely on the same technique to quantify the so-called 'water consumption' associated with a typical American car. As described in Section 1.2, water consumption refers to the amount of water vaporised during a process and/or embedded in a material, that is water that is not immediately recoverable. They also compared the water consumption to the total water use of the car and found 60 kL and 363 kL, respectively. The breakdown of water consumption and water use reveals a contribution of material production (9%; 47%), parts production (1%; 10%), original equipment manufacture (OEM) assembly/production (1%-4%; 1%-2%), the use phase (in terms of fuel production for 160 000 km of driving distance) (87%; 42%) and recycling (~0%; 1%), respectively. They also highlight "*the significant uncertainty and ambiguity that exists in [life cycle assessment] databases and literature regarding water use and consumption data*" (Bras et al., 2012).

In their study of the total water requirements of an Australian household, Crawford and Pullen (2011) take into account the water associated with motor vehicles. They find that motor vehicles are responsible for the use of 16 452 kL of water over 50 years. Yet, their study does not consider public

transport modes and provides a total estimate instead of a water intensity per passenger kilometre for car transport. It is interesting to note that their water use figure for a single vehicle over a life cycle of 17 years is 2 234 kL or 131 kL/year. This figure is 3.6 and 1.38 times higher than the water use figures obtained by Bras *et al.* (2012) (assuming a 10 year life span for the car) and Schweimer and Levin (2000), respectively. This higher figure is probably due, among other factors, to the use of the more comprehensive input-output approach (see Section 3.2), avoiding the truncation error associated with the process analysis approach. The water requirements quantified by Crawford and Pullen (2011) also reveal the significance of the water intensity of biofuels in comparison, i.e. considering the overall life cycle water demand of a vehicle over 17 years results in an annual water demand only 32% higher than the water demand associated with the production of biofuel only.

Saari *et al.* (2007) have produced water intensity figures for different transport modes in a Finnish context. In their work, the authors determined the average water intensity of different road-transport modes (e.g. cars and buses) on different types of roads (e.g. motorway or regional road). They also evaluated the water intensities of freight transport. Their assessment includes material inputs calculated using a German process-based database of embodied water from the Wuppertal Institute. The allocation of the water embodied in transport infrastructure was performed based on either the traffic volume or the gross vehicle weight. Their analysis showed that the allocation technique chosen has a significant influence on the final results. Based on a traffic volume allocation, they found a water intensity per passenger-kilometre (pkm) for cars of 2.98 L/pkm, 6.57 L/pkm, 8.65 L/pkm and 27.95 L/pkm for motorways, a main road, a regional road and a connecting road (local road), respectively. They considered a 270 000 km driving distance in determining the water requirements associated with the operational phase of the car's life cycle. If a car is driven 15 000 km per year as in Schweimer and Levin (2000), this equates to 18 years for the service life of the car. Using this figure, the average water use per year for a car as calculated by Saari *et al.* was 30 kL. This figure is 18% and 68% lower than those presented by Schweimer and Levin (2000) and Bras *et al.* (2012), respectively, and represents only 23% and 30% of the figures obtained by Crawford and Pullen (2011) in Australian conditions (using input-output data) and by Lampert et al. (2016) for a biodiesel-powered car in the United States, respectively.

Most existing studies rely on process data to quantify the water requirements of road passenger transport. Only the study of Crawford and Pullen (2011) determines water requirements using the

more comprehensive input-output analysis but this is done only for cars and does not include associated infrastructures. Saari *et al.* (2007) determine water intensities per passenger kilometre for cars but do not include non-material inputs such as insurance, registration and others. Lampert et al. (2016) quantify the water intensities associated with fuel production and take into account the fuel efficiency of different cars to estimate water intensities per vehicle-kilometre. However, their study does not cover other transport modes or requirements upstream in the transport supply chain. A more comprehensive assessment of the total water requirements of urban transport modes is required to provide a deeper insight into the extent of water use for transportation.

3 Quantifying total water requirements of transport

This section describes the method used to quantify total water requirements of transport modes. It starts by describing the case of Melbourne, Australia before providing an overview of the input-output analysis technique used. The combination of input-output data with transport data is then explained before presenting data sources used in this study.

3.1 The case of Melbourne, Australia

The city of Melbourne, Australia is used as a case study to determine the water requirements of its most significant transport modes. This section describes the city, the current state of its transport system and provides the data sources used in this study.

According to the latest census Melbourne is a city of 4 million inhabitants (ABS, 2011a) making it the second most populous city in Australia (after Sydney). It is located in the south-east of Australia, at the North of Port Philip Bay. Characterised by a dense CBD with high-rise buildings and sprawling low-density suburbs, Melbourne has an average population density of 1 556 inhabitants/km² (BITRE, 2011a). This density is lower than other major global cities such as Paris, France with 21 196 inhabitant/km² in 2009 (INSEE, 2012) or Tokyo, Japan with 6 029 inhabitants/km² in 2011 (Tokyo Metropolitan Government, 2011). Melbourne public transport includes trains, trams and buses. The tram network of Melbourne is the largest in the world with 250 kilometres of tracks (Yarra Trams, 2013) running through the grid layout of the city. Figure 1 presents a simplified map of Melbourne showing its inner, middle and outer suburbs as well as its location within Australia.
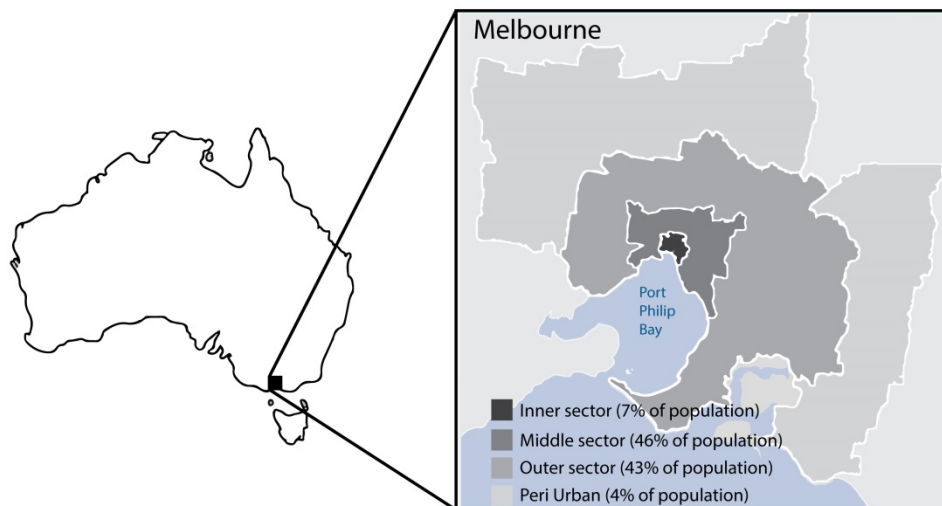
Figure 1: Simplified map of Melbourne and classification of its urban areas. Adapted from BITRE (2011a)

Melbournians rely mostly on cars for transport. According to BITRE (2011a), 75.1% of journeys to work are travelled by car in the Melbourne working area (inner, middle and outer sectors, see Figure 1). However this figure fluctuates greatly between inner and outer sector suburbs with 46.2% and 83.4%, respectively. Conversely, the share of public transport is higher in the inner city. Trams and trains are the preferred mode of public transport in the inner city with 51.9% and 40%, respectively. In the middle and outer suburbs, trains dominate public transport use with 74.1% and 84.2%, respectively. Overall, trains represent 71.2% of the commuter public transport use, followed by trams (16.7%), buses (10.6%) and others (1.5%, e.g. taxi) (BITRE, 2011a). For this reason, and due to the unavailability of data for trams and buses, only trains are considered in this study. Similarly petrol cars represented 87.6% of all vehicle-kilometres travelled in Victoria, Australia in 2010 (BITRE, 2011c) and are therefore the only type of cars considered in this work.

A recent report by Public Transport Victoria (PTV, 2012), the authority in charge of managing trams, buses and trains in Melbourne and the state of Victoria, shows a recent uptake in public transport patronage. The most dramatic increase can be observed for Metropolitan trains with 94% more passengers transported since 1998-1999 and a 54% increase since 2004-2005 compared to 51% and 25% for trams, respectively. This further reinforces the focus on trains as they are not only the most significant public transport mode but also the fastest growing.

The total water requirements of petrol cars and passenger trains, both regional and metropolitan are therefore considered in this work. The quantification of these requirements relies on the use of input-output analysis.

3.2 Input-output analysis

Input-output analysis is a top-down macroeconomic approach that relies on bi-dimensional matrices representing sectors of an economy. For each column representing an economic sector *s*, the entry in each row represents the input of its associated sector *r* into *s.* An input-output matrix therefore represents all transactions across the economy from every sector into another. Because of these linkages, input-output analysis can be used to show the repercussions of modifying the input of one sector on all other sectors in the economy. Also, because input-output analysis comprises all recorded transactions across the economy, it covers the entire supply chain of a product or service making it more comprehensive than other techniques with a narrower scope, e.g. process analysis (Majeau-Bettez et al., 2011).

Leontief (1970) first developed a method to combine these sectorial economic transactions with environmental data. This combination can be used to determine the total intensity of the environmental indicator studied per monetary unit, e.g. water: L/currency unit, for each sector. These sector-based intensities can be used to determine the environmental impact of a product, based on its price and the sector it belongs to. Input-output analysis has been used to determine the environmental burdens of an extremely wide range of products such as building materials, consumer goods, financial services and others. Multi-regional input-output analysis (MRIO) goes beyond input-output analysis by taking into account international trade in a detailed manner. MRIO tables comprise the inputs and outputs of economic sectors from different regions (a region can be a country, a province, or any other economic entity). Recently, several databases for world MRIO analysis have been compiled. These include but are not limited to the GTAP database (Andrew and Peters, 2013), the Eora database (Lenzen et al., 2012; Lenzen et al., 2013b) and the WIOD database (Timmer, 2012). MRIO analysis will not be used in this paper but its future application is envisaged as discussed in Section 4.

Water use is one of the environmental indicators that can be coupled with economic input-output data. This produces a list of sector-based water intensities expressed in L/currency unit for a given sector. The first study combining water use and input-output analysis was conducted by Isard and

Romanoff (1967). Subsequently, the water intensity of economic sectors has been established in different countries such as Australia (Lenzen and Foran, 2001).

Previous studies that have quantified the total energy requirements of transport modes (inter alia Lenzen (1999) and Chester and Horvath (2009)) have demonstrated that input-output analysis is the best available technique for determining indirect environmental requirements for various transport modes. For this reason, and due to the unavailability of process data for water use in transport, a pure input-output analysis is used in this study.

3.3 Determining total water requirements of transport modes

Figure 2 illustrates the overall approach used to quantify total water requirements of transport modes. The overall approach consists of multiplying the detailed financial expenditure, by the total water intensity of the corresponding input-output sector as in Lenzen (1999) and Chester and Horvath (2009). The resulting water requirements are clustered by use, summed for each mode to obtain the total requirements and normalised by passenger-kilometre for comparability. Each of these steps is described below in detail in this section.
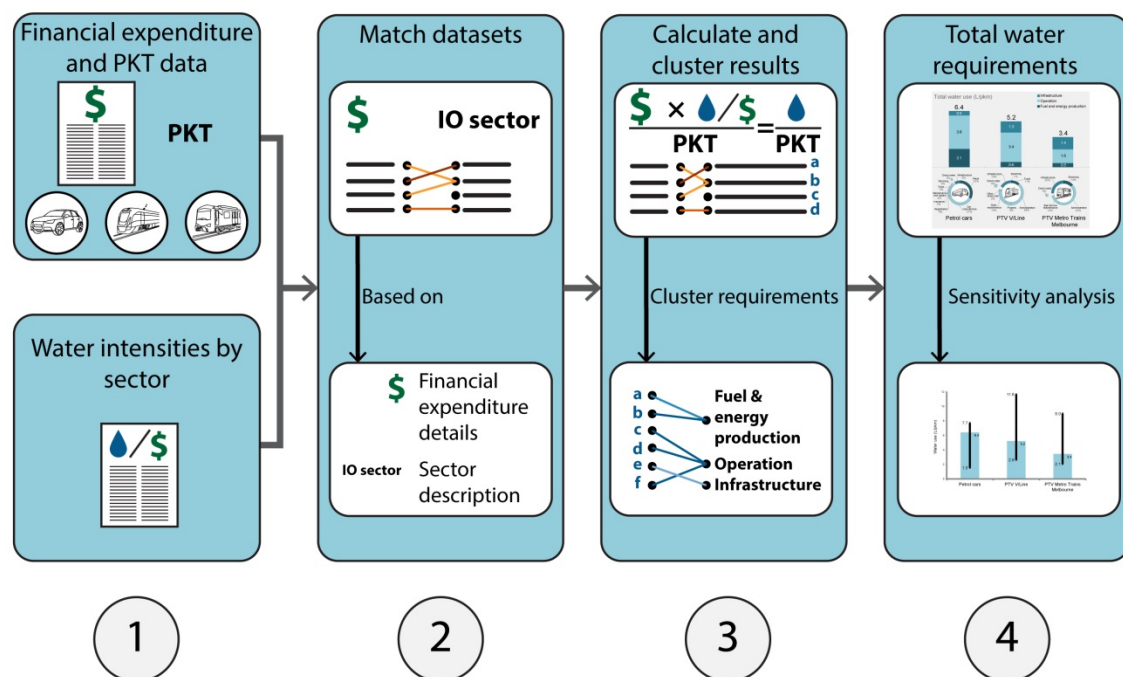

Figure 2: Overall method. Note: IO: input-output, PKT: passenger-kilometre travelled.

Firstly (stage 1 in Figure 2), two separate datasets have to be obtained: detailed financial expenditure data for each transport mode assessed and the total water intensities of all input-output

sectors. Financial expenditure data consist of a list of financial transactions, over a year, on a range of products (e.g. tires) or services (e.g. railway maintenance). In addition, the total passenger kilometre figure per transport mode is required to normalise the results. Data sources are explained and discussed in detail in Section 3.4.

Secondly (stage 2 in Figure 2), the financial expenditure data are matched with their corresponding input-output sector. This matching consists of relating the product or service on which money was spent to its input-output sector. To this end, the detailed description of what is included in each sector (known as product details) and provided by the Australian Bureau of Statistics (ABS, 2001a), is used. While some items can be hard to allocate because they might belong to two sectors, this was not the case in this study. Table 1 provides examples of input-output sectors, their water intensity and financial expenditures that were allocated to these sectors.

Table 1: Total water intensities based on input-output data of the Australian economy for the year 1996-1997 and expenditure examples, for selected sectors

Sector	Total water intensity (L/AUD)	Sample expenditure
Road transport (used for cars)	17.7396	-
Railway, pipeline and other transport (used for trains)	19.5107	Customer service
Petroleum and coal products	32.8773	Gasoline
Rubber products	36.0675	Tire replacement
Motor vehicles and parts; other transport equipment	31.5280	Car maintenance
Railway equipment	22.2407	Rail infrastructure
Electricity supply	51.1383	Electricity for Metro trains
Legal, accounting, marketing and business management services	45.9868	Administration and management of rail companies
Other construction	21.8093	Road infrastructure

Thirdly (stage 3 in Figure 3), the total water requirements associated with each financial transaction are calculated. This is done by multiplying each financial expenditure (e.g. the annual spending of a train operator on electricity, customer service, corporate management, rail service maintenance, infrastructure maintenance and renewals and others) by the water intensity of the sector to which it belongs (in L/currency unit), summing the total requirements, and dividing by the number of passenger-kilometres travelled (PKT). The average total water requirement is therefore obtained as per Equation 1. This means that no particular driving distance or service life is allocated for a vehicle. Instead, the intensities calculated should be seen as average intensities for the transport mode over a year. This approach depends significantly on the breakdown of the expenditures and on the number of sectors available (resolution) of the input-output model used. This is further discussed in Sections 3.4 and 5.2.

$$TWI_M = \frac{\sum\limits_{r=1}^{R} E_{r,M} \times TWI_{r,M}^{s}}{PKT_M} \qquad (1)$$

Where: TWI_M = Average total water intensity of transport mode M, in L/pkm; r = Requirement of transport mode M; $E_{r,M}$ = Annual monetary expenditure on requirement r of mode M in currency unit; $TWI_{r,M}^{s}$ = Total water intensity of sector s associated with requirement r in L/currency unit; and PKT_M = Total annual passenger-kilometres travelled for mode M in pkm.

Once the total water requirements are calculated for each mode, these are clustered into three distinct categories: fuel and energy production; infrastructure and operation. This breakdown is similar to Lenzen (1999) to facilitate comparability. The following expenditures are considered under each category:

Fuel and energy production:

- Fuel (petrol for cars and diesel for regional trains)
- Electricity (to operate stations and trains)

Infrastructure:

- Roads construction and maintenance
- Railway construction and maintenance

- Railway stations

Operation (all other expenditure, including):

- Vehicle maintenance and repair

- Vehicle manufacturing

- Administration, insurance, advertising, customer services

- Direct water requirements.

Using this breakdown improves the comparability of the results with the energy and greenhouse gas emissions intensities calculated by Lenzen (1999) for the same transport modes. Section 5.2 compares these intensities and discusses the findings.

It is important to highlight that environmental requirements associated with public expenditure on infrastructure, notably roads, are problematic to determine, as highlighted by Lenzen (1999). Indeed, the public investment in roads cannot be solely allocated to cars because it is also necessary for buses, trucks and all other vehicles using roads (such as bikes). Investment in rail infrastructure was calculated based on the associated expenditures of each operator. Shared investment with other operators or state-level investments were not taken into account, notably for regional rail which can share infrastructure with freight trains. Street lighting is particularly problematic since it is shared not only by cars, trams, buses and trucks as stated by Lenzen (1999), but also by bike riders and pedestrians. This makes the allocation of street lighting incredibly complex and most likely of little significance when divided among so many modes. For this reason it is not taken into consideration. The shared road infrastructure requirements will be allocated, as in Lenzen (1999), according to the VKT where buses and trucks are penalised by a factor of 2 and motorcycles are rewarded by a factor of 0.5, based on their sizes. Buses, trucks and motorcycles are only considered for this allocation purpose and are not included as part of the transport modes considered in the study.

Fourthly (stage 4 in Figure 2), the total water requirements of each transport mode, expressed in L/pkm and broken down into separate expenditures and the three categories mentioned above are compared. Expressing results per PKT allows the comparison of different transport modes. Yet, this normalisation is highly sensitive to the average occupancy rate of the mode (Chester and Horvath, 2009). Indeed, PKT are often calculated from passenger trips using an average trip length or from vehicle-kilometres travelled (VKT) using an average vehicle occupancy. Both approaches can result

in significant uncertainty. This uncertainty is likely to influence the results as the least water-intensive mode cannot always be identified. A sensitivity analysis of the results to the average occupancy and related PKT is conducted in Section 4.2. This sensitivity analysis considers low and high boundaries for the occupancy of each transport mode.

This section has described the overall method used and the calculation process. Section 3.4 presents data sources and discusses them.

3.4 Data sources

Data pertaining to financial expenditure, input-output-based water intensities and passenger-kilometres travelled is required to calculate the total water requirement for each transport mode.

The financial expenditure for the operation of cars is based on the Household Expenditure Survey (ABS, 2011b). Further costs for road infrastructure are obtained from BITRE (2011b) and allocated to cars using the method described in Section3.3 based on data from BITRE (2011c) and ABS (2004). Costs associated with the provision of public transport were sourced directly from the operators, in this case Metro Trains Melbourne and V/Line, based on a direct contact with their administration and their publically available annual reports, respectively. This provides highly specific financial data for these operators and improves the reliability of the results compared to considering average data for train operators. Transport data such as vehicle-kilometres travelled and passenger-kilometre travelled are obtained from the annual report of PTV (DTPLI, 2013) for public transport modes. All financial expenditures are converted to 1996 terms based on the total inflation rate of the Reserve Bank of Australia in order to use monetary rates that are consistent with the associated input-output water intensities.

The water intensities for each sector of the Australian economy are based on input-output tables of the Australian economy for the year 1996-1997 (ABS, 2001b) which includes 106 sectors. More recent sectorial water intensities for Victoria, taken from Lenzen (2009) could be used. However, the associated dataset of 104 sectors (aggregated from 344) focuses on agricultural sectors which are known to have the largest embodied water demand. It therefore disaggregates agricultural sectors (63/104) and aggregates other less water intensive sectors, such as transport, construction, equipment and others (41/104). This significantly affects the usability of the data for the purpose of this research. The dataset used has a sectorial resolution of 106 sectors and conserves a reasonable level of disaggregation for non-agricultural sectors (69/106). This study therefore favours sectorial

resolution to more recent, but more aggregated data. Furthermore the input-output tables used have a very similar sectorial classification as those used in Lenzen (1999) providing a better comparability of water intensities with his energy and greenhouse gas emissions intensities. Some of the sectors within the input-output table used are listed in Table 1. The data sources for each item are provided in Table 2.

Table 2: Water requirements of major passenger-transport modes in Melbourne, Australia.

		Transport mode		
		Petrol cars (Victoria)	Regional trains (PTV V/Line)	Metropolitan trains (PTV Metro Trains Melbourne)
Passenger task	VKT (million km)	37 870 [a]	22.1 [b]	21.9 [b]
	Average occupancy (passenger/vehicle)	1.202 [c]	49	175
	Passenger trips (million)	—	13.2 [b]	225.5 [b]
	Average trip length (km)	—	82	17
	PKT (million pkm)	45 520	1 074 [d]	3 834 [e]
Cost	Specific cost (A¢/pkm)	33.5	49.7	*Confidential* [g]
	Absolute operating cost (million AUD)	15 236 [f]	538.4 [d]	*Confidential* [g]

Note: Figures may not sum due to rounding.

[a] Based on BITRE (2011c): a report by the Bureau of Infrastructure, Transport and Regional Economics on the road-vehicle travel statistics for each Australian state and territory based on vehicle fuel sales

[b] Based on DTPLI (2013): the annual report by the Victorian Department of Transport, Planning and Local Infrastructure that provides statistics on all public transport modes in Victoria.

[c] Based on Ausroads (2013) which is the association of Australasian road transport and traffic agencies. It provides expert knowledge in the field of road transport.

[d] Based V/Line (2013): the annual report by V/Line, the operator of regional trains in Victoria, providing detailed expenditure figures and other social, economic and environmental statistics.

[e] Based on internal data from Metro Trains Melbourne.

[f] Based on data from ABS (2004, 2011b) and BITRE (2011a, c): compiled from a range of data including the household survey, average road travel statistics and the Victorian population accounts.

[g] The operator did not allow the release of this information.

4   Results

The results of the study are presented in this section. The total water requirements by transport mode are given followed by the sensitivity analysis of the results to average vehicle occupancy.

4.1 Total water requirements

Figure 3 presents the total water requirements of each transport mode by use, as defined in Section 3.3, and provides a detailed breakdown of the contribution of each water requirement category towards the total.
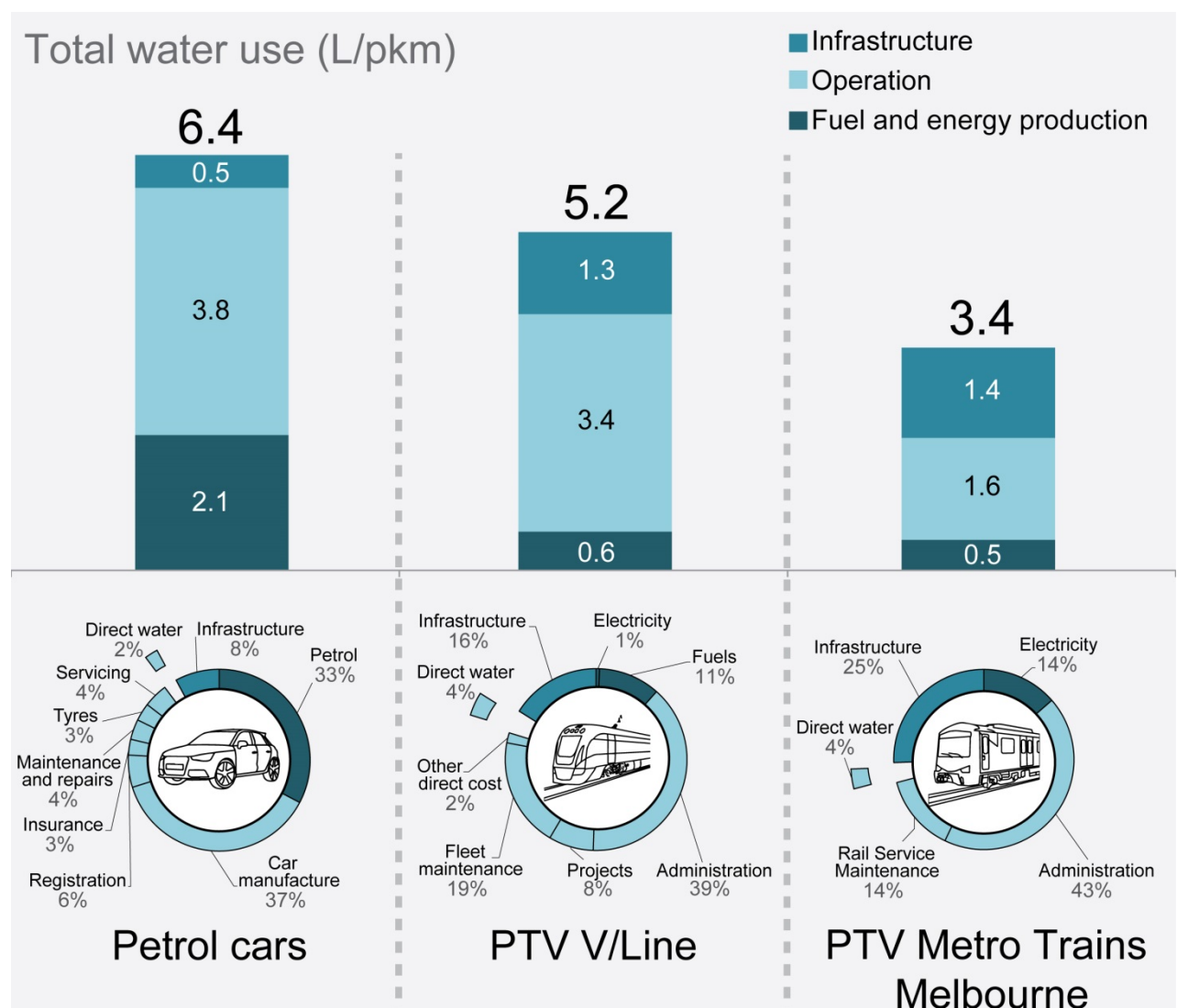

Figure 3: Specific water requirements of major transport modes in Melbourne, Australia, by use.

Results show that cars are the most water intensive transport mode (6.4 L/pkm) followed by V/Line diesel trains (5.2 L/pkm) and Metro electric trains (3.4 L/pkm). An average person going to work by

car on a trip of 25 km would have required the equivalent of two months worth of drinking water for one person when he/she reaches his/her destination (based on a 2.5 L/day drinking water requirement). Considering a 40.8 km return trip by Metro train and a 67.6 km return trip by V/Line (based on average travel distances for Melbourne middle and outer suburbs from the Department of Economic Development, Jobs, Transport and Resources (2016)) results in total water demands of 138.7 L and 351.5 L, or ~87% and ~220% of the daily residential water demand per capita (160 L) in Melbourne (Melbourne Water, 2016), respectively. Water requirements for transport are therefore very significant.

The significance of the water requirements is further demonstrated by comparing the intensities found to those associated with the production of biofuels, per vehicle-kilometre. The water requirements of petrol cars is 7.7 L/vkm (6.4 × 1.202). This is higher than the nominal intensity associated with the most water intensive biofuel (6.57 L/vkm for biodiesel) in Lampert et al. (2016). In comparison, Lampert et al. (2016) found that fuel-production-related water requirements of a diesel car are 0.42 L/vkm, or less than 6% of the total requirements found for a petrol car in this study. This shows that the total water requirements of typical transport modes operating on traditional fuels can be equivalent to those associated with the very water intensive processes of biofuel production. While research on the water demand of transport has typically focused on fuel production and biofuels, this study shows that considering total requirements is equally important, and is broken down into different uses for each mode.

Fuel and energy requirements represent 33% (2.1 L/pkm), 11% (0.6 L/pkm) and 14% (0.5 L/pkm) of the total for cars, V/Line trains and Metro trains, respectively. This is due to the higher overall efficiency of trains compared to cars regarding the transported dead weight per passenger. Also, even if Metro trains are electric-powered-multiple-units trains, meaning that their engine efficiency is much higher than the combustion engine of locomotive-driven V/Line trains, the overall water requirements associated with energy use is very similar to the V/Line. This is due to the more water intensive nature of electricity generation (51.13 L/AUD) compared to diesel fuel production (32.87 L/AUD). In this study, the electricity generation mix is dominated by coal combustion (black coal followed by brown coal). However, the water intensity of the electricity generation sector can vary greatly between states or regions. This study is located in Victoria, Australia which relies mostly on wet brown coal for electricity generation and the water intensity of the electricity sector is therefore adequate. However,

hydroelectricity has much higher water requirements and therefore electric trains in places relying heavily on hydroelectric dams for electricity generation, such as Tasmania, Australia (Hydro Tasmania, 2015) or Norway (SSB, 2016), could have a much higher water requirement in such contexts.

Operational requirements are also highest for cars with 3.8 L/pkm (mainly due to car manufacture), followed by 3.4 L/pkm for V/Line and 1.6 L/pkm for Metro trains. The water intensity of car manufacturing is mostly due to the production of aluminium, steel and plastics, as reported in Bras *et al.* (2012) and Schweimer and Levin (2000). Other operational services for cars, such as insurance, registration, servicing, tyres and maintenance represented 22% of total water requirements and are very rarely taken into account in other studies. The higher figure for operational requirements of V/Line compared to Metro trains is probably due to the lower occupancy rate (56% compared to 66%) and related PKT (~1.1 billion pkm compared to ~3.8 billion pkm) for a similar figure of VKT (~22 million vkm). The operational requirements in terms of stations, staff and maintenance is likely to be high because of the extended network for relatively few people transported.

Infrastructure requirements represent 8% (0.5 L/pkm), 16% (1.3 L/pkm) and 25% (1.4 L/pkm) of the total water requirements for cars, V/Line and Metro trains, respectively. The low contribution of infrastructure for cars most likely results from the consideration of a total average for Victoria which is based on roads with high variations in cost per kilometre. If passenger kilometres are allocated based on the type of road as in Saari *et al.* (2007), infrastructure requirements are expected to have a much higher contribution than in the current study.

Direct water requirements represent less than 2% and less than 4% of the total for cars and trains, respectively. This shows that the majority of water use associated with passenger transport modes is indirect. In other terms, transport operators have little direct control on their water use and strategies aimed at reducing water used directly by transport operators might have a very limited influence on reducing water use associated with transportation. For example, Metro Trains Melbourne metered water usage (i.e. water that is monitored by meters in buildings and on site) for 2011-2012 was 134 102 kL. This represents less than 1% of their total calculated water use. While water saving strategies by transport operators are praiseworthy, they must be complemented by other actions targeting indirect water requirements as will be discussed in Section 5.

4.2 Sensitivity analysis on occupancy rates

A sensitivity analysis of the results for variations to the average occupancy of vehicles is conducted using peak and off-peak average occupancies for public transport modes. The occupancy rate for trains is considered as 25% and 110% of the total seating capacity for low and high occupancy rates, respectively. These occupancy figures are based on the study of Chester and Horvath (2009) on the life cycle assessment of transport modes in the USA. The total seating capacity is based on the N-type carriage for V/Line (regional) and the X'trapolis and Comeng Electric Multiple Units (EMU) for Metro Trains Melbourne (metropolitan). These vehicles are the most representative of the fleet of each operator. The average occupancy range for cars is estimated to vary between one (the driver) and a maximum of five. Table 4 provides the occupancy rates used for each transport mode.

Table 3: Average, low and high occupancy rates used for the sensitivity analysis, by mode.

Transport mode	Average occupancy (passenger/vehicle)	Low occupancy (passenger /vehicle)	High occupancy (passenger/vehicle)	Seating capacity (passenger/vehicle)
Petrol car (Victoria)	1.2[a]	1	5	5
Regional train (V/Line)[b]	49[a]	22	97	88[c]
Metropolitan train (Metro Trains Melbourne)	175[a]	67	293	266[d]

[a] Based on figures from Table 2

[b] Occupancy rates and seating capacity for a regional train are expressed in passenger/carriage

[c] Based on the N-type carriage that is most commonly used by V/Line

Figure 4 presents the sensitivity of the results to the occupancy rates of transport modes, demonstrating considerable variability. At low occupancy, cars are the most water efficient transport mode (7.7 L/pkm) since trains result in very high water expenditure (11.6 L/pkm and 9 L/pkm for V/Line and Metro Trains, respectively) to move a relatively small number of people. At the high occupancy rate, results are closer with cars still being the most efficient (1.5 L/pkm) followed by Metro Trains (2.1 L/pkm) and V/Line trains (2.6 L/pkm). This sensitivity analysis demonstrates the considerable effect that occupancy rates can have on the water intensity of passenger transport.

The position of the error bars in Figure 3 informs us of the potential opportunities for improvement related to occupancy. The longer the error bar below the average value, the more potential exists because of greater divergence from the maximum occupancy. In this regard, cars have the highest potential in reducing their water intensity because they operate close to their minimum occupancy, at 1.2 passengers. This greatly highlights the benefits of car sharing as a non-technological means to reduce the environmental impacts of cars. Car sharing can also reduce energy use and greenhouse gas emissions as highlighted by Rabbit and Ghosh (2013) in their study on car sharing in Ireland, and can significantly reduce transportation life cycle costs as shown in Stephan and Stephan (2016). Trains yield less potential than cars in reducing their water intensity since they operate closer to the maximum occupancy rate.

This evaluation of the occupancy rate on the water requirements is basic since it does not take into account the increased fuel usage for cars or operational requirements for trains when transport modes operate near their maximum capacity. A more detailed investigation of the influence of occupancy rates is therefore needed.
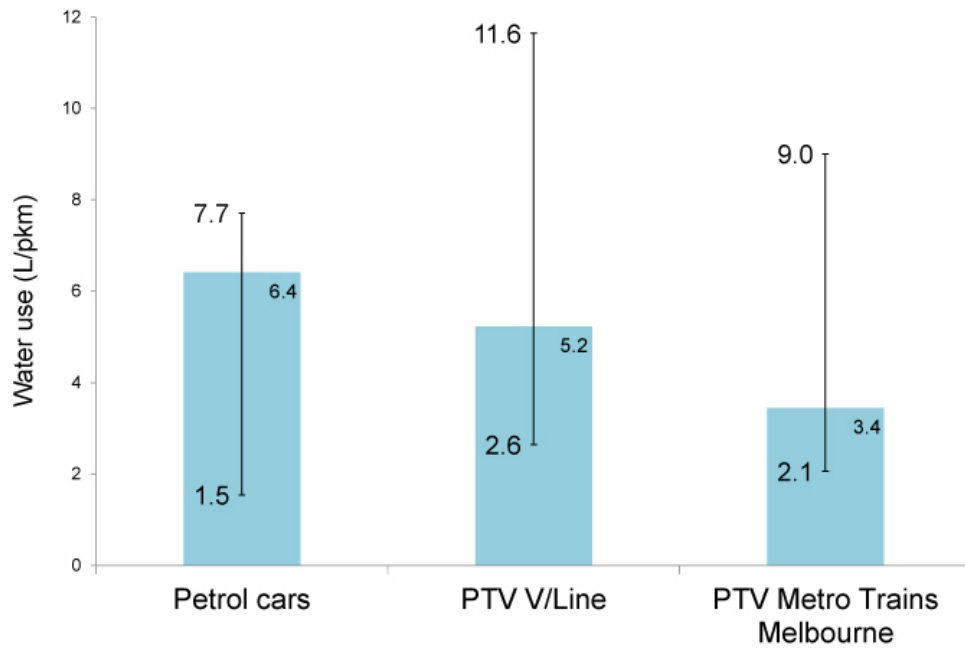
Figure 4: Sensitivity analysis of specific water requirements of major transport modes to occupancy rates.

5 Discussion

This paper presents the results of an analysis of the total water requirements of different passenger transport modes, namely petrol cars, regional diesel trains and urban electric trains. Results show that urban electric trains have the lowest water requirements per passenger kilometre travelled (PKT) followed by regional diesel trains and petrol cars. This section discusses ways of reducing these water requirements, compares the breakdown of water intensities to their energy and greenhouse gas emissions counterparts, and presents the limitations of this study.

5.1 Reducing the total water requirements of passenger transport

This study shows that Melbourne's water usage could be abated by reducing car usage and favouring public transport since the latter has lower water requirements. The recent increase in public transport patronage (PTV, 2012) is an encouraging sign in this regard. Favouring public transport modes also results in a number of environmental benefits such as improved air quality in cities (Molina and Molina, 2004) (mostly if renewable energy is used to generate electricity), less traffic jams, more walkable streets (Kenworthy, 2006), reduced parking space requirements, and other benefits. Another action would be to favour car sharing in order to increase the average occupancy rate in cars which is currently at 1.202, a very low figure. For instance, increasing the average

occupancy rate to 1.6 would reduce the water intensity of cars by 25% to 4.8 L/pkm, a figure lower than the water intensity of regional trains. Car sharing also reduces the total number of cars on the roads and leads to less congestion and improved air quality as demonstrated by Fellows and Pitfield (2000) in their study on the West Midlands area in the United Kingdom. These measures, combined, can significantly reduce the total water use associated with transport at a city level.

Reducing water requirements at a transport mode level requires the involvement of multiple actors as previously shown by Scown et al. (2011). As Figure 2 clearly shows, direct water requirements represent a very small share of the total. This means that the majority of the water requirements are indirect and often occur outside the direct sphere of influence of transport operators or car users. For example, a car buyer has virtually no control over the water embodied in the car he/she purchases. Therefore reducing the embodied water in car manufacturing, which represents 37% of the total, falls more under the responsibility of the car manufacturer which in turn relies on a number of suppliers for car components. The supply chains involved in supplying transport services are therefore extremely complex and it becomes harder and harder to influence actors to reduce their water use as we move further upstream in the supply chain. The same applies for public transport modes (e.g. trains for Metro Trains Melbourne are manufactured in France using materials imported from elsewhere). For these reasons, while water saving schemes at the operator level (e.g. in buildings and railway stations) is a praiseworthy approach that raises the awareness of employees and can significantly direct water usage (Morrow and Rondinelli, 2002), it must be complemented by measures to reduce indirect water use. For example, the most significant contributor to the water requirements of both diesel and electric trains is administration, representing 39% and 43%, respectively. Based on a structural path analysis (Miller and Blair, 2009) of the corresponding input-output sectors, this indirect demand is due mostly to the operation of administrative services, notably in terms of embodied water in infrastructures for water and electricity delivery, followed by water use for accommodation and food. This clearly shows the interconnected nature of the economy and the importance of water saving initiatives throughout the supply chain that could result in less infrastructure needs for water which in turn require less embodied water. One manner of achieving water reduction measures could be setting up a charter that obliges subcontractors to abide by water saving principles. These would in turn require that their suppliers or subcontractors reduce their water use and so on upstream in the supply chain, as shown by Stephan and Robert (2006) in their study on environmental improvements

in the supply chains of 87 plants producing printed packaging. Ultimately, the joint effort of multiple actors can lead to a reduction in the total water use associated with transport modes.

Other means of reducing water use and consumption across the economy could be to increase water tariffs (Campbell et al., 2004; Zetland and Gasson, 2013) and a sustained investment by the government in water recycling and supply infrastructure. By giving more economic value to water, using it sparingly will become a noteworthy prospect for managers, users, suppliers and operators alike. Supporting such policy by a reward program for users who actually use less water in order to incentivise their efforts could also help improve its effectiveness. Similarly, a more efficient water distribution infrastructure that includes recycling and reusing collected water can significantly reduce mains water use (Marlow et al., 2013). The effect of increasing water tariffs, investing in water supply and recycling infrastructure and the associated water policies should be further investigated.

5.2 Comparing water, energy and greenhouse gas emissions requirements

In order to further analyse the calculated water requirements and situate them within broader environmental indicators, these are compared to the equivalent energy and greenhouse gas emissions (hereafter referred to as 'emissions') requirements quantified by Lenzen (1999). The total energy and emissions requirements found by Lenzen (1999) for petrol cars, V/Line and Metro Trains are 4.4, 2.7, 3.3 MJ/pkm and 0.34, 0.24, 0.31 $kgCO_2e$/pkm, respectively. This shows that regional diesel trains have the lowest energy and emissions intensities among the three considered transport modes, compared to electric urban trains for water. However, both public transport modes had lower energy and emissions requirements than petrol cars.

Figure 5 compares the contributions of each of the direct, fuel and energy production, operation and infrastructure towards the total water, energy and emissions requirements of each transport mode. It shows a substantial difference in the contribution of direct requirements which are significant for energy and emissions, notably for cars where they dominate the rest. Another major difference is the contribution of operations towards the total water intensity compared to energy and emissions. Indeed, operations represent only a small fraction of the total energy and emissions requirements but they are significant when it comes to water and this is due to the large water requirements associated with administration (see Section 5.1). Figure 4 also shows that reducing energy and emissions requirements can be achieved by targeting direct processes (while ensuring that reduced

requirements are not simply shifted upstream in the supply chain), contrarily to reducing water requirements where a more integrated approach is needed.
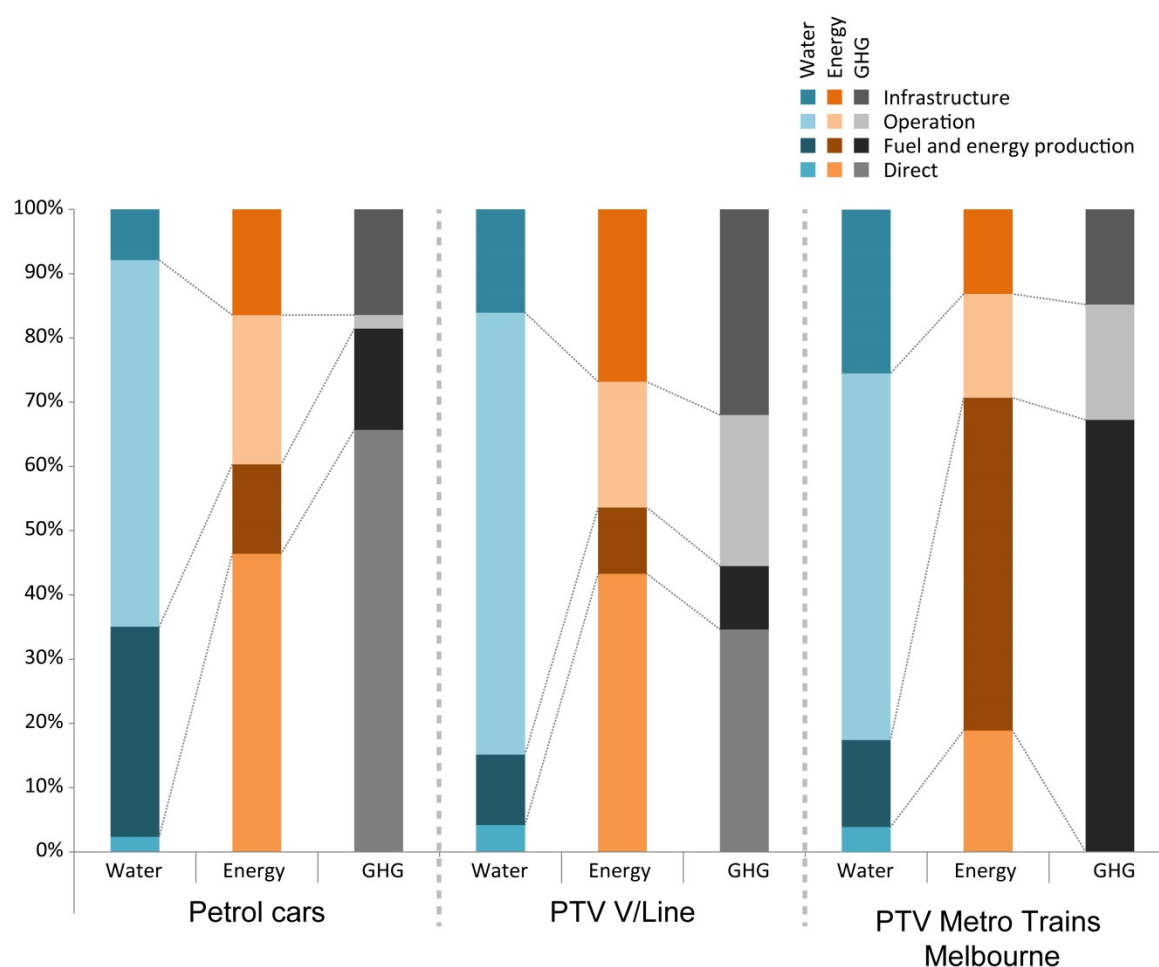

Figure 5: Water, energy and greenhouse gas emissions requirements of major transport modes in Melbourne, Australia, by use. Note: energy and greenhouse gas emissions (GHG) breakdowns are based on Lenzen (1999).

5.3 Limitations of the study

This study suffers from a number of limitations, namely uncertainty in input-output data, the exclusion of water quality considerations, the use of an average water intensity for cars on all kinds of roads and the analysis of only one city. These limitations are discussed hereunder.

The first limitation of this study is the high level of uncertainty present in input-output data, and arising from a range of sources, including primary data, input-output table calculations, derivation of water intensities (or multipliers), the aggregation of multiple products into a single sector and others (Lenzen, 2000). Uncertainty in input-output data is usually about 50% (Crawford, 2011) but can reach

up to 85% (Lenzen, 2000). This can highly undermine the results of any study that uses input-output data. In this study, a total of 12 unique sectors (11.3% of available sectors) are used across the three transport modes. The petrol car expenditures share only one sector with metro trains (the 'Other construction' sector associated with the construction of infrastructure) and three sectors with V/Line trains ('Other construction', 'Petroleum and coal products' (for fuel and diesel production, respectively) and 'Government administration' (for car registration and the 'franchise performance penalty' expenditure in V/Line). The shared sectors between cars and metro trains represent 8% and 25.5% of their total water intensity, respectively. The shared sectors between cars and V/Line trains account for 46.3% and 29.4% of their total water intensity, respectively. In parallel, all of the sectors used for metro trains are also used for V/Line trains and the remaining sectors used in V/Line (and not in metro) account for 28.4% of the water intensity of V/Line trains. V/Line diesel trains and cars also rely on similar sectors for significant shares of their total water use. Assuming that the water intensity of certain sectors can be significantly different to others without other sectors being affected (which is extremely unlikely), uncertainty in the water intensity of the sectors will not greatly affect the water requirements ranking between trains. The ranking between cars and trains can vary to a larger extent, and notably between cars and electric trains because of the smaller contribution to water intensity from shared sectors. However, in reality, the interdependence of economic sectors means that uncertainty in the data is more likely to affect similar sectors in the same order of magnitude of uncertainty. While the actual water intensities of each transport mode can vary greatly depending on uncertainty in the data, the ranking of the transport modes suffers less from this uncertainty but is highly affected by occupancy rates (see Section 4.2). More disaggregated input-output tables that rely on more robust data are required to reduce the level of uncertainty and improve the robustness of the results. Including process data in the inventory is another possibility and is discussed in the following point.

Another limitation of this study is the consideration of all water as having the same value. For example, water extracted in a water-scarce region is considered to have the same value as water extracted in a water-abundant location. The environmental impact in terms of water scarcity is not considered. Also, this paper considers the total water use. However, most of the water used is put back into the hydrosphere in a usable state. Relying on water consumption, as advocated by Bras *et al.* (2012) can provide information on the amount of water that becomes unusable in the process. A

solution to deal with these issues is to rely on multi-regional input-output (MRIO) analysis and to enrich it with process data, creating a hybrid multi-regional approach. MRIO analysis can capture the local specificities in terms of water scarcity (Cazcarro et al., 2013; Lenzen et al., 2013a). This can therefore differentiate the value of water or its impact based on its origin. Also, enriching such a model with process data, on for example the water consumption during the car or train manufacturing process, can reduce uncertainty by providing more accurate data. This should be done using recent input-output data that is highly disaggregated to improve accuracy. Such analysis will help support strategies for reducing water use and consumption in a more informed manner and using a more context-specific approach.

The third limitation of this study is the consideration of an average water intensity associated with cars, regardless of the type of road used. In their study on Finnish road transport modes, Saari *et al.* (2007) clearly demonstrated the significant influence of the road type on the water requirements associated with cars. They found that the water embodied in small connecting roads results in a very high water intensity (27.95 L/pkm) compared to motorways (2.98 L/pkm) or main roads (6.57 L/pkm) when infrastructure requirements are allocated based on traffic volume. For this reason, the figure obtained in this work should be considered as an average figure that can vary greatly depending on the type of road the car is usually driven on. More detailed research is needed to clearly evaluate the influence of infrastructure water requirements on road transport in an Australian context, and in other locations.

The actual water intensities found in this work are relevant for Melbourne, Australia only as they are based on local expenditures and transport data. Also, this study did not consider trams and buses that are also used in Melbourne. Additional cities and transport modes, including freight, have therefore to be considered in order to provide a more comprehensive understanding of the water requirements of transport. This is only possible if public and private transport operators provide transparent data on their financial expenditure, fleets and operational structure, which is not always the case.

6 Conclusion

This study has assessed for the first time the total water requirements of different passenger transport modes. It used the city of Melbourne, Australia as a case study and assessed three different transport modes, namely cars, regional diesel trains and urban electric trains.

Results show that urban electric trains are the least water intensive transport mode, followed by regional diesel trains and cars. In other terms, in order to reduce water use associated with transport, cities should focus on supporting public transport modes. It was also shown that the occupancy rate has a major influence on the water intensity of transport modes as a higher occupancy results in a lower water intensity. This strongly supports the case of car sharing as this can significantly reduce the water use associated with car transport. The total water intensities calculated in this study were found to be significant and comparable to those associated to the water-intensive process of biofuel production, on a per vehicle-kilometre basis. Using average daily travel distances, a typical trip by car (28.8 km), urban rail (40.8 km) and regional rail (67.6 km) represents up to ~115%, ~87% and ~220% of Melbourne's daily per capita water use (160 L) , respectively. In addition, this study showed that reducing the water intensity of a transport mode requires the involvement of multiple actors, across the supply chain providing the transport service. Since direct water requirements are insignificant compared to indirect requirements, most of the water use occurs at nodes in the supply chain outside of the sphere of influence of the operator or the car user. Water efficiency should therefore be propagated across the supply chain in order to observe net reductions in water use.

It is clear that further research is needed to better understand and assess water use associated with transport. This includes the use of multi-regional input-output analysis and hybrid analysis to assess water use in a more reliable way and differentiate water quality and scarcity. Also, additional cities and transport modes should be assessed to allow the comparison with other studies and provide a more comprehensive understanding of water use in transport. This will ultimately contribute to reducing our total use of water.

Acknowledgments

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