

AN ANALYSIS OF THE ENERGY EFFICIENCY OF THE BICYCLE

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Introduction

Ireland depends to a great extent on energy imports, and transport is the single most energy-consuming sector (39%); this dependency has grown significantly in recent years, up 51% over the period 1990-2004[1]. Further, Irish transport is very car dependent, by European Standards. Therefore the price of oil and issues of security of supply are significant concerns for Ireland. A growing number of voices are also questioning the social, health and environmental costs of car dependence [2].

This paper reviews the bicycleⁱ, from an energy perspective. The bicycle offers an unparalleled energy efficiency, compared especially to the motor car, for urban transport; it is not only the most efficient means of utilising human power for transport, but also offers a speed, range and flexibility that compares very favourably with alternatives. Cycling is increasingly being seen as an essential component of a sustainable future for urban transport [3].

The energy efficiencyⁱⁱ of the bicycle is considered from three perspectives: operation (i.e. riding), manufacture (of bicycles) and infrastructure (building and maintaining roads).

Some consideration is given to factors that affect the energy performance of the bicycle, which is however, found to be close to optimal already, and has been so for many years.

Finally, this paper makes an analysis of the energy implications of a modest uptake in cycling in an Irish context.

Comparative Analysis

In considering the energy efficiency of the bicycle we make comparisons with two other modes of transport: walking and the motor car. This is appropriate as the bicycle sits fairly evenly between walking and the motor car, in terms of speed; typical values, in an urban environment are: walking: 5kph, cycling 15kph, driving 50kph; i.e. the cyclist is about three times faster than the walker and three times slower than the motorist.

Walking is not normally considered a means of transport at all, but is in fact an essential component of every journey, as anybody with mobility impairment knows very well. It is also by far the most flexible. As we shall see, motorised transport requires a massive investment in energy for the necessary infrastructure; by comparison, a walker's requirements are very modest indeed.

We restrict our analysis to journeys typical in an urban environment i.e. the distance that can be covered by bicycle in half an hour to an hour. We recognise that while the average motorist can, on occasion, drive for many hours, the average walker or cyclist is not able or willing to do the same. There is also evidence that around thirty minutes is as long as most people are prepared to travel on a regular basis, regardless of the means of transport [4].

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- i The term "bicycle" is used to mean pedal cycle, as opposed to a motorcycle or any other powered two wheel machine; the term "cyclist" is used to mean "a person riding a bicycle"
 - ii Energy data are commonly found in an array of units e.g. oil in barrels, electricity in kWh (kilowatt-hours), food energy in Calories, other energy in BTUs (British Thermal Units) etc.; to facilitate easier comparison, all energy figures in this paper are presented in Joules and comparative data in mega-joules per passenger-kilometre (MJ/pkm).
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Energy and Energy Efficiency

It is important to distinguish between energy consumption and energy efficiency. Energy efficiency is of interest, in the current context, in so far as it facilitates a reduction in energy consumption, for transport. However, historically, improvements in energy efficiency have consistently been associated with not a decrease but an increase in total energy consumed [5]. This is especially so in the transport sector. The efficiency of the internal combustion engine may be higher now than it was fifty years ago, but the total energy consumption of the transport sector is higher, not lower, over the same period; that is, simply there are more cars, and they are driven further – and faster. The current point is not so much that a bicycle is an efficient means of converting human muscle energy into kinetic energy, which it is, but more that the bicycle offers a means of transport, of a person and a modest load, over a distance typical of urban travel, that requires far less total energy (per passenger-kilometre) than a motor car.

Food Energy

The bicycle is differentiated from conventional motorised transport in that it consumes no fuel at all in operation. While the bicycle has no motor and consumes no external fuel, it does of course consume energy; that is human energy. The same is true of the walker.

Unlike a motor or engine, a human being consumes energy all the time, even when resting or asleep. This base level of activity is called the Base Metabolic Rate (BMR). Various formulae have been proposed to calculate the BMRⁱⁱⁱ, based on height, weight and age. Typical values are 60 – 80W. The amount of power a human being can generate to do useful work varies much more, not just by height, weight and age, but also by general health and fitness. Also, unlike a motor or engine, a human being can generate a lot more power for short periods than for longer periods. The amount of power a human being can generate can be expressed as a function, or rather a multiple, of BMR [6]. For moderate exercise, that can be maintained for an half an hour to an hour i.e. walking or ordinary cycling, the value is around 3 i.e. the energy available is about 200W. For comparison, the multiple given for sedentary activities is about half that i.e. 1.5 or 100W [7]; at the other extreme an Olympic sprinter expends a massive 5KW over a 10 second spurt [8]. We take 200W as the amount of power available that an average cyclist, or walker, can maintain for half an hour to an hour.

Human energy comes of course from food energy. The conversion of food energy into human (i.e. kinetic) energy is complex and depends on both the food and the person. As it happens, the efficiency with which a human being can convert chemical (food) energy into kinetic energy is broadly similar to the efficiency with which an internal combustion engine can convert chemical (fossil fuel) energy into kinetic energy, about 20% [9]. However, the efficiency with which a cyclist can convert food energy into distance travelled is much higher; anticipating our results, in an urban environment, a cyclist can achieve a “miles-per-gallon” of about 670mpg [10], roughly 20 times that of a motor car in similar conditions^{iv}.

However, food energy is not a primary energy; it is of course derived from plants, directly or indirectly i.e. by eating animals. In a pre-industrial environment, food energy was derived mainly from solar energy i.e. through photosynthesis; there was also a modest input of human energy, for agricultural labour. At present, however, our food production is dependent on a massive application of external energy, mostly fossil fuels, for fertiliser, pesticides, transport, processing, packaging, storage, retailing, cooking etc. Our food production is in fact stunningly inefficient in energy terms; many multiples of the food energy derived is needed to produce and deliver it [11].

iii Base Metabolic Rate; well-known formulae include the Harris-Benedict equation, the Katch-McArdle formula and the Cunningham Formula

iv mpg (miles per gallon) persists despite metrication, but l/100km (litres per 100 kilometres) is now preferred

The Bicycle in Operation

Discussions of the amount of energy developed by cyclists and speeds attained tend to concentrate on the extremes attainable. However as a means of transport, rather than for sport, it is appropriate to consider more modest efforts i.e. the 200W discussed above. What can be achieved by a cyclist expending 200W?

For comparison, consider a pedestrian using a similar amount of energy. A normal human being, in reasonable health can walk at about 5kph. A human being in particularly good shape could, rather than going much faster, maintain this effort for an extended period, even all day.

Under average conditions i.e. on a reasonable road, on the level, expending a similar amount of energy, a cyclist can travel at about 15kph i.e. about 3 times the speed of a walker. A reasonably fit cyclist, on a decent machine, can easily surpass that and manage 20 – 25 kph, or up to five times faster.

If we take the lower speed of 15kph as a reasonable average, the cyclist can cover 15 km (about 9 miles) in an hour or 7.5 km (about 4.5 miles) in half an hour. If our average cyclist, developing 200W, can cover 15km in an hour then the overall energy efficiency of the bicycle is $(200 \times 60 \times 60) / 15 = 48,000$ joules per kilometre, or ~ 0.05 MJ/pkm. Note that a walker, having a speed, hence range, one third of a cyclist, will have an overall energy efficiency of 0.15MJ/pkm.

By way of comparison, a motor car might do 10 – 20 km per litre of petrol. A litre of petrol yields ~ 35 MJ, so the energy efficiency of a (single occupancy) vehicle is 1.7 – 3.5 MJ/pkm. For the sort of journeys for which the bicycle is a reasonable alternative a lower energy efficiency is more likely, so we will use a figure of 3.5 MJ/pkm; this is just the energy of use; we shall also consider the energy of manufacture and of infrastructure.

The Electric Bicycle

An interesting comparison can be made by considering the electric bicycle. Although the electric bicycle is somewhat heavier than the pedal bicycle, mainly due to the motor and battery, the gross weight is still comparable. The wind profile of a pedal and electric bicycle are very similar. The surprising result is that the electric bicycle is actually more efficient than the human powered bicycle. Lemire-Elmore (2004) [12] finds that a life-cycle analysis (i.e. including the energy cost of battery technology and the total energy cost of additional food needed by an active cyclist) shows that an electric bicycle actually consumes 2 - 4 times less primary energy than human riders eating a conventional (i.e. non-vegetarian) diet. This is due less to the high efficiency of the battery and motor and much more to the enormous energy inefficiency of the food system, alluded to previously.

Bicycle and Car Manufacture

It is not a simple matter to determine the energy needed to manufacture a bicycle, a car or any other form of transport. There is an energy cost embodied in the raw materials and energy costs at each stage of production. For comparative purposes, and also because the information is much more widely available, we consider first the energy cost of motor car manufacture. We want to determine the energy cost per passenger-kilometre so we also need to determine a value for the lifetime mileage^v for a bicycle and a car.

The lifetime mileage for a car is relatively straightforward to determine, since this information is logged by the vehicle's odometer. A average (Irish) annual mileage is 15,000km (10,000 miles) [13]. A car might be driven for say 7 - 10 years, so in round figures we use 100,000 km as a lifetime mileage for a car. The lifetime mileage of a bicycle is harder to determine, but even taking into account the relative range of a car and a bicycle it is likely to be much lower, since many bicycles are little used. However, for this purpose we assume a commuter cyclist, covering a single journey of 5km, say 4 days a week for 40 weeks a year, to arrive an

v For lack of another word, we use the term "mileage", even though we measure distance in kilometres

annual mileage of 1600km. We assume a bicycle lasts longer than a car, say 15+ years, so the lifetime mileage of a bicycle could be ~25,000km.

The energy cost of car manufacture varies considerably by model and other factors. The energy efficiency of car manufacturing has also improved considerably over the years, not least because regulation now demands high and increasing rates of recycling, which significantly reduces the energy cost, especially of that embodied in steel. We will take a figure of 30GJ from a UNESCO study [14]. We therefore arrive at a manufacturing energy cost of 30GJ / 100,000km = 0.3MJ/pkm.

The energy cost of bicycle manufacture can be estimated approximately by using the energy cost of car manufacture and the relative weights of a car and bicycle. Taking a car weight as 2T and a bicycle as 10kg we arrive at an energy cost for a bicycle of 0.15GJ. We therefore arrive at a manufacturing energy cost of 0.15GJ/25,000 = 0.006MJ/pkm; we will use a slightly higher value of 0.01MJ/pkm, as bicycle manufacturing does not enjoy the same economy of scale, in terms of energy, as car manufacturing.

Bicycle and Car Infrastructure

The last component of our energy assessment is the energy cost of the road network. While the approximate energy cost of laying or maintaining a kilometre of road is relatively straightforward to ascertain, it is much more difficult to determine the energy per passenger-kilometre for the vehicles that use the road. There is a distinction between the energy cost of a new road and the energy cost of its maintenance and different grades of road have a different degree of use, different maintenance schedules and different energy costs. A rough calculation is as follows.

Ireland has a total of about 20,000km of "main" roads and 80,000km of "minor" roads [15]; the latter is an usually high figure. From a Canadian study [16], we use an energy cost of "road rehabilitation" of 250GJ per lane-kilometre. We assume main roads are "rehabilitated" every 5 years and minor roads every 10 years; we ignore multi-lane roads. The total energy cost, per year, is therefore $(20,000/5 + 80,000/10) * 250G = 3PJ$.

The total number of cars on Irish roads is about 2M [17]; we use the same figure as earlier for average annual mileage of 15,000km. We therefore arrive at a figure of $3PJ / (2M * 15K) = 0.1MJ/pkm$.

Since roads are a shared resource it is almost impossible to apportion an energy cost directly between cars and bicycles; instead, we use the weights and annual mileages to arrive at a relative energy cost. Using our previous weight ratio car:bicycle of 100:1, and a relative annual mileage of 10:1, the infrastructural energy cost for a bicycle is 0.1KJ/pkm.

Summary: Energy Efficiency

Mega-Joules per Passenger-Kilometre	Operation	Manufacture	Infrastructure	Total
Walker	0.15	-	-	0.15
Bicycle	0.05	0.01	0.00	0.06
Car	3.5	0.3	0.1	3.9
Car:Bicycle Ratio	70	30	1000	65

Notes

1. The energy cost of Operation is overriding, for both both cars and bicycles
2. The ratio of energy cost of Operation to Manufacture is about 10 for cars and 5 for bicycles
3. The Infrastructure energy cost is high but widely shared, hence low per pkm; the energy cost for bicycles is essentially zero, as bicycles use the infrastructure built for cars; we ignore cycle lanes, but conversely note that the highest road infrastructure costs are for motorways and other major roads not used by cyclists
4. The above figures ignore occupancy; obviously a car with multiple occupants will increase the energy efficiency (for Operation) by the same factor; however, average occupancy figures are low, rarely reaching even 2, and falling [18].

Comparison with CO2 Emission Figures

As a cross-check, it is instructive to make a comparison, from independent data, of the CO2 emissions of the car and the bicycle [19]. This comparison makes the assumption that primary energy consumption and CO2 emissions are related; given that car transport is nearly 100% dependent on imported oil and even manufacture and infrastructure are probably similarly dependent, this is not an unreasonable assumption.

Transport Mode	Kg CO2 per passenger-kilometre
Bicycle	0.005
Car	0.2
Ratio	40

Notes

1. The data given for the bicycle assumes a fairly leisurely ride; for a more vigorous effort, the carbon emissions are found to double
2. The data given for the car is 0.149 for a "normal" car and 0.242 for an SUV, at normal occupancy; a median figure of 0.2 was chosen
3. The data assume an aluminium framed bicycle, which has a much higher embodied energy than steel; however, it is suggested that these are now common
4. The ratio, of car:bicycle, for CO2 emissions, is 40, lower than our overall ratio for transport, 65, but still broadly comparable

Energy Efficiency and Bicycle Design

The design of the standard bicycle has been remarkably static for a long time. Alternatives have been considered, but none have made a significant impact on either utility or sports cycling. It might be supposed that any possible innovation that could yield a performance improvement would have been adopted or at least considered by the sporting community, but Cox (2009) finds otherwise [20]; innovation has been hindered, not encouraged; despite supposedly presenting a high profile image of cycling, cycle sport has been of limited relevance to the utility cyclist.

The main drain on the human rider's limited energy output is air resistance, even at modest speeds [21]. The other significant impediment is rolling resistance; this is partly a function of the road surface and partly of the bicycle itself. Despite the primacy of air resistance, most

cyclists find poor quality roads a significant energy drain as well. The need to deviate from a straight line i.e. to avoid potholes and other obstacles is also a safety issue.

All cyclists are significantly affected by slope; some of the energy expended climbing a hill is returned descending it: the potential energy gained climbing is returned as kinetic energy descending, but most of this kinetic energy is dissipated in air resistance, due to the higher speeds attained free-wheeling downhill.

Accordingly, the main focus of efforts to improve bicycle performance is reduction of the cyclist's frontal area. Some gain can be made within the conventional design by tipping the rider forward, hence the drop handlebars, seen on all sports cycles and most lightweight utility bicycles.

A greater improvement can be made by doing the opposite, that is by tipping the rider back rather than forward; this results in the so-called recumbent bicycle, which has the rider leaning back, with the feet level with the torso. This makes for a long wheelbase if the pedal cranks are kept behind the front wheel, although it is also possible to put the pedal cranks out in front. Other designs incorporate fairings, to reduce air turbulence and even offer protection from the weather. The recumbent also claims greater comfort. These machines are now commercially available and have broken records [22], but despite these real advantages they are rarely seen.

While the energy efficiency of the bicycle is both the subject of this paper and perhaps one its most notable features, it is worth noting a few other points. The main advantage of the design of the conventional bicycle, is the relatively high riding position that offers good visibility, both of and for the rider. The narrow width is also important to the utility rider, who has to share restricted road space with other road users. These are both significant safety considerations, that for most cyclists, override efficiency. Similarly, the so-called step-through designs sacrifice the simplicity and strength of the conventional diamond frame to offer a bicycle better suited to a rider wearing long or flowing clothes (traditionally woman's skirts) or to the rider less willing or able to swing a leg over the frame. So in practice, energy efficiency is only one of a number of factors that determine the use of the machine.

The Bicycle as an Energy Saving Initiative, Case Study: Limerick

In this section we examine the potential for energy saving, in the transport sector, that would arise from a significant change in urban transport patterns, in favour of cycling (and walking). We take Limerick as a case study, using the data presented in the city's Smarter Travel Bid [23]; in particular, we assume, for this purpose, that the targets set in this document, for a modal shift towards cycling and away from car dependence, are met.

The figures laid out in this document are presented for a target date of 2016, which we will use to determine a potential energy saving. The data for Limerick are given by "hubs" in the greater Limerick area, including the city centre and various outlying suburbs. There are a number of features of the current patterns of travel in Limerick that are peculiar to the city. The most striking reflect the large differences in car ownership and use between disadvantaged and more affluent areas. The upshot of this is that in relatively disadvantaged areas the modal share for walking is already above Limerick and National targets [24], due to low levels of car ownership; however cycling levels in these areas is even lower than the already low figures for more affluent areas [25]. This is perhaps an indication of the socially integrative potential of an overall increase in cycling.

For our purposes we will use the aggregate data for Limerick i.e. ignoring the significant, and interesting variations across the city. The targets for cycling are the most ambitious: cycling is projected to increase from 3% to 14% (nearly a five-fold increase), while walking and public transport are to increase only modestly [26].

To attribute an energy saving to a modal shift in favour of cycling it is necessary to consider what type of transport a cycle journey might displace. If a cyclist displaces a walker, it can only be for a very short journeys, due to the restricted range of a walker. A cyclist may well displace a bus journey, as for urban trips, a cyclist is likely to travel faster than a bus, taking

into account the time to walk to and from the bus stop, the time spend waiting for a bus and the relative slowness of the bus due to frequent stops.

Over time, cycling is also much cheaper than public transport, and of course far cheaper than a private car. However, since car ownership is so high in Ireland, it likely that many cyclists also (currently) have access to a car, hence for simplicity we will assume a cycle trip displaces a similar journey by car.

As we have established, a cycle journey that displaces a car journey offers an energy saving of ~65:1; this high ratio means that the potential of a modal shift in favour of cycling is therefore nearly equal to the displaced energy associated with the same journey by car.

The total number of annual vehicle-kilometres in the study is given as ~46,000,000 km [27] and the average vehicle-kilometres per trip is 17km. The current modal share of cycle journeys is given as 3%, so the share of total vehicle-kilometres for cycling is 3% of 46,000,000 km, or ~1,400,000km, per year. If this is increased by the projected factor of 5 then the displaced car mileage would be $4 * 1,400,000$ km or 5,600,000 km. Using our figure of 3.85MJ/pkm the total energy saved would be $3.85M * 5,600,000$ or ~20TJ per year, for Limerick.

The equivalent saving in CO2 emissions is therefore $0.2\text{kg/pkm} * 5,600,000 \sim 1,000,000\text{kg}$. The projected CO2 saving for the entire Smarter Travel initiative in Limerick is ~2,600,000kg [28], per year, so cycling would account for nearly 40% of that.

If we take these figures as indicative of the whole country, which is a considerable but not a wholly unwarranted oversimplification, and taking the population of Limerick as ~100,000 and of the whole country as 4.5M we could project a total energy saving for the country, under the terms of the Limerick Smarter Travel initiative of $20\text{TJ} * 4,500,000 / 100,000 = 900\text{TJ}$ or 0.9PJ

The total primary energy consumption of Ireland is given as 11.5MToe and the proportion of that attributable to transport is 39% [29], hence the total energy consumed by the transport sector in Ireland is $11,500,000 * 42\text{GJ} * 0.39 \sim 190\text{PJ}$, per year. From this we can say that the cycling initiative, as proposed by the Limerick Smarter Travel Bid, implemented nationwide, would result in a ~0.5% reduction in total energy consumption in the Irish Transport Sector. This is a modest figure, which suggests the private motor car, although pervasive, might not account for a very high proportion of national transport energy use; a fuller analysis is beyond the scope of the present paper.

Conclusion

This paper has demonstrated the very high energy efficiency of the bicycle, particularly when compared to the motor car, on which Ireland is currently so dependent. Alternatives to the motor car are often considered in terms of walking and public transport, but the the bicycle offers both a very high energy efficiency and a speed, range and particularly flexibility that competes very favourably.

The projected energy savings, based on the proposal in the Limerick Smarter Travel Bid are not large, but the dependency on the motor car is one of the most intractable problems of energy dependency in modern societies. A modal shift away from the motor car, in favour of cycling, offers a very accessible means of moving to a lower energy transport future.

A further aspect of cycling, beyond the energy efficiency considered in this paper, is the potential health benefit. Increased levels of modest physical activity, which is an integral part of cycling, is now regarded as perhaps the single most effective way of improving personal health.

In the context of high and rising energy prices, and widespread concerns for public health the bicycle is now accepted as an integral part of a lower energy future for urban transport.

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