Transportation Research Part D 13 (2008) 392–399

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

A comparison of carbon dioxide emissions associated with motorised transport modes and cycling in Ireland

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ARTICLE INFO

Keywords:
Exhalation
Transport
Occupancy
Indirect energy

ABSTRACT

Cycling is widely viewed as a transport mode with marginal environmental impacts. However, such a view fails to take account of such factors as the increase in carbon dioxide exhaled as a result of increased physical activity or the emission embodied in the manufacture of the bicycle. This paper presents estimates of emission factors for various forms of commuter transport in Ireland that allow comparison against emissions from cycling. When indirect energy is taken into account, the results presented here indicate that a cyclist commuting an equivalent distance to work releases an almost equal amount of carbon dioxide as that attributed to a passenger of an electrically propelled train at full occupancy during peak service times. Travel by bicycle is much less carbon intensive when compared to passengers travelling at off-peak times. Transport by car and sports utility vehicle is the most carbon intensive of the commuter modes of transport studied, however, travelling in a fully occupied car has an emission factor approaching that of off-peak bus transport.

1. Introduction

Since the middle of the last century, most developed countries have experienced a continuing increase in urban populations through population growth and in-migration. This has also been demonstrated by the Irish Central Statistics Office (ICSO, 1986, 1991, 1996, 2002, 2006), where urban in-migration began in the 1960s increasingly affluent and mobile urban populations have come to rely on private cars, prompting greater awareness of environmental impacts of transport, and especially the role of emissions to air in climate forcing. O'Leary et al. (2006) estimated that road transport in 2005 accounted for 65% of Irish fuel consumption in the transport sector and for >25% of Irish energy consumption. McGettigan et al. (2006) demonstrate that road transport results in the second highest greenhouse gas emissions arising from fuel combustion, exceeded only by those from electricity generation. As the population density of urban areas increase, greater opportunities exist for public transport and non-automated transport, which are generally regarded as creating less significant environmental impacts: indeed it is often assumed that cycling provides effectively carbon neutral transport for commuters. The human respiration rate is regulated to the level of physical exertion. Cycling requires an increase in the rate of supply of oxygen to the working muscles producing an increase in the production of carbon dioxide (CO_2) from metabolism. The speed of cycling and length (duration) of journey determine overall CO_2 emissions from human exercise metabolism.

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doi:10.1016/j.trd.2008.07.002

This paper seeks to quantify emissions of CO_2 associated with cycling, and compare these with emissions arising from other urban transport modes available in the city of Dublin, Ireland. These emission factors are translated into metrics of passenger kilometres, to determine whether motorised transport passengers would decrease their transport related CO_2 emissions by switching mode to cycling.

Our purpose is to compare the carbon emissions associated with a range of transport modes. It is considered important that all potentially important impacts be included in such analyses: to date impacts arising from human respiration have not been examined systematically. The commonly expressed view that transport by cycling has little or no environmental impact is based on analyses that have not taken into account the net increase in CO_2 emission due to increases in respiration and the energy required in cycle manufacture.

Carbon dioxide emitted through respiration and the combustion of fossil fuels, may drive climate change. It has been stated that all carbon contained in food is ultimately derived from atmospheric carbon originally fixed by photosynthesis and as such is carbon neutral. However, as most food is processed to some extent it will have associated embodied fossil carbon (Kennedy, 2007). This is also the case for unprocessed foods, whose production is dependent on on-farm mechanisation. The expenditure of on-farm energy will increase the yield of a product but will not affect its energy or carbon content and therefore will not directly affect emissions due to human respiration. Here emissions due to physical exertion and respiration are seen as being a worthwhile indicator to compare against vehicle emissions.

2. Transport emissions

2.1. CO_2 emissions from cycling

The amount of CO_2 exhaled by a human being is a function of the metabolic rate and substrate (fuel) used in oxidative metabolism. The amount of CO_2 exhaled for each litre of oxygen consumed in oxidative metabolism is termed the respiratory exchange ratio (RER). This ratio approximates to 1.0 if the predominant fuel is carbohydrate and to 0.7 if the predominant fuel is fat. Accounting for variation in body mass basal, or resting, metabolism consumes 3.5 ml O_2 kg^{-1} min^{-1} and excretes 2.95 ml CO_2 kg^{-1} min^{-1}, generating an energy equivalent to 4.18 kJ kg^{-1} h^{-1} or 1 MET. A value of 1.0 MET represents the metabolic rate associated with being seated at rest. For convenience, the metabolic rate associated with physical activity can be represented as a multiple of the basal metabolic rate. As the metabolic rate increases, the predominance of carbohydrate as a fuel and RER increase, and vice versa. Empirical measurement provides a good estimate of 'typical' rates of energy expenditure obtained whilst cycling for leisure, commuting or competition (Ainsworth et al., 2000). Leisurely commuting by bicycle at $\sim$16 kph is graded as a 4 MET equivalent energy expenditure with an RER estimated at 0.82. From these data the net emission of CO_2 km^{-1} for commuting by bicycle can be calculated as follows.

The amount of oxygen uptake is calculated as the body weight (75 kg) multiplied by the MET value for cycling multiplied by the time to travel 1 km (3.73 min at 16 kph)

$$3.5\ \mathrm{ml}\ O_2\ \mathrm{kg}^{-1}\ \mathrm{min}^{-1} \times 75\ \mathrm{kg} \times 4 \times 3.73\ \mathrm{min}\ \mathrm{km}^{-1} = 3915\ \mathrm{ml}\ O_2\ \mathrm{km}^{-1} \tag{1}$$

The amount of CO_2 emitted is calculated as a function of the RER. Multiplying by the appropriate RER translates oxygen demand into CO_2 emissions. A RER of 0.82 results in an emission factor of 3210 ml CO_2 km^{-1}. The NET emission of CO_2 is calculated by subtracting the CO_2 emission for an equivalent time at rest

$$3210\ \mathrm{ml}\ CO_2\ \mathrm{km}^{-1} - (3.73\ \mathrm{min}\ \mathrm{km}^{-1} \times 2.95\ \mathrm{ml}\ CO_2\ \mathrm{kg}^{-1}\ \mathrm{min}^{-1} \times 75\ \mathrm{kg}) = 2385\ \mathrm{ml}\ CO_2\ \mathrm{km}^{-1} \tag{2}$$

In this scenario, the CO_2 emission km^{-1} is calculated to be 2.385 l CO_2 km^{-1} (Table 1). Values for a range of cycling activity are also presented for comparison.

2.2. CO_2 emissions from motorised transport

All passenger kilometre emissions at peak times are calculated assuming maximum occupancy. Estimates for car transport are expressed in terms of maximum and normal occupancy. The emission factor for car transport was estimated using fuel consumption values for a range of engine sizes provided by Howley et al. (2003) and data on engine size distribution within the national fleet provided by DOEHLG (2004), resulting in an average emission estimate of 169 g CO_2 km^{-1}. For

Table 1
Carbon emission from cycling for an 'average', 75 kg person

	MET	l O_2 min^{-1}	RER	l CO_2 min^{-1}	l CO_2 km^{-1}	kg CO_2 km^{-1}
Description						
Less than16 kph (leisure, to work)	4	1.05	0.82	0.86	2.393	0.005
General (mixed intensity)	8	2.1	0.85	1.79	4.431	0.008
c22 kph leisure, moderate effort, prolonged	8	2.1	0.88	1.85	5.179	0.009
c26 kph racing, fast, vigorous effort, prolonged	10	2.63	0.94	2.47	6.13	0.010

Note: MET data from Ainsworth et al. (2000). Net value is calculated by removing resting CO_2.

sports utility vehicles (SUVs) an average emission factor of various models (including BMW, Hyundai and Chrysler) was calculated, including both petrol and diesel vehicles.

Emission factors for bus transport were generated using journey length and fuel consumption estimates provided by the company running Dublin buses (personal communication). For LUAS (the light electric train system operating in Dublin city), the traction effort curve, provided by the rail procurement agency, (Fig. 1) provides the amount of energy consumed by a tram at various speeds, and average speed was estimated for a typical tram journey on the basis of data provided in the light rail transit system website in http://www.lrta.org/luasindex.html. Given a line length of 15 km and journey time of 38 min, this results in an average speed of 24 km h^{-1}. From Fig. 1, a tram travelling at 24 km h^{-1} requires approximately 800 amps at 750 V. Fig. 2 demonstrates the electric current returns during braking. Braking frequency is dependent on many variables such as other traffic and weather conditions. To account for this a breaking speed of 10 km h^{-1} is estimated and it is assumed that a tram brakes during 10% of journey time. The amount of power required (in watts) is calculated by multiplying the voltage (750 V) by the current in amperes. If it is assumed that the average speed is maintained for an hour this results in an estimate of 600 kWh. If the same method is applied to braking then approximately 13.5 kWh are saved during braking. This results in an overall power demand of 586 kWh h^{-1}, during which the tram travels 24 km. This equates to 24.4 kWh km^{-1}. Based on the 2004 Irish electricity generation fuel mix, 1.0 kWh results in emissions of 0.6 kg CO_2. This suggests that a kilometre travelled by tram indirectly emits approximately 14.8 kg $CO_{2.}$ The peak time LUAS occupancy rate was estimated at 235 passengers based on data provided in the above website. This results in emissions of 0.06 kg of CO_2 per passenger kilometre.

In relation to DART trains (an electric commuter system operating in the greater Dublin area) it is estimated that at national scale in 2003 electric rail accounts for 2 kt of oil equivalent (kTOE) in electricity consumption (O'Leary et al., 2006). Based on the 2003 electricity generation fuel mix, 1.0 TOE (tonne of oil equivalent) results in emission of 7.57 tonnes of CO_2 (SEI, 2007). By applying the conversion factor of 7.57 tonnes CO_2 TOE^{-1}, the emissions for DART were estimated to be 15,140 tonnes of CO_2 yr^{-1}. This is divided by 1,970,000 train kilometres for 2000 (provided by Dodgson and Viegas (2001)), which results in an emission factor of 7.7 kg CO_2 km^{-1}. Journey distances have not increased significantly since 2000. This emission factor is increased by 33% during peak service to account for the extra carriages attached to trains at these times. (This is removed for off-peak estimates). The estimate of peak passenger capacity adopted here is 15,500 passengers in a complement of 114 carriages (DTO, 2005), resulting in a peak capacity of 135 passengers per carriage. Assuming an average of 7 carriages per train at peak time, results in an overall capacity of 945 passengers per train and an emission factor of 0.011 kg of CO_2 per passenger kilometre (Table 2).

2.3. Indirect emissions

In addition to the everyday CO_2 emissions from vehicles, their manufacture and transport to site of use also contribute significantly to atmospheric carbon. These sources of pollution may be discounted over the lifetime of the vehicle so that the longer the lifetime, the lower the annual emissions. The Department of the Environment and Heritage Australian Greenhouse Office (2003) published methods for the estimation of operation and manufacture energy requirements expressed as passenger kilometres, and thus directly comparable with the results of calculations described in the previous section.

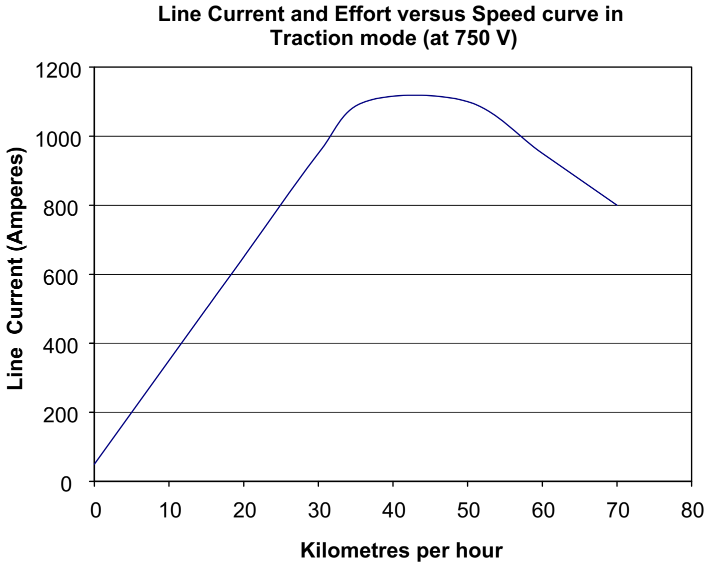

Fig. 1. Traction curve of a LUAS tram travelling the "red line".

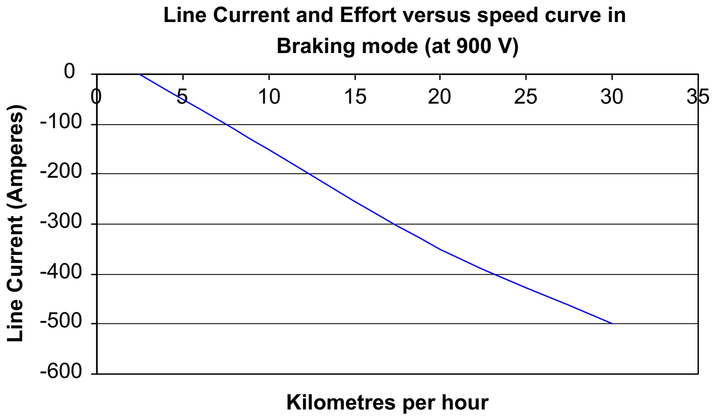

Fig. 2. Traction curve for a LUAS tram braking on the “red line”.

Table 2
Vehicle **kilometre** and passenger **kilometre** emissions

Mode	Max occupancy (cap vehicle^{-1})	Average speed (km h^{-1})	kg CO_2 km^{-1}	kg CO_2 Pass km^{-1}
Cycling	1	16	0.005	0.005
DART	945	30	10.22	0.011
Intercity bus	57	70	0.84	0.015
Dublin bus	90	13.5	1.45	0.016
City bus	50	20	1.26	0.025
Private car (max)	4	66	0.17	0.042
SUV (max)	5	66	0.26	0.052
LUAS	235	24	14.94	0.064
Private car (normal)	1.4	66	0.17	0.120
SUV (normal)	1.4	66	0.26	0.184

Table 3
Embodied energy per passenger km at average occupancy

Transport mode	Age (yrs)	km y^{-1}	Weight (kg)	MJ kg^{-1}	MJ km^{-1}	Occupancy	MJ Pass km^{-1}
DART (assumed 5 cars)	30	123,125	175,000	100	5.92	428	0.01
Intercity bus	13	151,894	12,000	100	0.61	30	0.02
Dublin bus	13	62,068	11,000	100	1.36	45	0.03
City bus	13	45,043	8000	100	1.37	25	0.05
Cycling	10	2776	15	200	0.11	1	0.11
Private cars	13	10,498	1000	100	0.73	1.4	0.52
SUV	13	10,498	1976	100	1.44	1.4	1.03

Estimates based on Irish data were calculated following similar methods (Table 3). Once the energy embodied in a vehicle kilometre was estimated, both peak and off-peak occupancies for each transport mode were applied to express energy requirements in passenger kilometres. The average annual journey distance travelled by Irish private cars is approximately 10,500 km (SEI, 2006). It is estimated that the average private car weighs 1.0 tonne and that motorised vehicles have an embodied energy coefficient of 100 MJ/kg. Following Zoboli et al. (2003), it is taken that road vehicles have an average life-span of 13 years. However, Ireland’s recent economic success and associated increase in expenditure suggests that value may be an understatement.

For transportation by bus, it is assumed that the normal occupancy is approximately half of peak occupancy. The annual journey distance of bus services was calculated by dividing the vehicle kilometre for each service category, as published in Bus Eireann (2004), by the number of vehicles in operation. Intercity, city and Dublin city, double-decker, buses are assumed to weigh 12, 8 and 11 tonnes, respectively.

Calculation of the embodied energy related to DART transport required a number of assumptions. Dodgson and Viegas (2001) reported an overall DART travel distance of 1,970,000 km for 2000. Given that there were 80 carriages in service in that year and assuming an average complement of five carriages per train, this indicates an average annual distance travelled of 123,125 km. It is assumed that a DART car weights 35 tonnes (taken as an average as most electrical carriages have an unladen weight of between 30 and 40 tonnes). Due to the varying nature of DART service provision, it is difficult to allocate embodied energy between peak and off-peak times. Therefore, the values adopted in the calculation of embodied energy

Table 4
Overall carbon demand of passenger kilometres

Mode	Emissions at max occupancy kg CO_2 Pass km^{-1}			Emissions at normal occupancy kg CO_2 Pass km^{-1}		
	Direct	Indirect	Total	Direct	Indirect	Total
Cyclist	0.005	0.0061	0.011	0.005	0.0061	0.011
DART	0.011	0.0006	0.011	0.028	0.0006	0.029
Intercity bus	0.015	0.0006	0.015	0.029	0.0011	0.031
Dublin bus	0.016	0.0008	0.017	0.032	0.0017	0.034
City bus	0.025	0.0015	0.027	0.050	0.0031	0.053
Private car	0.042	0.0103	0.052	0.120	0.0293	0.149
SUV	0.052	0.0162	0.068	0.184	0.0579	0.242

represent an overall average, inclusive of all levels of service and assumes that an average train comprises of five carriages with a complement of 428 passengers per train. This assumption is based on seven carriages in operation during peak times with full occupancy and four in operation outside peak times with 50% occupancy.[1] As the original carriages, which began service in 1984, are still in operation a functional lifetime of 30 years was chosen. The embodied energy of travel by bicycle was calculated using national data on commuting distances. The 2002 Irish Census returns (Irish Central Statistics Office, 2004) suggested that the average distance cycled to work is 5.47 km. It is assumed that the return journey is undertaken five times per week for 49 weeks per annum, resulting in an annual journey distance of ~2700 km. The estimate is based on an aluminium frame bicycle with a functional life of 10 years.

The International Energy Agency (IEA) publishes an estimate for the carbon intensity of global energy. This reflects the extent to which energy is dependent on fossil carbon. For 2004 it was estimated that 1 TOE in primary energy supply resulted in 2.37 tonnes of CO_2 being emitted into the atmosphere, giving a carbon intensity of 0.056 kg CO_2 MJ^{-1}. Applying this value allows the indirect carbon emissions embodied in Irish transport modes to be estimated and added to the direct emissions (Table 4). LUAS services have been in operation for a few years only and are in a process of expansion; reliable data were unavailable to estimate indirect emissions for this mode.

3. Results

The estimated values for net CO_2 exhalation for typical modes of cycling are presented in Table 1.

The CO_2 emissions per vehicle and passenger kilometre are shown in Table 2. Normal SUV and private car transport result in greater than 10-fold the emissions per passenger kilometre than public transport by the DART or bus services. At maximal occupancy private car or SUV emission per passenger km is similar to the LUAS but still 4-fold greater than that offered by travel by the DART. Cycling at a speed typical of the commuter cyclist reduces the carbon emission of the lowest form of motorised transport, i.e. the DART, by a further 50% and offers the lowest CO_2 emission per km form of commuter transport (Table 2).

Table 3 shows the embodied energy associated with transport modes at average occupancy. Both the SUV and the private car provide the highest embodied energy estimate. Due to its aluminium frame and relative low level of use, commuting by bicycle shows a higher embodied energy content than does public transport.

If the same method is adopted for peak occupancy but, in addition, apply the global carbon intensity of energy (measured kg CO_2 kJ^{-1}), then the wider impact of a passenger kilometre can be estimated for differing modes and level of use (Table 4). Normal occupancy is assumed to be half of peak occupancy. Note that the direct energy of off-peak DART transport assumes a train contains four carriages. Most notably, at maximal occupancy (during peak hours), the overall CO_2 emissions of a cyclist are equal to those of a DART passenger.

4. Discussions

In discussing the results it is important to provide a caveat. As can be seen in Table 4, peak DART passengers and cyclist demonstrate equivalent emission factors. This comparison should be viewed with caution as it is based on a number of assumptions. If the bike frame were composed of carbon steel, the embodied energy of cycling, as seen in Table 3, would be halved. This is mirrored by the assumptions needed in normalising the changing nature of DART service provision. This comparison does not seek to detract from the benefits of cycling. Given the differences in service provision involved (i.e. distances, speed and occupancy), it is unlikely that either form of transport provides a viable substitute for the other. Several assumptions are also made in allocating embodied energy estimates to a units of service, in this case passenger kilometres. Such assumptions allow recognition of the wide-ranging impacts associated with personal transport, beyond those of direct fuel combustion.

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[1] These estimates are used individually for the allocation of direct emissions to passenger kilometres.

Some commentators consider that the energy used to manufacture vehicles has already been consumed and the passenger has no capacity to effect change in the same way that they may influence direct emissions. Another point raised is the problem of allocating study boundaries. This is sometimes referred as the truncation error, whereby it is difficult to determine where the indirect demands of consumption effectively end. For example the indirect demand of transport could conceivably include the energy required for vehicle maintenance, road construction and maintenance as well the fugitive emissions released through the production of the fuel used in all these processes. To provide manageable boundaries, the energy required only for vehicle construction was included as it is more applicable to the overall functional life of a vehicle. However, estimates for indirect energy focus attention on issues surrounding vehicle life duration and intensity of use. For example, there is little use in producing a car that results in lower emissions but has a reduced functional life. Examining embodied energy reinforces the view that some products have a greater environmental impact during production than when in use, and vice versa.

4.1. Direct emissions

The choice of mode, and consequently the associated CO_2 emissions are dictated by a number of factors such as journey distance, number of passengers and the availability of existing services. Shorter trips are mostly undertaken by walking, and private car and bus modes are selected for most short to medium distance trips. In terms of direct emissions, an 'average' 75 kg person cycling 1 km at 16 km h^{-1} has an estimated direct carbon emission equivalent to half the emissions that would be allocated to a person travelling a similar distance by DART train during peak hours. While it is not unexpected that cycling represents the lowest emission estimate, it may come as a surprise that DART peak emissions do not exceed it by a greater margin. It should be noted that DART emissions are based on the 2003 Irish electricity generation mix. The future expansion of renewable energy generation and the replacement of oil by natural gas may reduce carbon emissions associated with DART transport. It is not inconceivable that in the future the direct emissions of an electric rail passenger will be comparable to those of a cyclist commuter. Combustion vehicles do not possess the same capacity to reduce emissions as those powered by electricity. During peak hours, a passenger travelling by intercity bus, DART and Dublin bus creates higher emissions than those created through either casual or more strenuous cycling. Beyond peak times, cycling remains the least carbon intensive. Public transport is considered more sustainable when viewed from the context of a car centric society. Here it is assumed that a trip by bus or train will displace a trip that otherwise would be taken by car.

The emission factors adopted in Table 2 are assumed to be representative of commuter conditions where passenger occupancy is full and exertion through cycling is at least moderate. Beyond peak times the occupancy of public vehicles is known to be reduced, resulting in higher emissions per passenger kilometre: official data were unavailable but anecdotal evidence suggests off-peak occupancy in Ireland is about one half that for peak times. As can be seen from Table 2, passenger usage is an important factor in determining the environmental impact of differing transport modes. Based on current estimates, the values in Table 2 demonstrate transport at its most efficient. The only means to further decrease emissions is to increase fuel efficiency. This may also be a factor at times when occupancy is inevitably reduced and unlikely to rise. While an occupancy rate of 10–20% may appear low, it is likely to represent conditions either late at night or early in the morning.

At peak times, public transport, with the exception of LUAS, results in lower CO_2 emissions per passenger kilometre than a fully occupied car. A fully occupied private car results in 33% greater overall emissions per passenger than the average value for bus transport services at half occupancy. Public transport accounts for less than 5% of final fuel consumption within the Irish transport sector, whereas 37% of annual transport emissions (5592 kt CO_2) are attributable to private car transport (O'Leary et al., 2006). If all private cars were driven at maximum capacity, annual transport emissions would reduce by >3600 kt CO_2. This is highly improbable given the difficulties in staggering working hours and the fact that not every additional passenger kilometre displaces a vehicle kilometre. However these estimates do point out that more efficient private car use, as well as increasing public passenger transport, has a role to play in increasing the overall energy efficiency of transportation.

4.2. Indirect and overall emissions

Private car transport creates the second highest indirect energy demand. Even at maximum occupancy, the embodied energy demand for private car mode is 0.18 MJ Pass km^{-1}, which remains the second highest estimate. This value is calculated for an average family private car: if the same method is applied to SUVs, the value becomes 1.03 MJ Pass km^{-1} at normal capacity and 0.29 MJ Pass km^{-1} at maximum capacity (assumed to be five). A fully occupied SUV retains a marginally higher overall emission factor than transport by car. This refutes the advantage of increased passenger capacity when measuring carbon emissions. The gulf between the direct and indirect emissions associated with cycling and those of other transport modes is reduced when compared against transport at peak times. It should be noted that the estimate of energy embodied in cycling is based on current commuting practices. As aluminium has a much higher embodied energy coefficient than steel, commuting by bicycle retains a high-embodied energy coefficient despite being used for daily commuting and having a lower weight per passenger ratio.[2] Anecdotal evidence suggests that sales of aluminium frame bicycles are now as high if not higher than for those with frames of carbon steel.

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[2] This is significantly in excess of the other vehicle categories and again emphasizes the value of examining the indirect demands of transport.

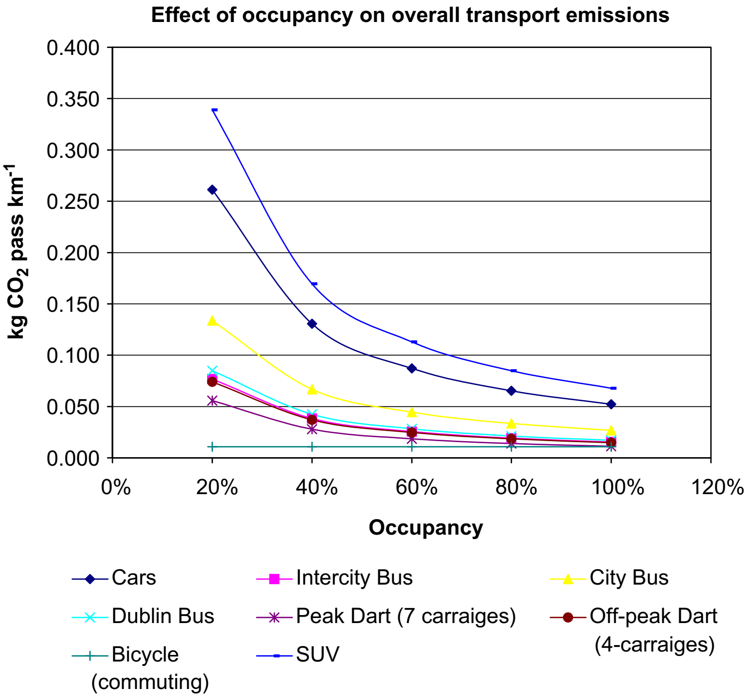

Fig. 3. Effect of occupancy on overall transport emissions.

Casual cycling will increase the indirect energy embodied in each kilometre. Interestingly the ratio between energy embodied during manufacture and direct emissions is highest for commuting by bicycle. This suggests that increased use has a greater capacity to reduce overall emissions per passenger kilometre than other modes. While a cyclist does have a lower (direct and indirect) emission factor than an intercity bus passenger during off-peak hours, the difference is not as pronounced as for other modes. An increase in the fuel efficiency of buses could potentially result in an emission factor equivalent to an active cyclist. For other modes, overall emissions are dependent on passenger occupancy. It should be noted that the embodied energy estimates for DART transport assumed that all trains were formed of the same number of carriages.

From Fig. 3, as occupancy increases, the difference (both relative and absolute) in emissions between modes decreases. This suggests that the factors that effect modal choice becomes less imperative at peak times when occupancy is highest. However there still remains a significant difference between private and public transport. Because of the stark distinction between DART services at peak and off-peak periods, separate estimates for peak and off-peak travel are included. Interestingly the emissions allocated to off-peak DART passengers closely mirror the emissions allocated to intercity bus transportation. Given the differences in the areas served by both modes it is unlikely that DART passengers have the opportunity to choose intercity bus as an alternative mode of transport and vice versa. This again reinforces the importance of service provision and in assigning emissions to personal transport.

5. Conclusions

All forms of transport have an impact on the environment, either directly or indirectly.

Even activities such as walking derive their energy from food produced using fossil energy. At peak times cycling has the lowest direct emissions per passenger kilometre but this differential increases significantly outside these times. DART transport at peak times provides the lowest direct combustion estimate. When the overall emissions, including the indirect emissions from manufacture are included, it is possible that the emissions of cycling may equal those assigned to DART passengers. While transport by private vehicles is the most energy intensive transport mode, a fully occupied average sized private car may compete with public transport services at certain off-peak times. However, despite its greater capacity, a full SUV has a higher emission factor per passenger kilometre. The impacts of human activity are more complicated than is often acknowledged. Including additional factors into analyses may provide counter intuitive findings. The overall impact of cycling is dependent on many factors such as diet, passenger fitness, speed and frequency of use.

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