Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Energy Policy

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

Assessing the energy implications of replacing car trips with bicycle trips in Sheffield, UK

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ARTICLE INFO

Article history:
Received 22 May 2010
Accepted 26 January 2011

Keywords:
Replacement ratio
Transport policy
Modal shift

ABSTRACT

A wide range of evidence supports policies which encourage people to cycle more and drive less, for health and environmental reasons. However, the likely energy implications of such a modal shift have remained relatively unexplored. In this paper we generate scenarios for increasing the cycling rate in Sheffield between 2010 and 2020. This is done through the novel application of a simple model, borrowed from population ecology. The analysis suggests that pro-cycling interventions result in energy savings through reduced consumption of fuel and cars, and energy costs through increased demand for food. The cumulative impact is a net reduction in primary energy consumption, the magnitude of which depends on a number of variables which are subject to uncertainty. Based on the evidence presented and analysed in this paper, we conclude that transport policy has a number of important energy implications, some of which remain unexplored. We therefore advocate the formation of closer links between energy policy and transport policy in academia and in practice; our approach provides a simple yet flexible framework for pursuing this aim in the context of modal shift.

1. Introduction

Increasing the proportion of trips made by non-motorised transport in urban areas is desirable from environmental, health, and natural resource perspectives (Michaelowa and Dransfeld, 2008; Killoran et al., 2006; Woodcock et al., 2007, 2009; Dodson and Sipe, 2005). However, widespread awareness has so far failed, in most places, to transfer into effective policy action: cycling and walking still constitute a small proportion of trips in all but a few developed countries, and non-motorized transport has yet to pose a serious threat to the dominance of the car in the vast majority of urban settlements (Pucher and Buehler, 2008). This knowledge–policy gap has widened recently with the publication of evidence which strengthens the argument for political action on climate change, degenerative diseases, and oil depletion (IPCC, 2007; Barness et al., 2007; Aleklett et al., 2010).

Although these intractable problems have received much academic attention, the recommended solutions often tackle just one area, such as climate change adaptation or obesity drugs, at a time (Klein et al., 2007; Nature News, 2006). Such narrow 'solutions' could be effective if policy-makers faced a series of isolated problems, but instead, the issues relating to modal shift are interrelated aspects of a wider global predicament (Greer, 2008). For this reason, broad analyses tend to recommend integrated policies which tackle many issues simultaneously (e.g. Odum and Odum, 2001; Beddoe et al., 2009). Converting this theory into practice has proved challenging, however, the appropriate policy measures remain the subject of intense debate (Jackson, 2009). Reducing fossil fuel demand in developed countries, however, is one objective which receives support from a wide range of perspectives and is increasingly central to mainstream political priorities (e.g. Smil, 2008; Woodcock et al., 2007; Perman, 2003). This objective, and the evidence which supports it, provides a conceptual basis for this paper.

Transport is the fastest growing energy user globally and the sector consumes over 20% of primary energy supply; this is primarily due to car use (Smil, 2005). The conventional car is an exceptionally inefficient form of urban transport, typically consuming 2.9 MJ of fuel per person-km (pkm) if the driver is the sole occupant (MacKay, 2009, Fig. 20.23). Cyclists, by contrast, consume around 80 kJ/pkm of food, less than 1/30th of the primary 'fuel' requirements of cars. In developed economies, where car ownership has approached one car for every two people (World Resources Institute, 2009), the driver is often the car's sole occupant. In the

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doi:10.1016/j.enpol.2011.01.051

UK, for example, 38% of car journeys are single occupancy and the average occupancy has fallen from 1.64 to 1.60 between 1985 and 2008 (DfT, 2003, 20008b). Cars consume 74% of the diesel and petrol, and 10.6% of total primary energy supplied to the UK.[1] This prodigious use of primary fossil energy entails a wide range of negative consequences which can be mitigated by replacing car trips with less energy-intensive forms of transport.

This paper therefore analyses the energy implications of a modal shift. Energy-intensive transport is linked with a range of environmental, social and economic consequences such as greenhouse gas emissions, transport inequality and dependence on finite resources. However, reports evaluating transport policy often fail to see the common thread of energy running through each of these problems, focussing instead on individual metrics such as CO_2 emissions, metrics of psychological health, or economic return (e.g. Åkerman and Höjer, 2006; Barton and Pretty, 2010; Sloman et al., 2009). Energy implications, which cut across, and to some degree encapsulate, environmental, social and economic metrics, may provide a more holistic guide to policymakers than individual impacts and allow for more integrated decision making. Energy is the 'master resource', so minimizing energy wastage may be the best way to benefit all aspects of well-being simultaneously. But why investigate the energy implications of car to bicycle shifts (as opposed to other transport shifts)? The reasons are as follows: First, this shift may offer the greatest energy saving of any voluntary change in transport behaviour, in the short term.[2] Second, bicycle policies can be implemented rapidly during times of economic hardship, as they do not require the complex and capital-intensive structures demanded by motorized alternatives. Third, cycling is roughly five times more efficient and three times faster than walking, offering a far greater range of mobility for the same amount of time and effort (Komanoff, 2004; typical speeds of cyclists and walkers are 15 and 5 kph respectively). Fourth, policies to facilitate the car to bicycle shift are being rapidly implemented in many towns across the UK (Sloman et al., 2009) and the world (Dennis and Urry, 2009) so deserve attention. Finally, the modal shift from cars to bicycles exemplifies the multiple social purposes that can be served through policy aims framed as being about transport and energy. The narrow focus of transport planning on economic growth is now shifting towards more pluralistic aims (Banister, 2008; DfT, 2008a), and this is reflected in the wide range of places where modal shift policies are being implemented (Pucher et al., 2010). Because research into the energy implications of modal shift could be relevant in a wide range of locations, the methodology is presented in a generalised way that is easy to replicate. Many cities undergoing modal shift could have been used for this study. However, Sheffield is of particular interest as it is a hilly city with a low, but rapidly rising rate of cycling. Such case studies are rare in the cycling literature, which tends to focus on flat cities, with an already high cycling level. As a prominent Sheffield-based cycling advocate put it: "if cycling can work here, it can work anywhere in the world" (Bocking, 2010, personal communication).

The broad aim of this paper is to illustrate some of the veiled links that connect transport policy and energy use. The 'vehicle' used to illuminate these links is a quantitative analysis of the energy implications of a car to bicycle modal shift in Sheffield by 2020, which is developed and discussed in the following sections: After a brief description of Sheffield's current transport practices (Section 2), a model is used to provide three scenarios for the cycling rate in Sheffield by 2020 (Section 3). The resulting output is then analysed (Section 4), and discussed (Section 5) to explore the energy implications of the modal shift for each of the three scenarios.

The model we use for projecting cycling rates originates in the field of population ecology and was selected in response to the "need for simple, yet not primitive, easily applicable urban transportation models" (Supernak, 1983, p. 79). The model is simple (defined by only two parameters), flexible, and directly applicable to important concepts in transport planning such as carrying capacity and intermodal competition (see Section 3). While econometric models of transport choice (e.g. Hensher, 1985; Whelan, 2007) are frequently used and useful for identifying economic factors influencing transport behaviour, they were not suitable for this paper due to their lack of an innate time dimension, reliance on price assumptions, and complexity. The model was used to project the cycling rate in 2020 under different policy scenarios, with mode (cycling in this case) analogous to 'species' and trips made per year analogous to 'individuals' in population ecology. The three scenarios modelled in this way are referred to throughout the paper as: business as usual (BAU), a 'do nothing' baseline; hard pro-cycling policy (H), a purely engineering approach; and integrated pro-cycling policy (I), the most ambitious scenario which combines the engineering approach of scenario H with additional soft (non-engineering) measures. Details of how the model was calibrated and modified to create each scenario are provided in Section 3.

1.1. Previous research on the energy implications of modal shift

The energy requirements of motorized transport modes have been quantified on numerous occasions (Lenzen, 1999). However, the energy requirements of non-motorized transport have received far less attention (Coley, 2002), and the wide-boundary energy implications of shifts from one mode to another have not been quantified at all in the literature reviewed.

The complex relationships between energy use, transport and health are explored by Woodcock et al. (2007), who project that significant reductions in CO_2 emissions (and hence energy use) would result from a shift to non-motorized transport forms in London. The benefits would be multifaceted (including the indirect energy-saving effects of reduced obesity rates, number of traffic accidents, and dependence on fossil fuel companies), and could apply to rich and poor countries alike. However, much of this analysis is speculative, and the energy-saving potential of modal shift is not quantified. Ramanathan (2005) estimates the potential energy savings of a road to rail modal shift: if 50% of road trips could be replace by rail in India, his model suggests a 35% net reduction in energy use could be achieved. Such scenario-based studies are less common at the city level, however, and the energy costs and savings of car to bicycle shifts is new academic territory. Generalized models of energy use in transport have however been developed, which can be applied in a wide range of circumstances.

Climate change mitigation provides a motive for many recent transport-energy use studies. Åkerman and Höjer (2006) produce 'images' of the Swedish transport sector in 2050. Their analysis suggests that drastic cuts in energy use and associated emissions are only possible if behavioural and technological measures are pursued in parallel. Fels (1975) presented a generalized equation for calculating the total energy requirements of different transport

[1] In 2008, the UK consumed 22,709 million litres of motor spirit (petrol in the UK, gasoline in the US) and 25,686 million litres of diesel (DECC, 2009), or 727 PJ and 991 PJ respectively. Cars consumed 95% of the UKs motor spirit, and 36% of the UKs diesel (DECC, 2009), a total fuel consumption of 1050 PJ. Total UK primary energy consumption in 2008 was 9840 PJ in the same year (DECC, 2009); cars consumed 10.6% of this.

[2] Carbon rationing, flight quotas, and increased fuel taxes may offer greater energy benefits, but these are not voluntary.

vehicles, but did not explore the consequences of future shifts. Lenzen (1999, p. 286) applied modified versions of Fels (1975) model to the transport system of Australia and found that "indirect requirements of energy and greenhouse gases form a significant part of the total requirements for all modes of transport", supporting broad-boundary approaches. In addition, Lenzen's analysis suggested that modal shift offered great potential for energy savings in the passenger sector, and that "the use of bicycles should be encouraged wherever possible" (Lenzen, 1999, p. 287). At the system level, it was calculated that bicycles use 0.6–0.8 MJ/pkm, while cars use around 4.4–4.8 MJ/pkm; energy savings of around 4 MJ/pkm could be expected if bicycle trips directly replace car trips. Such an approach would allow, given realistic scenarios of modal shift, the energy implications of future shifts in transport behaviour to be quantified. Neither Margaret Fels nor Manfred Lenzen, however, explore this possibility in detail, other than mentioning the transport modes which seemed to be energetically favourable, and possible policy responses.

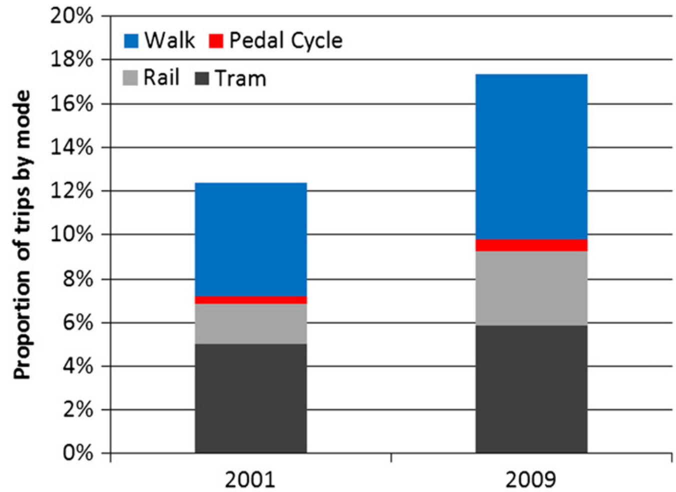

Fig. 1. Modal split of alternatives to car and bus trips in Sheffield, 2001 and 2009.

2. Sheffield's transport system in context

Investigating the past will put the city in context and provide a background against which future scenarios can be compared. Sheffield is a large city (with a population of 534,500) in South Yorkshire, England. Topographically it is decidedly hilly.[3] The climate is typical for central Britain: cool and despite the rain shadow of the Pennine hills to the west, prone to rain at all times of year. These basic geographical characteristics give some indication of why the transport system is currently car-dominated and energy-intensive.

Data from Sheffield City Council's annual transport census (SCC, 2010) show that motorized modes account for 92% of trips, and that single-occupancy cars dominate transport in the city: the mean car occupancy in Sheffield of 1.3 is notably below the national average of 1.6, and car trips account for just over half (54%) of all trips citywide. Sheffield is therefore highly car-dependent, although the use of cars appears to have plateaued in the city during the last decade, and car dependency is worse in many other areas of the UK, especially in rural settlements.[4] Within this context, the car to bicycle modal shift should be seen as part of a wider trend, from road-based motorized transport towards non-road and non-motorized transport forms (Fig. 1).

Regarding car trips and bicycle trips in particular, the bicycle trips to car trips ratio (BCR) is a useful metric to track relationship between cars and bicycles. In the period 2001–2009 the average BCR recorded by Sheffield City Council's transport survey (SCC, 2010) was just 0.008: car trips outnumbered bicycle trips by 123:1. By 2009 the BCR had risen to 0.011, and various lines of evidence suggest the BCR will continue to rise.[5] These trends have been driven by changes at the global, national and local level (Dennis and Urry, 2009; Vigar, 2002). Before developing a model of modal shift in Sheffield, we briefly consider local transport policies which have affected car and bicycle use in the city.

2.1. Policies affecting car use

Sheffield has a long tradition of high levels of public transport use, especially bus use. As a district within the former South Yorkshire County Council area, bus use grew in the City as the County Council introduced a blanket subsidy of bus fares between 1974 and 1986. Immediately before the 1985 Transport Act (bus de-regulation) and the abolition of the Metropolitan County Councils in 1986, bus travel was capped at 2p for a child and 10p for an adult. This policy resulted in lower car ownership and use in Sheffield than in most other parts of the country. There is also evidence that the policy suppressed demand for cycling, as the number of cycle trips roughly doubled in the few years after the demise of the 'cheap fares'. In the late 1980s, following bus de-regulation, car use grew rapidly in Sheffield, approaching the levels found in other UK cities. The policy response was to embrace the 'New Realism' of Goodwin et al. (1991) and implement bus priority and demand management measures along commuter corridors in the South of the City. However, this policy was not consistently applied across the City, as other corridors were the subject of road widening and new road building. It is debatable whether this latter approach has created or accommodated traffic growth.

Sheffield was amongst the cluster of cities to develop new-generation tram systems in the early 1990s. The tram system, much more so than buses, has been successful in attracting higher-income and car-owning passengers. Whilst the tram system serves only around a fifth of the City on four lines, patronage has grown consistently since its installation.

2.2. Policies affecting bicycle use

Planning for cycling in Sheffield has also evolved over the last few decades. In the 1980s and 1990s, there was an emphasis on hard measures – creating sections of cycle route, either through City Council investment or through planning gain as new development took place. This tended to create a disjointed patchwork of facilities, rather than the joined-up network of routes that most newcomers to cycling need. As mentioned, car use grew after bus deregulation, but it did not grow consistently across the city. A notable success in regeneration without traffic growth has been the City Centre Masterplan. This plan was published in 2000 and

[3] With an average of 4.8 25 feet contours per mile of A road (main routes), Sheffield is rated as Very Hilly relative to other English cities by Sui et al. (2000).

[4] The number of car trips recorded in the Council's transport census peaked at 585,482 in 2004 which has fallen to 546,384 in 2009, a drop of 6.7%.

[5] A number of pro-cycling policies have been implemented in Sheffield since 2000, including a Council-funded project undertaken by Pedal Ready, a Sheffield-based, cooperatively run cyclist training group, to encourage pupils to travel to school by bicycle. It is thought that this will cause the cycling rate to increase in the mid-term, as the young cyclists grow up. Another line of evidence which suggests the BCR will continue to increase comes from car sales data in the UK: sales peaked in 2003 and declined steadily until 2006 (Bonilla, 2009). Between March 2008 and March 2009, the number of new car registrations fell dramatically, by 30.5%, as the UK economy contracted (Financial Times, 2009).

Please cite this article as: Lovelace, R., et al., Assessing the energy implications of replacing car trips with bicycle trips in Sheffield, UK. Energy Policy (2011), doi:10.1016/j.enpol.2011.01.051

has guided the economic regeneration of Sheffield City Centre to date. Of significance for car use is its emphasis on improving the public realm, especially by creating a high quality pedestrian core, improving facilities for public transport users and making the city centre more accessible for cyclists. It involved a number of streetscape improvements that removed 1960s dual-carriageways, pedestrian subways and footbridges and replaced them with pavement widening, surface-level crossings, soft landscaping and trees as well as good quality lighting and materials. In addition, the growth in city living (a ten-fold increase in the resident population) and regeneration schemes which included cycle routes and parking, has meant that cycling in the City Centre has grown more quickly than anywhere else in the City. Between 1980 and 2009, cycling in Sheffield City Centre has grown by over 200%.

2.3. Future plans for transport policy

The future of transport policy and planning for cycling will be guided by the Department for Transport which emphasises an objectives-led approach.[6] Regarding cycling, many sections of Sheffield's on-road and off-road cycle paths have been joined together. This has coincided with a shift of emphasis, towards implementing soft approaches alongside infrastructural changes. This is in line with the findings of a study commissioned by the National Institute for Health and Clinical Excellence (Killoran et al., 2006). A number of projects have been implemented in the past few years that take an individualised approach to overcoming people's perceived barriers to cycling (akin to the 'integrated' scenario posited in this paper). Learn to Ride days, Cycle for Health, Bike It and other projects have shown very high benefit to cost ratios, because they successfully get more people cycling safely. These measures (which the DfT has dubbed 'smarter choices') are likely to increase their share of local transport spending in the coming years, especially as cuts in public spending reduce the likelihood of expensive infrastructure projects getting financial approval. Notwithstanding these achievements and prospects, and despite a general acknowledgement of the health and environmental benefits of active travel, there has been a modest level of investment in cycling in Sheffield relative to some other UK cities and continental Europe, which seems likely to continue. This reflects a belief amongst key decision makers that it is not worth diverting substantial investment from other transport, as cyclists make only 1% of trips. The hills are also perceived by some as an insurmountable barrier preventing widespread shifts from car to bicycle. Despite widespread awareness of the benefits of cycling, future cycling policy is expected to be constrained by a prevailing view: that investment in cycling will not attract sufficient numbers to significantly reduce congestion and CO_2 emissions, or improve quality of life.

3. The potential for bicycle trips to replace car trips

The previous sections demonstrate that a shift to cycling is desirable from a number of perspectives and already underway in Sheffield, albeit from a low cycling baseline. This section presents three scenarios of the cycling rate in Sheffield from 2010 to 2020: business as usual (BAU), hard pro-cycling policy (H), and integrated pro-cycling policy (I). Based on these scenarios and analysis of past data, the number of car trips replaced by bicycle trips is estimated for the year 2020.

A consistent method was used to project the number of car trips replaced by bicycle trips in each scenario: First, the number of additional bicycle trips that can be expected to replace a typical car trip in Sheffield (the replacement ratio) is inferred from available data. Second, the potential increase in bicycle trips from 2010 to 2020 is calculated for the three scenarios, based on a simple model borrowed from population ecology. Third, the number of car trips replaced by bicycle trips is calculated by dividing the additional number of bicycle trips that occur in 2020 by the replacement ratio. It is important to remember that these scenarios simply illustrate what *could* happen, based on a simple model and observations of past growth rates in cycling in other cities. The scenarios are not predictions of what will happen, or what should happen (Masser et al., 1992); they are intended solely as a tool to facilitate the assessment of the energy consequences of possible car to bicycle modal shifts in Sheffield, to inform decision makers and methods in energy/transport policy. External factors, over which local decisions have limited control, may, however, dominate cycling rates in the city. High oil prices, for example, may increase cycling rates, while policies at the national level, such as car industry subsidies and congestion charging, may either increase or decrease cycling rates, depending on which energy and transport policy paradigms prevail in the UK during the 2010s. Because of the large potential impact of these external factors, it is assumed that they stay constant over time and in each scenario. This assumption is unlikely to hold in reality, but making it enables the use of a simple model to compare the energy outcomes of different scenarios. While the calculations of energy savings may only apply in an abstract world defined by the model, our thesis is that the resulting insights into the potential for transport policy to influence energy usage could have a range of implications in the real world.

3.1. How many car trips are replaced by each additional cycle trip?

The effectiveness of bicycle promotion as a strategy for tackling climate change, oil depletion, and a range of other problems depends largely on the capacity of bicycle trips to replace car trips. This can be defined mathematically as the replacement ratio (*RR*)

$$RR = \frac{\Delta B}{-\Delta C} \tag{1}$$

where ΔB is the change in bicycle trips and ΔC is the change in car trips that can be attributed to changes in the cycling rate, during a given time period and in a predefined geographic area. The replacement ratio can be interpreted as the number of additional bicycle trips required to replace or prevent a single car trip. For example, if cycling is predominantly recreational and car use is barely affected by additional cyclists, the replacement ratio will be high (hundreds of cycle trips could be needed to replace a single car trip). In this case there would be little point in promoting cycling from an energy perspective. Therefore, when used to measure how successful pro-cycling policies have been, low *RR* values are desirable while high *RR* values are undesirable. Moreover, there is considerable potential for the replacement ratios associated with a range of modal shifts (e.g. car to bus, bus to tram, etc.) to be used in the evaluation of the environmental consequences of diverse transport policies. In this paper, however, the replacement ratio is used only with respect to the car to bicycle modal shift.

Despite the concept's simplicity and potential for policy evaluation, little work has been done to determine replacement ratios. In the context of car to bicycle modal shift, the replacement

[6] Transport policy in the UK is expected to contribute to social, environmental, economic, safety and quality of life objectives (DfT, 2008a).

ratio appears to be a novel concept, at least in the academic literature reviewed for this paper.[7] Consequently, no systematic methodology has been tested to quantify this important metric of the car–bicycle relationship and new methods must be developed to do so.

The replacement ratio cannot be measured directly, and varies widely over space and time, as illustrated by the following examples. In the mountain bike hotspot the Dalby Forest in the UK, the *RR* is likely to be negative, perhaps around -3: many mountain bike enthusiasts drive to the forest in cars containing 2–4 people so an additional car trip can be expected for every few additional bicycle trips in the area (1).[8] In urban settings with a poor public transport system, but high car ownership (e.g. large Australian cities (Dodson and Sipe, 2005)) however, the replacement ratio is likely to fall during times of high oil prices: car trips are the most common type of trip in this environment, and when oil prices are low, most bicycle trips can be assumed to occur for leisure purposes (resulting in few car trips being replaced). When oil prices rise, the *RR* can be expected to fall as additional bicycle trips are made to replace increasingly costly car trips. Similar falls in the replacement ratio could be predicted if more people see the bicycle as a healthy and convenient alternative to the car, but the point is the same: *RR* varies over time.

Not only does the replacement ratio vary over space and time; it also varies depending on the transport policies used to generate additional bicycle trips. If cycling investment is directed predominantly towards leisure cycling, it is expected that the replacement ratio for the additional bicycle trips will be high (i.e. many cycle trips are needed to replace a single car trip). If, however, policy targets urban commuters (e.g. the UK's Cycle to Work Scheme) or car drivers in general (Sustrans, 2010), the replacement ratio of the resulting bicycle trips is likely to be relatively low. The bicycle trips generated by the congestion charge in London, for example, are likely to have achieved a replacement ratio approaching 1, as car users would have had most to gain from switching to bicycle. Future research could test this hypothesis, although adequate data may prove hard to come by. Attempts to quantify replacement ratios are further complicated by the little-understood relationship between recreational and commuter cycling rates.[9]

In light of these complications, it would be naïve to treat the replacement ratio as a single, unchanging number. Instead, in this paper, the *RR* is defined as the average number of additional bicycle trips required per car trip replaced *within a specific context:* Sheffield between 2010 and 2020. Estimates of the *RR* will allow the number of car trips replaced by, and energy implications of, the three cycling scenarios in our model to be calculated. As such, the *RR* values used here are subject to revision based on much needed new evidence. With the above caveats in mind, three approaches for estimating replacement ratios were used: quantification of the car–bicycle relationship use using linear regression, analysis of reason for trip data, and analysis of data from the Cycling Demonstration Towns project (Sloman et al., 2009). These methods are briefly explained below. From the latter method, the most relevant to the impact of future policies in Sheffield, *RR* values were assumed to be five for scenarios BAU and scenario H, and three for scenario I.

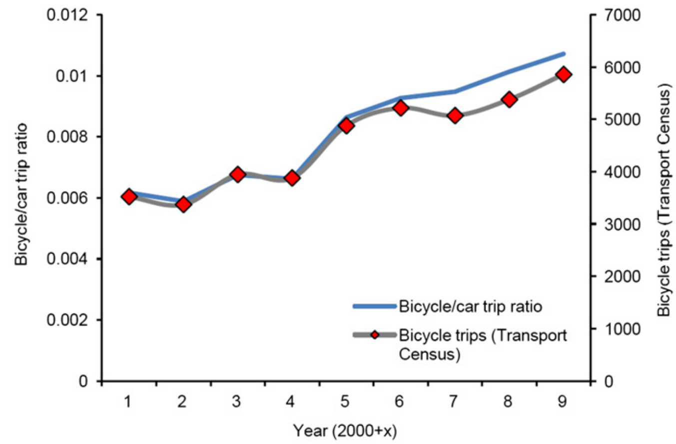

Fig. 2. The ratio of bicycle trips over car trips and the total number of bicycle trips observed in the Sheffield Transport Census in the years 2000–2009 (SCC, 2010).

3.2. *The relationship between car use and bicycle use*

Linear regression could theoretically be used to determine how car use changes as a function of bicycle use, with the gradient of the trend line representing an estimate of $-1/RR$. In Sheffield, however, because the car is dominant, the number of car trips fluctuates by several thousand trips each year, leading to a low signal–noise ratio; the absolute cycling rate or the BCR ratio may therefore be better metrics of modal shift. Fig. 2 shows the steady increase in both of these measures over time, corresponding to a 7% annual increase in the rate of cycling in Sheffield between 2001 and 2009. There is a negative correlation between car use and bicycle use, but it is implausible to suggest that 25,000 car trips were 'replaced' by the additional 2000 bicycle trips which were counted between 2000 and 2009 in Sheffield's annual Transport Census.[10]

Instead, bicycle trips likely contributed slightly to the decline, with walking, public transport, and fewer trips accounting for the rest (see Fig. 1). Multiple regression could be used to account for the cross-transferability of transport modes, for example by using the equation $C=\gamma B+\sum_{i=1}^{n}\beta_i X_i+\alpha$, where C and B are the number of car and bicycle trips per year, the second term is a weighted sum over n independent variables X_i (such as the price of oil), and γ, β_i and α are coefficients to be calculated. This approach would allow confounding variables (such as the growth in train trips and the decline in total number of trips) to be held constant, allowing the coefficient associated with B to be interpreted directly as $-1/RR$ (the number of car trips replaced by a single bicycle trip). However, the data requirements of this approach exceed the number of data points available in Sheffield at the city level;[11] a different approach is required.

[7] In the field of population ecology, an analogous concept is the *coefficient of competition*, which is defined as the 'competitive, inhibitory effect' of one species on another (Begon et al., 1996, p. 105). In transport planning, ambiguous concept of *modal choice* has been applied to estimates of the modal split in models which have remained relatively unaltered for decades (Banister, 2002). In addition, transport planning has tended to focus narrowly on economic growth (Masser et al., 1992). Partly for these reasons, a 'paradigm shift' has been called for in transport planning (Masser et al., 1992; Banister, 2008).

[8] This example shows that the *RR* does not always imply a causal relationship between car and bicycle use, it is simply a statement of the relationship between two variables.

[9] It has been suggested that increased recreational cycling rates can indirectly lead to increased commuter cycling rates, although this is not always supported by evidence (Parkin et al., 2007).

[10] In 2001, 570,873 car trips were recorded in Sheffield's Transport Census; by 2009 this number had dropped by 4% to 546,385 (SCC, 2010).

[11] Assuming five predictor variables are used, an effect size of 2%, a desired statistical power of 0.8, and a p-value of 0.05, a minimum sample size of 643 would be needed. At the city level, only nine data points (2000–2008) are currently available.

3.3. Reason for trip data

Questionnaires asking a random sample of cyclists if their bicycle trips replaced car trips could potentially provide a dataset from which the replacement ratio could be estimated. Unfortunately, no such dataset exists for Sheffield. Sustrans records data on the impact of its cycling policies on car use in certain areas, from which an indication of the localised *RR* could be derived. However, Sustrans (2010) does not provide data for Sheffield, and their data regarding other locations were not available at the time of writing.

Given the limitations of localised data, the *RR* in Sheffield must be inferred indirectly from other places. National reason for trip data, which are based on questionnaires about how and why people travel, provide a useful source of information about the overlap between car trips and bicycle trips. The Transport Statistics Bulletin (DfT, 20008b) provides a breakdown of trip numbers by reason and mode. When expressed as percentages of column and row totals, these data can be used to estimate the extent to which growth in one mode of transport will replace another, assuming the total number of trips per year, and the proportion of trips made for each reason, remain constant. Applying this method to the bicycle–car relationship results in *RR* of 2.2 (see Supplementary information).

3.4. Data on modal shift following pro-cycling policy

Although national reason for trip data tells us much about the extent to which bicycle trips currently overlap with car trips in Great Britain, the resulting *RR* value of 2.2 may not be relevant for additional bicycle trips caused by pro-cycling policies in Sheffield. The assumptions about total trip number and the proportion of trips made for different reasons are questionable, especially over the timespan investigated in this paper: Pro-cycling policies could change the total number of trips within Sheffield if cyclists make shorter but more frequent trips, for example. In addition, the proportion of trips made for each reason may shift under scenarios which encourage certain types of trips over others. Thus, empirical data on the impact of previous pro-cycling policies may be considered a more reliable source of information on which to base the *RR* of additional bicycle trips caused by pro-cycling policies in Sheffield.

A recent source of such data is the Cycling Demonstration Towns project, phase 1, which constitutes a useful case study of the short-term impact of pro-cycling investment at the Local Authority level in the UK. Under this scheme, six English towns received enhanced funding for a range of pro-cycling measures, amounting to about £10 per inhabitant per year between 2005 and 2009 (Sloman et al., 2009). Some funding was also allocated for monitoring the cycling rate in these towns and, although the authors stress the results' inability to prove causal relationships, there was a clear signal of increased bicycle use (by 27%, in aggregate) in the study towns. Evidence of concomitant decreases in other forms of transport arises from surveys of how children travelled to school in five of the study towns: the number of car trips fell by 1.4 percentage points following a 7.3% increase in the rate of cycling. This indicates a *RR* of 5.2 (applying Eq. (1)). Using this value as the basis of the city-wide *RR* in the model is also problematic, however: On one hand it could be seen as an underestimate because the potential for increased total trip numbers is excluded from the analysis (pupils can only take so many trips to schools per year). On the other hand, the 5.2 *RR* estimate could be seen as an overestimate because the proportion of trips made by car in this case study is relatively low (just under 40%) compared with the national average of 65% (DfT, 20008b), and it could be expected that car trips to school are especially resistent to change due to safety concerns from parents about alternative modes of transport. The net impact of these factors is unknown, underlining our uncertainty about how the *RR* is influenced by different circumstances.

There are clear problems with all the methods of estimating future values of the *RR* presented here, not least the dynamic and non-linear nature of behavioural change. Considering that (Sloman et al., 2009) directly investigates the impacts of policy intervention, while DfT (20008b) merely describes the national transport system, we decided to use a *RR* value based on the former study (rounded to five for simplicity) in our model for business-as-usual (BAU) and hard (H) pro-cycling policy scenarios. In the more ambitious integrated policy scenario (I) however, we assume that the *RR* falls to three as a result of soft-policies targeting car users, for whom bicycle trips are most likely to replace car trips. This idea, that pro-cycling policies can be directed specifically to reduce car use, is supported by Sustrans (2010). Due to the data limitations outlined above, and the problems associated with projecting social change, it should be clear that these assumed values represent preliminary estimates rather than firm predictions of the *RR* in Sheffield between 2010 and 2020 (although, given adequate monitoring, this would be a prediction that could be tested). The impact of this uncertainty is explored in the sensitivity analysis in Section 4.5.

3.5. How quickly can cycling rates increase?

It is clear from past literature that cycling has become an integral part of the transport systems of a few pioneering cities. However, estimates of the *rate of change* are of particular interest here, as they can inform plausible scenarios of future cycling rates in Sheffield. Pucher et al. (2010) present a systematic review of pro-cycling policies in cities across the world, which shows impressive growth rates in cycling following relatively modest pro-cycling investments. The implied growth rates of cycle trips following various city-wide pro-cycling policy interventions are presented in Table 1. These show a wide range of annual cycling growth rates is possible, and that cycling rates have more than doubled in less than a decade in some places. Although the data on which the reported growth rates may not be consistent across all studies, Table 1 provides strong evidence that average annual growth can exceed 10% per year for sustained time periods.

One could argue that such high growth rates are context-specific, and as such, may not be applicable to Sheffield. However, Sloman et al. (2009) find that the *average* bicycle trip growth rate in six Cycling Demonstration Towns in England was 6.2% between early 2006 and late 2009, following relatively modest (by European standards) pro-cycling investment.

Table 1
City case studies of bicycle policies and growth rates.

Case study	Main policy	From	To	Change (%)	Rate (%/year)	Reference
Barcelona	Integrated	2005	2007	135	53.2	Pucher et al. (2010)
Bogotá	Soft	1995	2003	300	18.9	Pucher et al. (2010)
Bristol	Hard	2003	2008	51	8.6	BCC (2009)
London	Hard	2003	2008	62	10.1	DfT (2010)
Paris	Integrated	2001	2007	150	16.5	Pucher et al. (2010)
Portland	Hard	1992	2008	369	10.1	Sloman et al. (2009)
Sheffield	Hard	2001	2009	76	7.3	SCC (2010)

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Faster localised shifts occurred within this aggregate result, including Darlington, which increased the share of trips made to school by bicycle by over 400%, from 1.2% to 6.1%, in 4 years. A package of soft, individualised pro-cycling measures known as "TravelSmart" is also reported to have caused very rapid shifts in transport behaviour in a number of towns (Sustrans, 2008). Increases in the walking and cycling rate exceeding 20% were reported after just 1 year, and this was associated with declines in car use of approximately 10%, implying low *RR* values associated with the additional bicycle trips generated through the scheme. Such ex-post studies are relevant to scenarios of future cycling rates in Sheffield, as they imply that the cycling growth rate could plausibly exceed the 7% that has been observed in recent years, if effective pro-cycling measures are implemented.

The average rates of increase presented in Table 1 cannot remain constant forever though, as this would imply unconstrained exponential growth, an impossibility given limits on the number of trips people can make. Growth rates in cycling must be dynamic and, ultimately, constrained by some kind of carrying capacity.[12] The notion of a dynamic growth rate constrained by a saturation point is captured neatly by the basic single-species model of population ecology (Begon et al., 1996):

$$\frac{dP}{dt} = rP\left(\frac{K-P}{K}\right) \tag{2}$$

where r is the maximum potential growth rate, which tends to 0 as the population (P) reaches the ecosystem's carrying capacity (K) over time. Each of these variables has a direct analogy in transport behaviour. With respect to the cycling rate, P is analogous to the number of bicycle trips made each year (B); K represents the capacity of the urban environment to facilitate bicycle trips; and r represents the maximum rate at which the population can alter its transport behaviour. Consequently, we suggest that population ecology provides a useful framework for modelling and conceptualizing modal shift.

Within this framework, cycling becomes a 'species' of transport and bicycle trips the individuals of this species, whose number fluctuates over time. The ecological analogy usefully describes how different species compete with one another: in this case car driving and cycling compete mutually and with other transport forms for the scarce resources of space, passenger time, and capital which are found in the urban ecosystem. If the analogy is correct, this suggests that the B can be substituted for P in Eq. (2). This implies that B is a dependent variable which fluctuates in partially predictable cycles of growth, plateaus and decline, in response to various internal and external factors (Odum and Odum, 2001), a view supported by analysis of past data.[13]

As well as its relevance to shifting transport patterns, the ecological analogy has the additional advantage of providing a mature set of concepts and equations for reference. The models of population ecology have been refined, tested, and extended to include the concepts of interspecies competition, coefficients of competition and ecological niches. Such ideas, and their associated models, could potentially be used in the analysis of modal shift.[14]

For the purposes of this paper, however, we deploy a simple model which excludes the more advanced concepts of population ecology, although they may provide rich potential for future work. In creating scenarios of the future cycling rate, we therefore road test the application of population ecology to the realm of modal shift.

3.6. Scenarios

For the reasons described above, a simple population model was selected to project future cycling rates in Sheffield. Integrating Eq. (2) with respect to t and substituting B for P results in the following equation (see Zill et al., 2009, pp. 79–80 for method):

$$B_t = \frac{KB_0e^{rt}}{K+B_0(e^{rt}-1)} \tag{3}$$

where B_t is the number of bicycle trips made in any particular year, t represents the year in question beyond the year 2000 (in the year 2003, for example, $t=3$), r is the rate of unconstrained growth, and K is the maximum carrying capacity of the environment. In order to produce projections for the *total* number of bicycle trips in Sheffield, rather than projections for number trips counted in Sheffield's transport census, the proportion of all trips made by bicycle (0.58% in 2009) was multiplied by a fixed estimate of the total number of trips made in Sheffield by all modes (553 million).[15] The values of r and K were calculated for the baseline scenario (BAU) by fitting Eq. (3) to the census data displayed in Fig. 2 using least-squares analysis. To project the effects of policy intervention, the same model was used, beginning this time in 2009:

$$B_t = \frac{KB_9e^{r(t-9)}}{K+B_9(e^{r(t-9)}-1)} \tag{4}$$

where B_9 is the number of bicycle trips made in 2009 (3.15 million trips) and the t–9 components represent a 2009 start date for the model (9 can be replaced with n to represent a model start date in the year $2000+n$). The hard pro-cycling policy scenario (H) was modelled by doubling K to represent more cycle-friendly infrastructure. The integrated policy scenario (I) was modelled by a three-fold increase in K and a 50% increase in r, to represent an environment more conducive to cycling, and an increased rate of social change due to soft policy measures. The reasons for altering r and K in this way are outlined below. The resulting projections of cycling rates are presented in Fig. 3.

3.7. Scenario BAU – business as usual

In the business as usual scenario, no pro-cycling measures are made, and cycling rates continue their slow ascent, approaching K (4.5 million trips per year, the value which provides the best model-data fit) by 2020. This growth represents a lag between policy intervention and behavioural change, as people continue to respond to the pro-cycling policies of the 2000s. As the number of trips approaches saturation, however, the rate of increase slows. Policy intervention may be needed to increase the rate of change above the 2.5% average annual increase projected for scenario BAU.

[12] Although cycling is a highly accessible form of transport, evidence from cities with a high cycling rate suggest some kind of saturation point is reached, beyond which additional policy is needed to increase the cycling rate further (Pucher and Buehler, 2008).

[13] On decadal timescales, time-series data on the adoption of new transport modes can display the same sigmoid form as do graphs resulting from Eq. (2), with near-exponential growth rates in the early stages of the model and eventual plateaus, implying some kind of carrying capacity K (e.g FitzRoy and Smith, 1998, Fig. 1).

[14] For example, equations of interspecific competition have been developed to include several species, which could be substituted by competing transport modes. In addition, the language of population ecology may help conceptualize modal shift. First hand accounts from cyclists often contain direct or indirect reference interspecific competition with cars. McKenna and Whatling (2007) interviewed nine regular commuter cyclists and found that competition for space with cars was one of the main reasons why some were considering travelling to work by car instead.

(*footnote continued*)

[15] The latter value was calculated by multiplying the average per capita trip rate in the UK between 2002 and 2008 (1021) by Sheffield's population (534,500) (SCC, 2010; DfT, 20008b)). This approach assumes that per-capita trip rates in Sheffield equal those in the UK, an assumption which could be modified in the light of additional data.

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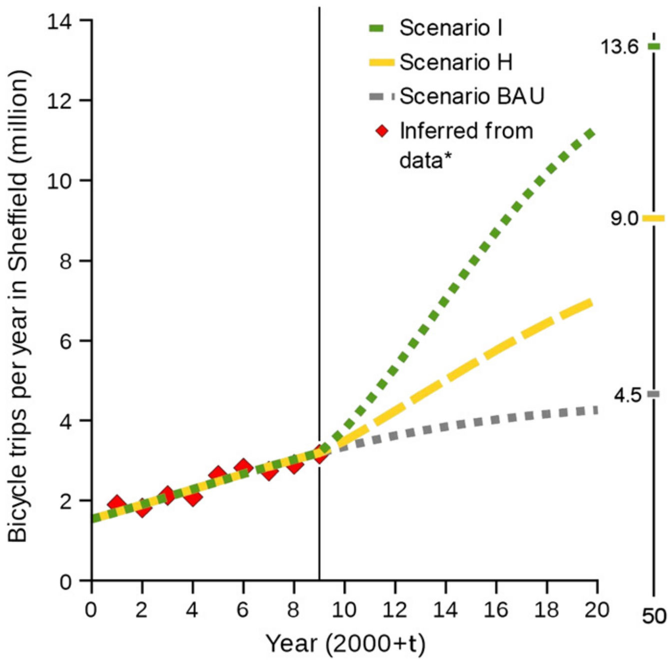

Fig. 3. Scenarios for the future cycling rate in Sheffield. *The points from 2001 to 2009 were calculated by multiplying the proportion of trips made by bicycle each year in Sheffield (SCC, 2010) by Sheffield's population and the national average trip rate (DfT, 2008b).

3.8. Scenario H - hard pro-cycling policy

The hard pro-cycling scenario is composed of engineering schemes which, in combination, make cycling safer and more convenient in Sheffield. Previous case studies indicate that a doubling of the cycling rate can be expected following the implementation of a range of hard pro-cycling policy measures.[16] However, engineering approaches do not always lead to large cycling increases in the short-term (Ogilvie et al., 2004). For these reasons, K was doubled in this scenario, while r was left at 0.17. Previous case studies suggest that the following hard pro-cycling investments would prove successful in Sheffield:

- Provision of separate cycling lanes on major radial and circular routes;
- Continued construction of bicycle parking spaces, with emphasis on covered and lockable stores;[17]
- "The physical design of road facilities to force slower speeds", thereby increasing the convenience of bicycles relative to cars (Noland and Kunreuther, 1995, p. 78).

3.9. Scenario I – integrated pro-cycling policy

This final scenario comprises a multifaceted pro-cycling agenda, including the hard policy measures mentioned above and a range of soft measures to encourage car drivers to travel more frequently by bicycle. It is expected that such an approach would increase the potential rate of change (represented by a 50% increase in r), and further increase Sheffield's carrying capacity for bicycles (a tripling of K), compared to the baseline scenario. In addition, the RR of additional bicycle trips drops from 5 to 3 in this scenario, to reflect the ability of soft measures to target single-occupancy car drivers. These parameters reflect the success of integrated policies at influencing the rate of cycling in the past. This approach is neatly summarised by Pucher et al. (2010, p. 106): "Substantial increases in bicycling require an integrated package of many different, complementary interventions, including infrastructure provision and pro-bicycle programs, as well as supportive land use planning and restrictions on car use." In Sheffield, such an integrated approach would likely include:

- The provision of bicycles to rent throughout the city similar to the Velib scheme in Paris.
- Regular, council-endorsed 'Cyclovia' events during the warmer months (whereby major streets are made car-free to promote public health and social cohesion).[18]
- Expansion of the Council's School Travel Plans in Sheffield.[19]
- Creating car-free zones in Sheffield.
- Expansion of Sheffield's innovative scheme to provide free bicycle training within the city (Pedal Ready, 2009).

The above measures are likely to be effective based on past experience, but many other options are available, including some innovative schemes which have not been tried anywhere. For example, a variant of the Velib scheme could link rental price to the vertical distance cycled: cyclists who only free-wheel down hill would pay more. This could further incentivise fitness and counteract the logistical problems of bicycle rental schemes.

3.10. Projections of the number of car trips replaced by bicycle trips

With projections of the cycling rate and replacement ratio of additional trips for 2020, we are now in the position to estimate the number of car trips that could be replaced by bicycle trips. Applying Eq. (1) to the data displayed in (3), the number of car trips replaced by bicycle trips can be projected for 2020:

4. Quantifying the energy implications of modal shift

Armed with three scenarios of the number of car trips replaced by bicycle trips in 2020, it is now possible to estimate the associated energy savings. MacKay's (2009) approach to energy

[16] The construction of a comprehensive network of dedicated bicycle lanes was projected to cause a three-fold increase in cycling rates (from 2.7% to 7.7%) in the short term, based a statistical model based on questionnaire data of why people do, and do not, choose to commute by bicycle in urban Pennsylvania. (Noland and Kunreuther, 1995). Such a city-wide network of bicycle lanes was completed in Delft in the 1980s and this was associated with 3% increase in the cycling rate. Bicycles already made up 40% of the modal split before the study began, however, and there already existed a large network of cycle lanes before the intervention began (Wilmink and Hartman, 1987). If such an intervention occurred in a city with a lower cycling baseline, such as Sheffield, it is fair to assume the increase would be far greater.

[17] Noland and Kunreuther (1995) found safe bicycle parking spaces to be an important determinant of the perceived convenience of the bicycle relative to other transport modes. The decision to cycle to work instead of travelling by car is made based on the *relative* convenience of different modes, so reducing the ease of car-use, for example by reducing the area of Sheffield's city centre dedicated to car parks, may also be an effective strategy.

[18] This measure could have additional advantages. A council-endorsed mass-cycle would help legitimise the 'Critical Mass' movement in Sheffield, and enhance Sheffield's reputation as an international city by making explicit links with well-known Cyclovias in cities such as Bogota and Paris.

[19] 95% of schools in Sheffield currently have already adopted School Travel Plans, covering 99% of school children. However, the number of children trained in safe road cycling could be greatly enhanced. In 2009, 2300 children were trained to Bikeability level 2 (on-road cycling), up more than tenfold from the number trained in 2000. This scheme is considered by the Sheffield City Council to be a cost-effective means of ensuring long-term growth in bicycle use in Sheffield. This is supported by evidence from the national level: Cairns et al. (2004) found that School Transport Plans were effective, resulting in up to up to 20% reductions in the number of car escort trips. 41% of 5–10 year-olds in the UK travel to school by car, implying that policies encouraging this age group to cycle to school could be associated with a low RR, in addition to health benefits.

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Table 2
Summary data for the scenarios.

Metric units	Max. rate of change (r) (%/year)	Carrying capacity (K) (m/year)	Increase in cycling (ΔB) (m/year)	Mean rate of increase (%/year)	Replacement ratio (RR)	Car trips replaced (ΔC) (m/year)
BAU	17	4.5	1.1	2.6	5	0.21
H	17	9.1	3.8	6.9	5	0.77
I	26	13.6	8.1	10.8	3	2.71

analysis is used, whereby a first approximation based on a few plausible assumptions is made and then refined with additional data.

4.1. Fuel savings

The most obvious component of the total energy use of car-based transport systems is the fuel burned in the engines. The average fuel economy of car journeys in Sheffield in 2020 (η_C) is projected to be 9.58 l/100 km[20] and the mean trip distance of cars is expected to be 13.7 km, the national average (DfT, 20008b). Because bicycles are predominantly used for shorter trips, the mean distance of car trips *replaced* by bicycle trips ($\overline{D}_C$) will be lower: $\overline{D}_C = 5$ km appears to be a reasonable estimate, based on available evidence, and the average length of bicycle trips that replace these car trips is assumed to be shorter still ($\overline{D}_B = 4.1$ km) because of the distance saved through shortcuts and avoidance of parking problems.[21] The following formula combines these estimates with the projections of ΔC presented in the previous section (Table 2), to calculate the fuel savings (ΔF) of car to bicycle modal shift:

$$\Delta F = \Delta C \times \eta_C \times \overline{D}_C \tag{5}$$

Respectively for BAU, H and I, this results in fuel savings of 3.5, 12.5, and 44.2 TJ/year by 2020.

4.2. Energy costs of vehicle manufacture

The total energy requirements of modern transport systems comprise more than fuel costs however; vehicle and guideway manufacture also contribute to the total. These additional components are captured in Fels (1975) generalized equation:

$$E_{vkm} = E_F + \frac{Em_v}{L_v} + \frac{Em_g}{L_g}. \tag{6}$$

This equation included for the first time the embodied energy costs of vehicle (Em_v) and guideway (Em_g) production, in addition to the fuel requirements per unit km (E_f), in a single formula. The embodied energy costs of vehicles and guideways are expressed per unit distance by dividing by their lifetimes in vehicle kilometres and vehicles, for cars (L_v) and roads (L_g) respectively. Due to lack of recent evidence on the energy costs and lifespans ;of roads and bicycle paths in the UK, only the energy costs of vehicle manufacture are included in the main analysis. Inputting estimates[22] of the embodied energy and lifespans of bicycles and cars results in an additional energy cost of 1.83 MJ/vkm for car trips (the energy consumed in the form of fuel is 2.9 MJ/vkm), and 0.19 MJ/vkm for bicycle trips. Including manufacturing increases the net energy savings of modal shift by a third in scenarios BAU and H, and by 42% in scenario I.

4.3. Embodied energy costs of food and fuel

Bicycles are sometimes portrayed as 'the zero emission option'. This statement is clearly misleading with respect to bicycle manufacture (unless second-hand bicycles are used), even though the implied emissions from bicycle manufacture are around 1% of those associated with car manufacture. In the usage stage however the phrase appears, at face value, to be correct.[23]

But the 'zero emission' tag omits any possibility that humans could alter their levels of food intake, and the associated emissions, in response to increased activity. Coley (2002) analyses precisely this problem, and finds that people *do* increase their food intake when they become more active. He calculated the chemical and embodied energy of the additional food used by cyclists to be 94 and 539 kj/km respectively, assuming a fixed embodied:chemical energy ratio of 5.75. It is assumed that the change in food demand from driving is negligible.[24]

Taking Coley (2002) values, the energy costs of increased food consumption due to increased activity levels (E_{food}) can be calculated for Sheffield as

$$E_{food} = \Delta B \times Em_{food} \times \overline{D}_B \tag{7}$$

where Em_{food} is the embodied energy of food and $\overline{D}_B$ is the mean trip distance by bicycle (4.1 km). This additional energy cost of cycling is a significant proportion (around 2/3 for scenarios BAU and H, and 2/5 for scenario I) of the energy savings of reduced fuel consumption.

[20] The average fuel economy of the UK fleet is currently 8.55 l/100 km (3.4 MJ/km) (MacKay, 2009). The energy efficiency of cars in the UK has been improving at a steady rate for the past decade, however, and will continue to do so in the future. On the other hand, urban car journeys, which bicycle trips are most likely to replace, are associated with worse than average fuel economies. These counteracting trends can be included by combining the projected fleet-wide fuel economy in 2020 (7.66 l/100 km) with the increased fuel consumption of urban driving (25%), resulting in the 9.58 l/100 km. The 7.66 l/100 km by 2020 figure is derived from realistic implementation of EU targets requiring *new* cars to emit no more than 95 gCO_2/km, (4 l/100 km) by 2020, a 6% annual decrease. Even if the target is met, fleet-wide efficiency will respond more slowly (Kwon, 2006). In fact, *fleet-wide* CO_2 emissions per km (proportional to fuel consumption) declined by 1% annually between 2001 and 2008 (Khan, 2009). Assuming the UK fleet's fuel consumption decreases at the same rate in the future η_C will reach 7.66 l/100 km by 2020. The 25% figure is based on data from the Vehicle Certification Agency (2010).

[21] The distribution of trip distances for cars in the UK is skewed. 55% are less than 8 km (5 miles) (DfT, 20008b), but a smaller number of longer, often inter-city trips has a disproportionate influence on the mean. Generally, only shorter car trips are replaced by bicycle, so $\overline{D}_C$ lies somewhere between 0 and 8 km. The same dataset shows that the mean trip length by bicycle is 4.1 km. The average distance of car trips replaced, however, is expected to be slightly higher, as cyclists often take short-cuts unavailable to car users (Litman, 2004; personal observation). In addition, finding car parking space in Sheffield can take time, leading to longer trip distances.

[22] For cars, Em_v=274 GJ per car (MacKay, 2009, p. 94) and L_v=150,000 km (BP, 2002; Schmidt et al., 2004) (OECD, 2001:201). For bicycles, Em_v can be approximated as 1% of Em_v for cars (typical weights are around 10 kg for bicycles, and 1000 kg for cars). This approximation coincides with a published estimate based on a breakdown of the material inputs of new bicycles: Em_v=3.73 GJ (www.wattzon.com). As with cars, lifespan estimates for bicycles are complicated by the variable lifespans of individual components. L_v=20,000 km is deemed to be a reasonable estimate by Cherry et al. (2008), and this figure is used here.

[23] No pollution can be seen emanating from an accelerating bicycle, and the human power source can be assumed to require food and drink inputs regardless of his or her activity levels.

[24] One could argue that driving increases ones marginal food intake in a similar way, but it seems that driving requires no more energy than average, everyday activities such as housework and shopping, based on an inventory of activity types and metabolic rate (Ainsworth et al., 2000). In fact the relative metabolic rate of "driving at work" (MET = 1.5) is lower than that of many other common activities such as "childcare" (MET = 2.5–3) and "putting away groceries" (MET = 2.5) (Ainsworth, 2003).

Table 3
Components of net energy savings for each scenario.

Component	Scen.	Effect (TJ/year) ΔC	Effect (TJ/year) ΔB	Net saving (TJ/year)	Per cap. (MJ/year)
Fuel	BAU	3.5	–	3.5	6.5
	H	12.5	–	12.5	23.4
	I	44.2	–	44.2	82.6
Vehicle manufacture	BAU	2.0	−0.8	1.2	2.2
	H	7.0	−2.9	4.1	7.8
	I	28.4	−6.1	18.7	35.0
Food and fuel production	BAU	0.3	−2.4	−2.1	−3.9
	H	1.0	−8.5	−7.5	−14.1
	I	3.4	−18.0	−14.6	−27.3
Cumulative energy savings	BAU	5.7	−3.2	2.5	4.8
	H	20.4	−11.3	9.1	17.0
	I	72.3	−24.1	48.3	90.3

Similarly, the embodied energy of fuel can be quantified with reference to the energy return on the energy invested (*EROEI*) of its production. Using Cleveland (2005) estimate for the US, we assume a fixed embodied:chemical energy ratio for fuel production at the petrol station of $1/13$, although this is subject to revision.[25] This estimate of embodied energy increases the total energy costs of fuel use by 8%. Including the embodied energy content of additional food requirements, and reduced fuel use, the overall energy saving for each scenario is reduced by 60% for scenarios BAU and H, and 33% for scenario I, compared with fuel savings alone. The relative importance of each of these components, and the impacts of altered assumptions, are considered in the remainder of this section.

4.4. Comparing the major energy implications of modal shift

A major result is that the estimated energy implications of modal shift vary in response to the inclusion of additional components of the wider transport system (Table 3). Fuel still constitutes the single largest energy implication of car to bicycle modal shift, although the often overlooked embodied energy inputs of vehicle manufacture are substantial: our model suggests that, assuming a linear relationship between new car sales and distance driven,[26] reduced demand for cars increases the energy savings associated with car–bicycle modal shift scenarios by approximately $1/3$ in scenarios BAU and H, and by $2/5$ in scenario I. The energy impact of increased food demand is approximately double that of decreased car demand in scenarios BAU and H, although this relationship changes in scenario I (in response to a lower *RR*), where the two factors are approximately equal. Sensitivity analyses suggests that manufacturing costs become dominant as the *RR* drops below 3. These findings support calls for environmental policy to address high-energy diets and car purchasing practices, issues that are often tackled in isolation from transport policy in areas such as public health and the economy. Thus, the magnitude of indirect energy consequences presented in Table 3 hint to links between transport policy and other, traditionally separate, policy realms. For example, a public health campaign that successfully promoted cycling *and* healthier food could simultaneously reduce the energy costs of car use and the energy costs of food production.

These results help reveal some under-reported energy consequences of transport policy, but they may mask others. Because the energy-saving estimates treat all primary energy sources as equal, without weighting for quality or scarcity, they provide little indication of the complexity of energy flows in Sheffield's transport system. The omission of 'energy quality'[27] is important because some fuels are more desirable than others (e.g. in terms of energy density, ease of transportation, and emissions). The omission of scarcity is pertinent in the light of recent predictions of an early peak in global oil production (e.g. Aleklett et al., 2010) and the finding that the decline rate of large oil fields is faster than previously thought (IEA, 2008; Höök et al., 2009). If such projections turn out to be correct, reduced dependency on liquid fuels may become an important benefit of a car to bicycle modal shift, in Sheffield, and elsewhere.

The extent to which the modal shift scenarios described in this paper can deliver reduced dependence on liquid fuels is limited, however: even under scenario I, the cumulative reduction in car fuel usage per year amounts to less than one percent of the fuel burned in cars in Sheffield in 2009.[28] This result indicates that transport policy may need to focus on other types of modal shift such as increased rates of public transport use and walking, increasing car occupancy, and reducing demand for energy-intensive forms of transport, if more substantial changes in fuel dependency are to occur during the next decade.

4.5. Sensitivity analysis

The assumptions upon which our model is built are based on imperfect evidence which is dated, untested, sparse, aggregated, inconsistent, or a combination of these things. The paucity of data on key parameters of transport systems at national and city levels suggests that data collection and dissemination can make an important contribution to, or even be considered *as*, energy policy. Paucity of data also highlights the need for critical analysis of the model parameters, and the potential impacts of this uncertainty on the results.

Table 4 shows that the model results are highly sensitive to alterations in the assumed value of the replacement ratio (*RR*), especially if the assumed value decreases. If the *RR* is halved, for example, the energy savings are more than doubled, a result which highlights the importance of investigating this parameter (see Section 3). The results are also sensitive to relatively small alterations in the mean average distance of car trips replaced ($\overline{D}_C$). This indicates one way of making bicycle policy more effective in energy terms: by encouraging cyclists to replace lengthy trips (e.g. to out of town shopping centres) with shorter trips (e.g. to local shops). Conversely, if only short car trips are replaced, the energy savings would be dramatically reduced.

[25] Estimates of the *EROEI* (energy aquired ÷ energy expended) associated with liquid fuels vary. Here we use Cleveland (2005, Fig. 6) estimate that $EROEI \approx 13$ for gasoline in the US. It is important to remember that other estimates have been made. Treloar et al. (2004) (cited in MacKay (2009)) estimate that 1.4 units of energy are required for every 1 unit of gasoline ($EROEI = 2.5$), although this seems rather low given estimates that global crude oil production has an *EROEI* of around 18 at the well-head (Gagnon et al., 2009). Cleveland's (2005) estimate of upstream energy costs in gasoline production may be considered as conservative for 2020 given recent declines in *EROEI* (Cleveland, 2005) and estimates that upstream energy inputs are around 14% and 16% of the chemical energy contained within diesel and gasoline respectively, implying lower *EROEI* values (CONCAWE, 2008). The figure used here is therefore subject to revision.

[26] This relationship is a direct result of Fel's (1975) Eq. (6). At the aggregate level, such a relationship is a logical outcome of the finite distance that cars travel (old cars must be replaced after they have been driven a certain distance). This assumption could be modified as new evidence emerges.

[27] Defined by Cleveland (2005, p. 770) as the "relative economic usefulness per heat equivalent unit of different fuels and electricity."

[28] The energy content of fuel burned in cars in 2009 can be approximated as the total number of car trips made in Sheffield (340 million), multiplied by the fuel economy of car trips (3.4 MJ/km), multiplied by the average distance travelled per car trip (13.9 km), which is 16 PJ. The fuel saving under scenario I amounts to 44.2 TJ or 0.3% of the estimated energy content of fuel burnt in Sheffield cars in 2009. All the numbers used for this calculation come from, or are derived from, values already mentioned in this paper.

Table 4
Sensitivity analysis: the impact on cumulative energy savings for scenario H.

Parameter symbol	*RR*	*EROEI*	L_v	$\overline{D}_C$	Em_{food}
Assumed value	5	13	150,000	5 km	539 kj/km
Impact of +10% change	−20%	−1%	−8%	22%	−9%
Impact of −10% change	25%	1%	9%	−22%	9%
Impact of +50% change	−75%	−4%	−26%	112%	−47%
Impact of −50% change	224%	11%	77%	−112%	47%

In comparison with the *RR* and $\overline{D}_C$ parameters, embodied fuel and food energy costs (*EROEI* and Em_{food}) have relatively little impact on cumulative energy savings. However, percentage changes in food production result in approximately the same percentage change in cumulative energy savings in our model under scenario H. It is worth mentioning here that interrelations exist between the sensitivity levels of the results, and the assumed central values of the parameters. If the central estimate of the *RR* were lower, for example, the sensitivity of the results to Em_{food} would decrease, while their sensitivity to *EROEI* would increase. This subtlety reinforces the importance of reducing the uncertainty surrounding the *RR*.

The results are also sensitive to the assumed mean lifespan of cars (L_v). Increases in this parameter lead to relatively small decreases, while decreases lead to larger increases, in cumulative energy savings. This could be relevant regarding the penetration of new technologies such as electric cars, and policies which influence the new and used car market.

While Table 4 focuses on the impact of altering one parameter at a time, it is clear that cumulative impact of uncertainty could be large. As an extreme example, if assumed values of *RR*, *EROEI*, and L_V all decrease by 50%, the cumulative energy saving in scenario H would increase by 400%. A 50% increases in the same parameters leads to a 94% decrease in cumulative energy savings. In sum, sensitivity analysis underlines the importance of constraining real world *RR* values and the potential for improved transport statistics and embodied energy analyses to enhance and clarify our understanding of the energy implications of modal shift.

5. Conclusions

Future work could quantify additional energy implications of each scenario, such as shower and laundry requirements of sweaty cyclists; the energy costs of degenerative diseases reduced by active lifestyles; and the fuel economy improvements that may result from changes in the traffic flow. However, the results presented so far allow tentative conclusions to be drawn about the energy implications of replacing car trips with bicycle trips in Sheffield:

- Plausible increases in the cycling rate would yield net energy savings.
- Reduced fuel consumption would be the largest single energy impact.
- If the rate of car purchase declines with the rate of car use, the resulting energy savings would be large.
- Increased food consumption may constitute a large indirect energy cost of increased cycling rates, unless countered by public policy.

The application of a simple population model to shifts in transport behaviour has been tested alongside a new concept for understanding the dynamics of competing transport modes, the replacement ratio (*RR*). Because of the high sensitivity of the results to relatively small alterations in the estimated *RR*, and the paucity of the data upon which our assumed values are based, developing more reliable estimates the *RR* in different contexts is a research priority that emerges from this paper. The model's projections of future cycling rates appear to be plausible when compared visually with time-series data from other cities, and the inclusion of a carrying capacity parameter (*K*) usefully informs explorations into the long-term impacts of mode-specific interventions. However, the population model needs to be refined and tested objectively against large datasets before it is uncritically accepted as a useful tool for transport planning. This could be done, for example, by deriving estimates of how the *r* and *K* parameters have responded to past changes in transport policy and testing the extent to which these estimates apply to different timescales, places, and policies. This 'testability' is one of the model's main strengths, alongside its flexibility to adapt to new data: it could, for example, be modified year-on-year by recalibrating the baseline scenario or altering certain parameters as better evidence emerges. Thus, as a method for quantitatively exploring the concepts of carrying capacity and growth rates, the ecological approach succeeds: although these concepts already existed in transport planning, the ecological model and analogues used in this paper provide a new framework for discussing them and exploring the future consequences of altering the parameters which define them mathematically.

Quantitative analysis can only go so far towards understanding the energy linkages in complex, interrelated systems, however (Smil, 2005): the ecological model is not intended to prescribe or predict future pathways. On the contrary, our analysis of the impacts of broadening system boundaries, the paucity of available data, and the impacts of the high level of uncertainty surrounding key parameters upon which the model depends, all serve to illuminate the complexity and interconnectivity of a large transport system such as Sheffield's. Given the suggestion that bicycle use can promote social cohesion and citizen well-being (e.g. EEA, 2008), and observations of wider social impacts of cycling uptake in Sheffield (Pedal Ready, 2009), it is expected that the impacts of car to bicycle modal shift will go beyond those described here. The energy impacts of social and economic change brought about may range from simple shifts such as reduced gym use to complex knock-on effects in the local economy (e.g. through altered shopping and holidaying practices). Given the multifaceted negative impacts of energy-intensive transport modes, predictions of an impending peak in global oil production, and the varying energy implications of different transport forms, we conclude that transport policy *is* now energy policy. New approaches will be needed to deal with this, and the framework presented in this paper provides steps towards investigating some of the previously unexplored energy implications of modal shift.

Acknowledgments

This project is funded by E-Futures Doctoral Training Centre, a programme funded by the Engineering and Physical Sciences Research Council (EPSRC). Thanks also to an anonymous reviewer for constructive comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2011.01.051.

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Please cite this article as: Lovelace, R., et al., Assessing the energy implications of replacing car trips with bicycle trips in Sheffield, UK. Energy Policy (2011), doi:10.1016/j.enpol.2011.01.051

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