Design speeds and acceleration characteristics of bicycle traffic for use in planning, design and appraisal

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Abstract

This paper reports the results of a study of a cohort of cyclists to determine their speed and acceleration characteristics relative to gradient and other influencing factors in order to supply data for planners, designers and appraisers of cycle infrastructure schemes. A cohort of everyday cyclists was supplied with a global positioning system device and a heart rate monitor and asked to collect data from their journeys in Leeds, UK.

The analysis determines the cyclists' speeds and accelerations at every point on their journey and elevation data, corroborated by mapping information, was used to determine the gradient. Two linear regression models of speed and acceleration were estimated and show that the influence of a downhill gradient on speed is less pronounced than the effect of an uphill gradient. The results indicate an eighty-fifth percentile speed on the flat of 22 kph, and for a downhill gradient of 3%, 25 kph. The power required to cycle has been estimated and shows that cyclists deliver around 150 Watts on the flat, but that this rises to around 250 Watts climbing hills. Mean acceleration on the flat is 0.231 m/s^2 and the average power output over the acceleration phase, which is of mean duration 26 seconds, is approximately 120 Watts. Air resistance accounts for approximately 70% of the resistive force when cycling at design speed.

It is recommended that designers adopt 25 kph as a design speed for gradients less than 3%, but that consideration should be given to design speeds of up to 35 kph for steeper gradients. Free-flow speeds in this range should be used when modelling mode and route choices and in benefit appraisal.

Keywords

Bicycle; GPS; Speed; Acceleration; Power.

1 Introduction

The basis of highway geometric design is the 'design speed' of motor traffic assumed for the class of road under consideration. It is based on the eighty-fifth percentile speed of motor traffic and determines the design of every geometrical component of the road including stopping sight distances, full overtaking sight distances, horizontal and vertical curvatures, transition lengths and taper lengths (Highways Agency, 1993). Road design is, hence, based on a physical attribute of the motor traffic stream, and provides a solid numerical basis for the development of appropriate engineering designs to create a highway network.

The bicycle is a vehicle, and is also capable of speed, although much design guidance has historically not considered this aspect in any detail, preferring to dwell on characteristics of cyclists as human based groupings, rather than the characteristics of the bicycle-rider combination as a vehicle. The result has been a series of fractured definitions which has served to emphasise the different nature of presumed ‘groups’ of cyclists, rather than their needs as users of vehicles capable of speed.

In addition to engineers as highway designers and traffic engineers, other transport professionals, including network planners, demand forecasters and scheme appraisers need an understanding of the speed characteristics of cyclists in order to estimate journey times, potential mode switching, route choices and the health benefits derived from the additional physical activity for new users of cycling as a mode.

This paper reports an analysis of speed of a cohort of cyclists derived from global positioning survey data and provides data on speeds and accelerations on different gradients. It provides a sound basis for designers to review guidance for the implementation of infrastructure for cycle traffic.

Section 2 outlines the reasons for the need for speed as a parameter in planning, design and appraisal for cycle traffic, and summarises the ways in which design guidance has portrayed cyclists to highway and traffic engineers. Section 3 provides a discussion on the physics of cycling as a preamble to a review of the literature on cycling speed and effort. Section 4 provides results from field work as a basis for understanding the bicycle-rider combination as a vehicle. Section 5 discusses the results with conclusions and suggestions for further work being presented in Section 6.

2 Speed as a design input and the portrayal of cyclists

Transportation involves the movement of discrete vehicles around a network. Geometrical and other characteristics of the network are determined in part by the speed of the vehicles. Some systems have tight control over the speed of the vehicles (for example, railways). Other systems (for example, highways) usually have a defined maximum speed, although compliance with the posted speed amongst users is variable. All aspects of geometric design for highways, for example overtaking sight distances, stopping sight distances, horizontal and vertical curve radii, lane widths, and lane tapers, are determined with reference to the adopted design speed. The adoption of such a speed standardises the nature of the network and makes it fit for purpose. The design speed varies depending on the class of road and is usually higher for high capacity inter-urban routes than urban streets with mixed uses.

The absence of an appropriate and consistently used design speed will have an effect on the capacity and safety of the network. It will also reduce the user’s perception of the utility of the route (contrast a country lane which has evolved from a horse track over time with an engineered highway) and may reduce the attractiveness of the route to users. So far as cycle traffic is concerned, there has been a range of assumptions made about the characteristics of the cyclist as a cycle user, as discussed below, and these ad hominem descriptions have pre-dominated in design considerations. This is evidenced by the lack of consideration given to design speed as observed by the authors in much network design for cycle traffic (for example, the expectation that a cyclist can "turn on a sixpence"). On the basis that a bicycle is a vehicle within a transport system, it is not appropriate to design for cycle traffic without reference to a design speed.

The first modern day UK guidance for designers of infrastructure for cyclists (IHT, 1996) tackled the question of the 'design cyclist', which arguably was a misplaced starting point, but the authors defined three groups as follows: vulnerable children, inexperienced adults, elderly people and those with some form of disability such as deafness; commuter adults reasonably confident in traffic, valuing speed and directness; and finally 'sports adults'. Indicative speeds for each group includes speeds of 10 miles per hour (16 kph), 15 miles per hour (24 kph), and 20 miles per hour and over (32 kph). The descriptions adopted in this national guidance contrast with the design criterion adopted for the 'National Cycle Network' promoted by the civil engineering charity Sustrans (1997), which suggests that designs should be suitable for a child aged twelve to use independently of adults.

The Dutch cycle design guidance document (CROW, 1993) introduced the concept of the primacy of the five attributes of route coherence, directness, attractiveness, safety and comfort. These have been much repeated in other subsequent guidance around the world (see Parkin, 2010, for comprehensive review of cycle design guidance) and this suggests that the Dutch guidance has come to be regarded as seminal. The Dutch guidance also provides a useful discussion of a cyclist's power requirements versus speed and suggests that a cyclist 'is at his (sic) most comfortable travelling at 16 to 20 kph on a quiet cycle track without any oncoming or crossing traffic to worry about'. Updated guidance (CROW, 2006) confirms that cyclists are heterogeneous in terms of age, gender and physical characteristics and suggests a design speed of 20 kph, with 30 kph adopted for 'through cycle routes' and up to 35 kph where there are gradients and speeds can be higher in the downhill direction. It suggests acceleration can be assumed to lie in the range 0.8 m/s^2 to 1.2 m/s^2 with braking in the range 1.5 m/s^2 (comfortable) to 2.6m/s^2 (emergency). In order for cyclists to keep their balance, the guidance notes that at speeds of less than 12 kph, greater width is required.

Some design guidance (e.g. Land Transport NZ, 2005) makes no mention of design speeds, other guidance mentions a speed (e.g. 20 kph in Irish guidance, DELG/DTO, 1998) but does not discuss how this might influence infrastructure design. The guidance for London (TfL, 2005) suggests 15 miles per hour (25 kph) except in areas shared with pedestrians where the design speed is suggested as 10 miles per hour (16 kph). These speeds are deemed to influence only visibility splays at junctions and minimum horizontal radii.

More comprehensive consideration of the impact of speed on geometry is provided by Scottish guidance (Scottish Executive, 1999), the UK Highways Agency (2005) and Lancashire County Council (2005). The Scottish guidance suggests a design speed of 30 kph for longer routes, 25 kph for commuter routes and 20 kph for access routes. Stopping and moving sight distances, and horizontal and vertical geometry are all derived from these speeds. The Highways Agency Design Manual for Roads and Bridges notes that speed varies by type of user and defines five classes: fast commuter; other utility cyclist; inexperienced utility cyclist; children and users of specialised equipment. It adopts a single design speed of 30 kph but notes that this may be reduced to 10 kph over short distances coupled with ‘SLOW’ markings painted on the running surface. The design speeds flow through into recommendations on sight distances and horizontal and vertical geometry design parameters. The effect of gradients is mentioned to the extent that designers should consider providing signs advising cyclists to proceed with care on downhill sections.

The Lancashire guidance suggests a design speed of 30 kph, with 20 kph adopted at particularly difficult locations. 40 kph is recommended for consideration on downhill sections. In addition to sight lines and horizontal and vertical geometry, the Lancashire guidance also provides taper dimensions for changes in lateral position within the highway. The design speed range is similar to that adopted in New South Wales, Australia, where a high operating speed range is assumed to be 25-40 kph, a medium range to be 20-30 kph and a low range to be less than 20 kph (Roads and Traffic Authority NSW, 2003).

The most recent UK national guidance (DfT, 2008a) replicates the five categories of cyclist identified in the Design Manual for Roads and Bridges (Highways Agency, 2005) with the exception that the third class is identified as ‘inexperienced or leisure cycle users’. Design speeds for commuter routes are suggested as being 20 miles per hour (32 kph) and for local access routes as 12 miles per hour (19 kph) with consideration being given to consequent sight distances and horizontal curve radii.

The selection of design speeds for rural roads (Highways Agency, 1993) is made based on forward visibility, alignment bendiness and the number of accesses per kilometre. For urban roads with a 30 mile per hour speed limit (48 kph), the design speed for establishing geometry and visibility is set higher than the speed limit at 60 kph, so as to permit, as the standard suggests, a ‘small margin for speeds in excess of the speed limit.’

Perhaps the most striking outcome of this review of design speeds in guidelines for cycle design is the range of speeds mentioned (including 10 and 12 kph as minima; 16, 19 and 20 kph as middle range values for routes of lesser importance and 24, 25, 30, 32, 35 and 40 kph as high range values for through routes). It is also noteworthy however, that the effect of gradient on speed is only given particular treatment in very few documents. Finally, the writers of some design guidance have mentioned a design speed, but it does not appear to have influenced considerations of geometry to any great extent.

3 The physics and theories of cycling and effort

The rate of energy output, power, has been investigated by Whitt and Wilson (1982) and Wilson (2004) who summarised the power requirements of cycling in the following equation.

$$W = \frac{C_v}{\eta_{mech}} \left\{ \sum m g \left(C_r + \frac{s}{100} + \frac{a}{g}\left[1 + \frac{m_w}{\sum m} \right] \right) + 0.5 C_D A \rho \left(C_v + C_w \right)^2 \right\}$$

Where:

W = power (w)
C_v = speed of the bicycle (m/s)
η_{mech} = mechanical efficiency of the bicycle
$\sum m$ = mass of rider and machine (kg)
g = acceleration due to gravity (m/s^2)
C_r = coefficient of rolling resistance
s = gradient (%)
a = acceleration of the bicycle (m/s^2)
m_w = effective rotational mass of the wheels and the tyres (kg)
C_D = aerodynamic drag coefficient
A = frontal area of rider and machine (m^2)
ρ = density of air (kg/m^3)
C_w = headwind (m/s)

Whitt and Wilson suggest that a typical power output for a non-athlete cyclist is 75 watts and this may rise to 200-250 watts for healthy male touring cyclists and 350-400 watts for racing cyclists over periods of between 20 minutes and an hour.

Power in the context of human exertion is manifest in a heart rate raised above resting and thought of as ‘effort’. It would be feasible to monitor effort through variation in heart rate. However, there are significant differences in resting heart rate between individuals based on age, level of fitness and other medical conditions. As well as being affected by effort, heart rate is also influenced by other factors, such as stress. A cyclist’s heart rate will therefore vary not only as a result of additional muscular effort, but also as a result of differences in the ambience of the environment through which he or she is travelling.

Variation in the effort of a cyclist is also manifest in his or her speed and acceleration characteristics. It would be possible to estimate power output from the formulation offered by Whitt and Wilson based on a knowledge of the mass of the rider and bicycle, the frontal area of the bicycle-rider combination, the rolling resistance and mechanical efficiency of the bicycle and, in addition, knowledge of the prevailing wind condition. It would hence be possible to correlate data from surveys of speed, acceleration and heart rate in order to estimate a model relating objective measures of the cardio-vascular system to components of the environment through which a cyclist travels, and this work forms part of the stream of work presented here and is on-going.

Work relating to effort has focused on the additional effort required to cycle after a stop and because of gradient and quality of surface (Graham, 1998, Fajans and Curry, 2001 and Mercat, 1999). Mercat notes that, based on an average energy use of 100 watts, the energy required to get back up to speed is equivalent to riding 139 metres at constant speed and this is longer than Graham's estimate of 55m indicating a lower power output for Graham's cyclists. Fajan's and Curry found that stops every 530 feet as opposed to every 2,800 feet reduced the average speed for approximately the same exertion by 30% (from 14.2 mph to 10.9 mph). The work notes the importance of these results in planning for cycle traffic.

Graham (1998) developed three hypotheses of styles of energy consumption after a stop on a cycling journey and tested them on a sample of twelve everyday cyclists. The cyclists circumnavigated a 2.5km route involving seven roundabouts. Traffic was light and the cyclists repeatedly cycled the course, on some circuits pausing momentarily at the give way line to the roundabout, on other occasions progressing without pausing. Graham's three hypothesised styles are as follows:

- Hypothesis 1: the cyclist maintains a constant acceleration until normal cruising speed is reached. This would require additional energy relative to the case with no pauses and, as the average power output is therefore higher, would create additional stress and heat to the point of discomfort.
- Hypothesis 2: the cyclists' average power output during the journey is the same as if the cyclist maintained normal cruising speed throughout, this results in a cruising speed less than would be the case without pauses.
- Hypothesis 3: power output is constant so that normal cruising speed is reached asymptotically.

The trial with cyclists demonstrated that the actual average additional times on the circuit with pauses was closest to the extra time expected by Hypothesis 2, but Graham recognises the inadequacies of Hypothesis 2 by considering a journey where pauses are unevenly distributed. For example, were all pauses to occur in the first half of the journey, it is unreasonable to suppose that greater than average power output is maintained for the first half of the journey with the anticipation that 'recovery' will take place in the second half of the journey.

Speed surveys of cycle traffic are sparse in the literature. One notably innovative study used a floating bicycle technique (Pheby, 1982) to assess journey speeds and this revealed a speed range of 21.5 kph to 23.5 kph for space mean speed over four different journeys in London ranging from 580 metres to 1.86 kilometres in length.

None of the studies to date offers appropriate and clear guidance on appropriate speed and acceleration characteristics of cycle traffic useful to designers, planners or appraisers. The very important issue of variation in speed as a result of gradient is not fully explored. The work reported here uses global positioning system survey data observed from everyday cyclists to determine speed and acceleration characteristics for different gradients.

4 The study

4.1 The fieldwork

Sixteen volunteers (four female) were provided with handle-bar mountable Garmin™ Edge® 305 Global Positioning System (GPS) devices, which were able to record time-stamped x, y and z coordinates and input from a chest-worn heart rate monitor. Proprietary software is available to provide simple graphical outputs, but data was extracted for more comprehensive statistical analysis. Snowball recruiting of regular cycle commuters was used, which is a common technique where participants form a small sub-group of the population. The authors can not think of any link between the recruiting mechanism and the propensity of the participants to behave similarly with respect to cycling performance (for example they are employed by a variety of organisations and they are not all members of the same cycling club), and hence the sample has been regarded as a random selection of regular commuters.

Schutz and Chambaz (1997) found the 95% level of confidence in speed from a low cost GPS device for cycling to be 0.8 kph and this allows confidence in the methodology. Data was recorded using ‘smart recording’ to save data space and to easily pass the five devices between the sixteen cyclists in the cohort. However, the device only recorded when movement was detected and this meant that the heart rate was not recorded during a stop.

The cyclists were provided with the GPS device for a week and were asked to accrue 100 minutes of data based on their commuting journeys during Summer 2008 in Leeds, a city of 715,000 people in West Yorkshire, England. Leeds is the 274th most hilly district out of 376 districts in England and Wales with 89% of one kilometre squares within the district having a mean slope of 3% or more (Parkin et al., 2008)[1]. 38% of the cyclists were aged 30 and under, and 16% were aged over 50. The majority were of normal body mass index, but 5 were overweight and one was underweight. The types of bicycle used included touring (6), mountain (5), town/city (5), folding (1) and racing (1) bicycles[2]. All bar one of the cohort described themselves as either experienced or very experienced cyclists and thirteen had either frequent or very frequent recent cycling activity. The entire cohort carried luggage typically in the range of 2 to 10 kilograms in mass and the luggage was carried in a mix of rucsac, pannier and trailer. Most (13) professed to maintaining their bicycle to a ‘medium’ degree.

The average journey time amongst the cohort was 26.8 minutes with times ranging from 15 to 50 minutes.

4.2 Descriptive analysis

A total number of 547 starts were extracted from the data and after elimination of speed, acceleration and gradient outliers, 518 remained for analysis. The start phase was deemed to be complete after a measured speed was found to be slower than its immediately preceding measured speed. There were typically between one and four starts per journey. Table 1 summarises the data.

Insert Table 1 here.

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[1] Note that this dimension is calculated for the land mass as a whole and is not confined to gradients on the road network. The road network is likely to be flatter than the average hilliness of the land mass as a whole.

[2] Some cyclists used more than one type of bicycle.

There were more flat and downhill starts than uphill starts, but the mean gradient was about the same at either around 2% up or 2% down. The mean speed at the end of a start was just under 6 metres per second (21.5 kph), with the minimum speed being 6 kph and the maximum speed being a sizeable 40 kph. The speeds are distributed standard normal (Kolmogorov-Smirnov test p=0.267). There are fewer data for females, and their mean speed is marginally but significantly lower than the mean male speed (20.5 kph compared with 21.8 kph, F=4.221, p=0.04).

The mean acceleration was 0.247 m/s^2, again with the difference between males and females being significant (0.256 m/s^2 for males compared with 0.217 m/s^2 for females, F=8.932, p=0.003).

A check has been performed to confirm the accuracy of the gradients derived from the GPS data by comparing the altitude differences from the data with altitude differences from Ordnance Survey based mapping. This comparison has shown that the difference in gradient between the two sources is not significantly different from zero at the 95% confidence level.

4.3 Models for speed and acceleration against gradient

Linear regression models were constructed for the independent variables of speed and acceleration[3]. The gradient, differentiated between uphill gradient and downhill gradient, was found to be a significant independent variable, as shown in the results in Table 2 and Table 3.

Insert Tables 2 and 3 here.

Owing to the sample size, none of the person type variables collected as part of the study (age, Body Mass Index, experience of cycling, regularity of cycling, the type of bicycle used and its maintenance, and the amount and manner of carriage of luggage) was found to influence either speed or acceleration significantly. This is perhaps mainly due to the similarity between cyclists in the cohort: they were generally regular and experienced cyclists. Despite the descriptive statistics suggesting significant differences between males and females for speed and acceleration, neither model demonstrated a significant t-statistic for sex of cyclist, and hence this independent variable was omitted from the final models.

The model suggests that, on the flat, the mean speed of cyclists is 6.01 m/s (21.6 kph). For every additional 1% of downhill (negative) gradient, mean speed is increased by 0.2379 m/s (0.86 kph) and for every additional 1% of uphill gradient, the mean speed is reduced by 0.4002 m/s (1.44 kph). The implication of the model is that for a relatively modest downhill gradient of 3%, the mean speed of cyclists is 24.2 kph. The eighty-fifth

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[3] Various non-linear models were also investigated, and, in the most general case, the power to which the downhill and uphill gradients were raised was estimated by the model. These models however, did not increase the adjusted R-squared, and the estimated powers were near to unity. In the interests of parsimony, a linear regression model continued to be pursued.

percentile speed for this downhill gradient is 25 kph. At steeper gradients, cyclists will not be able to take advantage of the additional potential energy they are gaining and they will have to brake. This braking may be required because of the nature of the unfolding road conditions ahead of the cyclist: a limiting speed will be reached above which it would be unsafe to cycle because of the potential need to stop. Alternatively, the cyclist may simply not desire to travel as fast as gravity, less friction forces, would wish.

An uphill gradient reduces speed, and reduces it a rate greater than the increase in speed for a downhill gradient, with the mean speed at an uphill gradient of 3% being a still respectable 17.3 kph. The full effect of the cyclist having to increase his or her potential energy is felt by the cyclist and will be the limiting criterion on maximum speed in this case.

The relatively high t-statistic indicates small standard errors and this is also revealed through the fairly low difference between the mean speed and the eighty-fifth percentile speed discussed above. These small standard errors imply a consistency in speed across the sample and hence a high degree of reliance being able to be placed on these data for everyday commuter cyclists.

The mean acceleration on the flat is 0.231 m/s^2 and implies a time of 26 seconds to reach the ultimate mean speed of 21.6 kph. A downhill gradient of 3% implies an acceleration of 0.295 m/s^2 and an uphill gradient of 3% an acceleration of 0.197 m/s^2. The time to achieve the mean speed on a downhill gradient is 23 seconds and on an uphill gradient is 24 seconds. The reduced time to achieve the ultimate speed on the downhill gradient will result from the 'bonus' effect of the gradient, and this occurs at a point in the journey when the speed is low and hence not limited by comfort or braking issues.

Table 4 summarises speeds, accelerations and power inputs of cyclists for gradients ranging from 7% downhill to 7% uphill and is based on the regression models of speed and acceleration against gradient.

Insert Table 4.

When travelling at the final speed on the flat of 6 m/s, 70% of the 150 Watts is required to overcome air resistance. On uphill sections, cyclists are prepared to exert around 250 Watts. Negative power requirements imply that the gain in potential energy from going downhill is more than sufficient to create the speed and acceleration, and are hence notional. Note that the estimations of power are based on Whitt and Wilson's equation and their suggested average values for variables as identified in the notes to Table 4. Any variation between individuals and bicycles in terms of frontal area, mass, rolling resistance and mechanical efficiency are small in comparison with the assumption that there is no wind.

On commencement after a stop, the power output will be instantaneously zero, climbing to the power output at final speed. The average power output over this starting phase on the flat is approximately 120 Watts. The power requirement for rolling resistance, gradient resistance and the accelerations of the masses (bicycle and rider, and effective rotational mass of the wheels) vary linearly as they are proportional to speed. However, the power required to overcome air resistance increases as the cube of the speed. 60% of the power is required to overcome inertia, with only just over 20% being required to overcome air resistance. The calculated power outputs suggest that commuter cyclists do not engage in ‘sprint starts’, but built up their power output over the period of acceleration. The period of acceleration remains relatively consistent across downhill and uphill gradients, with the shortest start phase times appearing to be on the flattest terrain. Cadence is likely to be lower during the start phase and will create higher pedal forces and hence be noticed by the rider in a different way than the cardio-vascular exertions at final speed.

Even a relatively modest tail wind of 10 miles per hour (16 kph, not an uncommon occurrence in Northern Europe as a result of successive low pressure weather systems proceeding in an easterly direction from the North Atlantic Ocean) and a modest downhill gradient of 2% could create speeds of 37 kph for similar power output.

5 Discussion

Table 4 indicates that over the gradient range -3% to +3% the eighty-fifth percentile speed varies from 18 kph to 25 kph and this suggests that 25 kph is a reasonable design speed to adopt for cycle traffic[4]. For gradients above 3% designers should consider adopting a 30 kph design speed, and even this speed will be low if the prevailing wind direction is in the downhill direction, with bicycle speeds potentially reaching 35 kph or more. It should be noted that the maximum speed observed in the survey presented here was 40 kph. Cyclists are likely to conserve their momentum and even a very short section of a steep gradient will create high speeds, which may be maintained by cyclists for some distance after the gradient has flattened out.

A design speed of 25 kph calls into question the validity of speeds in the range 16 kph to 20 kph, which are frequently quoted in cycle design guidance reviewed in Section 2. The work presented here suggests that authorities should review their design guidance with a view to setting more appropriate design speeds and avoiding speeds that are lower than cyclists would normally wish to travel at. Such a design speed for free-flowing links within a network would also feed into a more accurate assessment of overall journey time for planning and economic appraisal purposes. This high observed speed may also reflect into a different level of health benefits, with higher speeds implying greater effort having been expended.

A question does arise as to unintended consequences if the design speed is in fact set at too high a level. It would create conditions in which cycle traffic could travel at speeds faster than they might otherwise travel at, although this would be naturally self-limiting for the majority of the population to a speed which is comfortable to maintain. It may mean that particular features along the route, such as areas where there are more pedestrians present, or where there are obstacles for which it remains impossible to provide the appropriate stopping sight distance, may then require some specific remedial

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[4] Eighty-fifth percentile design speeds are adopted for highway link design purposes (Highways Agency, 1993). The Department for Transport (DfT, 2006) has revised the base for considering speed limits on existing roads to a consideration of the mean speed as opposed to eighty-fifth percentile speed, but this is not relevant to geometric design for routes.

treatment. This would be no different than the sorts of considerations that need to be given to design for motor traffic.

The analysis has revealed a high degree of consistency in speed across the sample and across different gradients for the cohort of experienced cyclists. Less experienced cyclists than were evident in the cohort of surveyor-cyclists in the survey may exhibit lower speeds and accelerations. It should be realised, however, that people new to cycling will not remain novices for very long and will ultimately attain levels of fitness and confidence which would propel them to the status of experienced cyclists.

The majority of the cohort used routes within the public highway. On the one hand, such routes, particularly in the urban area of Leeds, would have resulted in their speeds being limited because of conflicts with other traffic and the need to negotiate the usual obstacles to free flow speed in the urban environment. On the other hand, it could be argued that the cyclists may have attempted to adopt speeds on motor-trafficked routes higher than they would otherwise have adopted in order to minimise the differential speed between themselves and motor traffic, hence minimising conflicts. This argument would suggest that the speeds obtained from the survey are higher than would otherwise be the case.

It would appear from the results that none of Graham’s three hypotheses fits the data: a revised hypothesis would suggest that cyclists increase power output during the acceleration phase and create generally constant acceleration during most of the start phase as in Hypothesis 1, but have reduced overall average journey time supporting part of Hypothesis 2, and may in the end approach normal journey speed asymptotically as suggested by Hypothesis 3. Real world road conditions, such as the need to pull out to overtake a parked vehicle, and general variability in speed while cruising, are likely in most cases to blur the final transition from ‘acceleration phase’ to ‘normal cruising speed phase’. Further data and analysis are required of the way that power varies during normal cruising speed, particularly over the length of an uphill gradient.

No data were collected on braking patterns on downhill sections, but it is clear that the benefit of cycling down a hill will be reduced by the need to maintain a speed at or below a safe level for the road conditions. A hilly area is naturally, therefore, a less advantageous area in which to cycle than a flat area.

The adoption of design speeds for cycle traffic should influence sight distances, horizontal radii and vertical curves and will allow for off-carriageway routes to be designed that are inherently faster and safer, hence making them more attractive to cycle users.

Equally importantly, however, an understanding of the speed of cycle traffic will inform the way in which the carriageway is divided for cycle traffic. Parkin and Meyers (2010) for example discuss the proximity of motor traffic to cycle traffic on roads with different speed limits. Frequently, streams of traffic need to be moved laterally within the carriageway where the width available for traffic changes. These width changes may result from: right turn facilities (left hand rule of the road) leading to a widening out of the overall carriageway and a need to move traffic around the central waiting turning traffic; extended footways to shorten pedestrian crossing distances; central refuge islands to assist crossing pedestrians; horizontal traffic calming features; bus boarders; and parking and loading bays. The distance over which these lateral changes in direction may be safely achieved is a function of the speed of traffic and appropriate dimensions need to be adopted. The Lancashire County Council (2005) guidance is the only guidance document which specifies taper lengths for cycle design speeds, suggesting a 1:9 taper for 40 kph and a 1:7 taper for 30 kph.

Route planners need to understand the extent to which new facilities might attract new cycle users, and also existing users of other routes. The mode and route choice decision making processes will depend in part on journey speeds, but will also depend on other features of the journey, particularly its ambience as influenced by the perception of risk to the cycle user. A number of studies have considered such choices at the disaggregate level (e.g. Wardman et al., 2007) and the aggregate level (e.g. Parkin et al. 2008) and their findings flow through into UK government guidance (DfT, 2008b) on appraising walking and cycling schemes. It is noticeable however, that the guidance is scant with regard to suggesting appropriate speeds for cycle traffic, mentioning only a speed of 14 kph in a case study example. The evidence provided in this paper offers practitioners a firmer basis for selecting speeds for such planning work.

A very significant area of benefit is in improved health through greater physical activity and these benefits are evaluated in the World Health Organization's Health Economic Assessment Tool for Cycling (WHO, 2008). Cavill et al. (2009) note, however, that there are many questions which yet remain about who should be counted into health benefits analysis and whether or not they are undertaking exercise in excess of the recommended minimum amount to generate the benefits. Good data on the speed and effort characteristics of cyclists engaged in every day cycling is required in order to understand more fully the health benefits which may accrue to new cycle users.

6 Conclusions and recommendations

The paper reports speed and acceleration characteristics from a study of a cohort of commuter cyclists in Leeds, UK, with a view to offering appropriate guidance on speeds of cycle traffic for infrastructure designers, planners and appraisers.

An international review of cycle design guidance reveals a wide range of suggested design speeds for cycle traffic from between 16 kph to 20 kph for routes of lesser importance to 24 kph and up to 40 kph for routes of greater importance. It is generally true, however, that the guidance does not fully account for the effect of gradient on speed of cycle traffic, nor does the adoption of a design speed fully inform the rest of the guidance on how the speed might affect geometrical design for cycle traffic.

Cyclists may adopt a great variety of approaches to the profile of their power input to a journey and these will be influenced by journey length, the number of stops, the gradients to be overcome and the prevailing wind conditions.

The model of cycling presented here shows that the sex of the cyclist is not significant, but that speed is influenced by gradient with an uphill gradient reducing speed to a larger extent than a downhill gradient increases speed. The mean speed on the flat is 21.6 kph, with the eighty-fifth percentile speed being 22 kph. The speeds are consistent across the cohort of experienced cyclists, and novice cyclists would, with increasing experience, be expected to adopt similar speeds.

It is recommended that designers adopt 25 kph as a design speed for gradients less than 3%, but that consideration should be given to design speeds of up to 35 kph for steeper gradients, particularly where the prevailing wind direction is in the downhill direction. These design speeds should be taken as significant influencing factors for off-carriageway horizontal and vertical geometry and sight lines, and should influence taper lengths within the carriageway. The speed values will also be useful in planning and appraising scheme proposals.

The analysis presented here is part of the first phase of work being undertaken to comprehensively analyse the speed and acceleration characteristics of cyclists. Further work will analyse speeds and accelerations at times other than after a stop. Larger cohorts will help confirm whether in fact there are any subtle differences between different typologies of cyclist. Analysis will be performed on the characteristics of a long hill climb, and the effort profile of cyclists relative to the profile of the hill. Further analysis will also use heart rate data.

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Table 1 Summary of gradient, speed and acceleration data

			All		Male		Female	
	Uphill gradients	Flat and downhill gradients	Speed m/s	Acceleration m/s^2	Speed m/s	Acceleration m/s^2	Speed m/s	Acceleration m/s^2
	n=191	n=327	n=518		n=408		n=110	
Minimum	1.34%	-8.39%	1.64	0.03	1.64	0.05	1.75	0.03
Maximum	9.34%	0.00%	11.04	0.71	11.04	0.71	10.14	0.54
Mean	2.21%	-1.95%	5.98	0.247	6.05	0.256	5.69	0.217
Std. Dev.	1.81%	1.87%	1.66	0.121	1.63	0.124	1.75	0.108

Table 2 Linear regression model for speed

Variable	Coefficient	t-statistic
Constant	6.01	64.35
Downhill gradient	-23.79	-6.20
Uphill gradient	-40.02	-9.07
Adjusted R-squared	0.266	

Notes

1 Downhill gradients are negative

2 Speed is in metres per second and acceleration in metres per second squared

Table 3 Linear regression model for acceleration

Variable	Coefficient	t-statistic
Constant	0.231	31.30
Downhill gradient	-2.125	-7.02
Uphill gradient	-1.149	-3.302
Adjusted R-squared	0.146	

Notes

1 Downhill gradients are negative

2 Speed is in metres per second and acceleration in metres per second squared

Table 4 Cyclists speed, acceleration and power

Gradient	Mean Speed		Eighty-fifth percentile Speed		Mean acceleration	Power at mean speed	Power during acceleration	Time to final speed	Mean Speed with 16 kph tail wind
%	*m/s*	*kph*	*m/s*	*kph*	*m/s*^{2}	*Watts*	*Watts*	*secs*	*kph*
-7%	7.68	27.6	8.05	29.0	0.380	-251	-32	20.2	
-6%	7.44	26.8	7.77	28.0	0.359	-183	-6	20.8	
-5%	7.20	25.9	7.49	27.0	0.337	-119	19	21.3	
-4%	6.96	25.1	7.22	26.0	0.316	-58	42	22.0	
-3%	6.72	24.2	6.94	25.0	0.295	0	64	22.8	
-2%	6.49	23.3	6.66	24.0	0.274	54	84	23.7	37.3
-1%	6.25	22.5	6.38	23.0	0.252	104	103	24.8	34.5
0%	6.01	21.6	6.11	22.0	0.231	151	120	26.0	31.7
1%	5.61	20.2	5.75	20.7	0.220	183	133	25.6	28.3
2%	5.21	18.8	5.40	19.4	0.208	211	143	25.0	24.9
3%	4.81	17.3	5.04	18.2	0.197	232	151	24.5	
4%	4.41	15.9	4.69	16.9	0.185	248	155	23.8	
5%	4.01	14.4	4.33	15.6	0.174	259	157	23.1	
6%	3.61	13.0	3.98	14.3	0.162	263	156	22.3	
7%	3.21	11.6	3.63	13.1	0.151	261	151	21.3	

Note, the power calculations assume:

1. *Air resistance based on a frontal area of 0.616 m*^{2}*, a drag coefficient of 1.2 and a density of air of 1.226 kg/m*^{3}*.*
2. *Inertia and potential energy changes based on a total mass of ride a bicycle of 95 kg and an effective rotational mass of the wheels of 0.95 kg.*
3. *A rolling resistance coefficient of 0.008 and a mechanical efficiency of the bicycle of 95%.*
4. *No head or tail wind.*