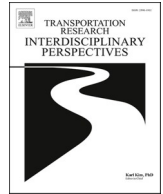


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## Space for cycling: A scoping review of recent evidence on the dynamic envelope for bicycle riding

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### ABSTRACT

How much space does it take to ride a bicycle? The aim of this study was to answer this interdisciplinary question as depending on perspective, this could be a technical, social or political question. We conducted a scoping review of recent research (2014–2025) to determine the current state of knowledge from an interdisciplinary perspective ( $n = 42$ ). Researchers primarily used naturalistic observation, controlled experiments, simulators, GPS data and mathematical modelling. Studies in our review identified many critical, independent variables including traffic flow, speed, path width, bicycle dynamics, path condition and bicycle static envelope. Synthesis of the research literature over the last 10 years suggests the *minimum* space needed to ride a bicycle from a technical perspective is a spatial envelope 1.5 m wide, 2.5 m high and a time headway of 1 s, which is inclusive of any bicycle length. While these parameters provide minimum mechanical benchmarks, the literature suggests that more space should be added from a social and behavioural perspective depending on the context and to enhance cycling modeshare, enjoyment, acceptability and rider safety.

### Introduction

Street spaces are finite with demands from an increasing number of modes to provide safe, accessible mobility. Providing space for people to walk, ride bicycles, use motor vehicles like buses, cars or trucks efficiently requires tradeoffs. In countries with low cycling, the approach has typically been car-centric or motor-normative, that is, prioritising the movement of motorised vehicle occupants (Newman and Kenworthy, 1989). While pedestrian access is mandated through standards specifying minimum width footpaths, cyclists are often allocated marginal spaces or required to share the lane with moving traffic or dismounting, walking their bicycle as a pedestrian. However, from a regulatory perspective, this spatial allocation is difficult to refute because we lack understanding of how much space cycling takes.

The core concept is “dynamic envelope”, which we define as the space and time occupied by a bicycle and rider in motion. Importantly, it is greater than the three-dimensional size of a bicycle, in order to account for the nature of balancing and steering a single-track vehicle, providing some mechanical room for error, and enough space between riders and other fixed objects such that bicycle riders feel safe and comfortable. To this we add a fourth dimension of time, to account for how close a bicycle rider may choose to ride to the person in front.

While current standards include guidance on the dynamic envelope for motor vehicles by means of “design vehicles” (Austroads, 2023) in many places such as Australia there is no dynamic envelope guidance for bicycles. Further, political, social and cultural norms often mean that gold-standard international guides (e.g., Dutch CROW), are dismissed as not being applicable to the local population or challenged for a lack of supporting evidence.

This situation plays out in cities globally. Guidance exists, however in practice it is challenged when the evidence behind the guidance isn't available, or cultural differences are cited as reasons why some guidance from one place isn't appropriate for use in others (Laing, 2022). This has brought us to question what state this evidence may be in. This scoping review aims to determine the state of practice and dimensions for the dynamic envelope of bicycle riding and in doing so provide evidence and knowledge gaps to further the production of knowledge in this contentious space. We do not intend to review cycling guidance, but rather the evidence behind it, asking a rather simple question. How much space does it take to ride a bicycle?

Readers may wonder why this is even in question. Surely the characteristics of cycles are well understood after the emergence of the bicycle as we know it in 1885? We propose a socio-technical perspective to the problem (Bijker, 1997) – one that can't be answered by a single

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discipline because there are characteristics of cycles, but also the rider. The politics of urban space are also a factor. We argue that investigating the dynamic envelope of cycling is an interdisciplinary problem: existing guidance considers all these aspects, resulting in spatial envelope recommendations that allow for riding, an amount of space in which to feel safe, but without demanding so much urban space as to be overreaching. Guidance suggests that an ordinary bicycle and rider needs a space 1.2 m wide, 2.5 m tall, and 1.95 m long (CROW, 2016). This guidance is based on decades of experience, following the citation trail as far back as Herfkens (1949).

What’s not in question is that using the bicycle for mobility has many virtues. Evidence from fields as diverse as climate science (Massink et al., 2011), public health (Giles-Corti et al., 2016), education (Simón-imas et al., 2024), economics (Gössling and Choi, 2015), civil engineering (CROW, 2016), and social justice (Chetty et al., 2014) describe that using bicycles for mobility is good for planet Earth, nations, cities, towns and humans.

With these benefits being so broad, it is curious that so many places don’t, often claiming they can’t, provide consistent, safe, and functional space for riding bicycles. Bicycles are used for a range of trip purposes (Napper, 2023), and these purposes lead to a diversity of cycling. Bicycle mobility consists of different people on different bikes, carrying out the mobility of their lives in different places. If we consider the simple question above, it is no longer simple. Which people are riding? What are they riding? What are they carrying? The variables continue.

Several cities and countries stand tall in this realm, the so-called “high cycling” places, where a person can reasonably expect to be able to ride safely to a destination of their choosing on a route suitable for their bike. High-cycling places across the Netherlands (Amsterdam, Utrecht, Rotterdam, Groningen), Denmark (Copenhagen) and latterly France (Paris) are the result of decades of concerted activism, research, policy and practice, including the generation and application of guidance for the planning of the bicycle transport system.

You may be fortunate to live in one of these high cycling places. If so, you might be the beneficiary of evidence-based guidance on designing for bicycles, enshrined in policy, and rolled out consistently. If you’re less fortunate, you may find some ad-hoc, disjointed, or simply unsuitable attempts to build ways for cycling. These include, but aren’t limited to zero-radius turns, cycling lanes narrower than your bike, isolated rather than networked paths, and “othering” of non-motorised mobility like walking and cycling into a combined, cramped space. While it may be easy to blame unsuitable infrastructure on those who plan these spaces, decision makers may only have some small amount of evidence on which to base their street design, or have had to rely on guidance from the high-cycling places that is ill-suited to the street in question given their own hostile policy environment. While the few guides that exist are trusted by bicycle transport planners and city cycling policy-makers, those around them will require evidence about what these guidelines recommend, before they relinquish space for cycling. It is worth noting the inherent sense of ownership in motor-privileged countries and the perceived high political cost of loss aversion, that is that reallocating space to cyclists is viewed as taking it from drivers.

Therefore, this research takes an interdisciplinary perspective and aims to take a step back and ask: How much space does it take to ride a bicycle? The following sub-research questions are posed with the hypothesis that there is scope for more work in this field:

1. What is the state of knowledge regarding “how much space does it take to ride a bicycle”?
2. What methods have been used by other researchers to build knowledge answering Q1.

These questions are not posed because of a lack of guidance. Even relatively “low-cycling” places like Melbourne produce guides for how to accommodate bicycles in the built environment (VicRoads, 2016). We acknowledge the CROW Design Manual for Bicycle Traffic (CROW,

2016) as the global benchmark for cycling guidance, based on a high number of citations from Australian, British, European and North American guides.

## 2. Method

To respond to the hypothesis that there remain knowledge gaps in this field, a scoping review method was used (Booth et al., 2021). A search string of [*bicycle AND envelope OR dynamic OR speed OR path OR width AND NOT shar\**] was applied in the Scopus database on 20th November 2024. Scopus was selected to provide a reliable means of retrieval. The inclusion criteria were: academic studies published in English; date range of 2014–2025. The exclusion criteria were: studies not available in English, studies that did not specify dynamic measurements. The references from cycling infrastructure design guides were also examined.

Our search returned 245 results. Two researchers screened the results, with disagreements in screening resolved by further investigation via abstracts and consensus by means of discussion. Title screening reduced the pool to 87, and abstract screening to 13. Reference mining from these results added a further 29 relevant resources, bringing the total to 42. Reference mining also identified cycling infrastructure design guides, which are not critically reviewed in this work, however are noted as the means by which the reviewed knowledge is transferred into practice. Fig. 1 describes the process followed.

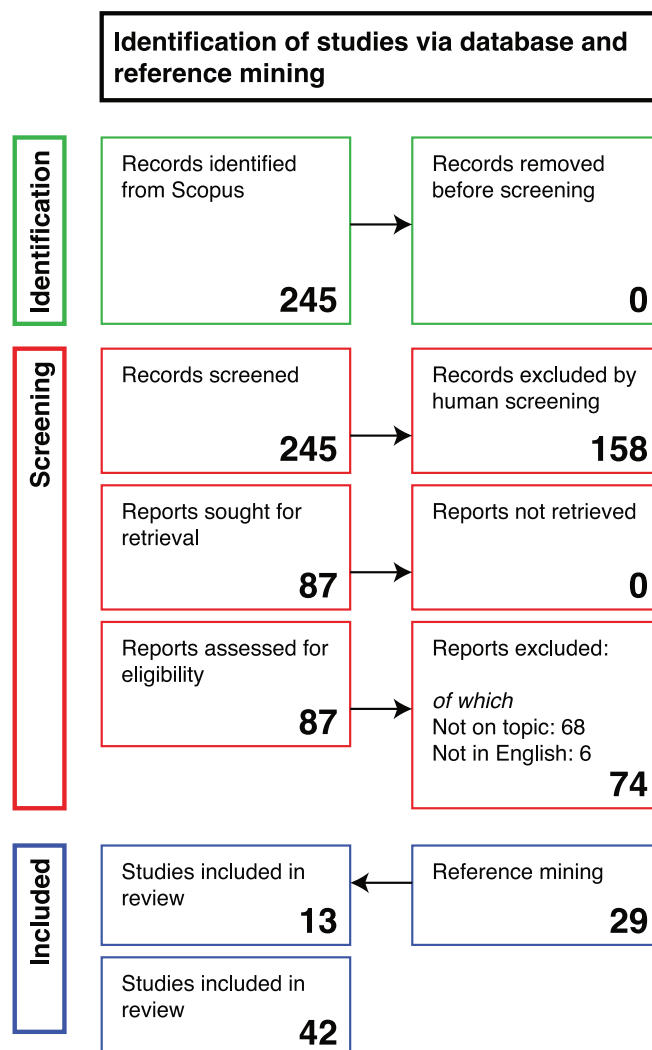


Fig. 1. PRISMA diagram of method (Page et al., 2021).

Excluded papers included a considerable volume focused on interactions between bicycles and motorised vehicles, most notably cars, the behaviour of drivers when in the vicinity of bicycles and the social effects of bicycle characteristics, for example how people feel about the speed of electric assist bicycles. These are valuable topics in their own right, but outside the scope of our research questions.

### 3. Results

A critical review of the 42 studies was conducted to answer the research questions. Overarching results are shown in [Table 1](#).

This research concerns the production of knowledge that leads to guidance on how much space it takes to ride a bike. We found that all guides cite evidence, and that some design guidance documents cite antecedent guides. The result of this is that some guidance is based on research carried out more than 50 years ago, but the knowledge of those experiments has become so enshrined in iterations of guidance that it is more or less preserved. We are not questioning the validity of experiments and research carried out in the past. We speculate that the age of some evidence may be out of tune with the introduction of new cycling technologies and habits.

Six dependent variables were identified that address the state of knowledge on the spatial envelope of bicycle riding, and six distinct experimental method categories. Variables, methods and the relationship between these are illustrated in [Fig. 2](#).

#### 3.1. Contributing factors to the bicycle envelope

Many independent variables contribute to the dynamic envelope needed to ride a bicycle, including bicycle characteristics, rider age, culture and topography. Independent variables for the dynamic envelope of a bicycle and rider included an array of social and technical factors. Social factors include independent variables such as whether a person is commuting, racing or recreating, running late, or carrying cargo or passengers. Technical independent variables include the geometry of the vehicle, availability and extent of electric assist, wind, and the infrastructure on which the bicycle is ridden. Research also examined a variety of dependent variables, which we grouped as traffic flow, speed, bicycle stability and dynamics, maintenance condition of paths and the bicycle's static envelope. Dominant perspectives in the literature were traffic modelling, traffic planning, and the prevention of crashes.

##### 3.1.1. Traffic flow

From the perspective of transport planning and engineering, the carrying capacity of bicycle lanes and paths is of particular interest as demonstrated by the number of search results returned in this review. Studies reviewed show the relationship between a bicycle's spatial envelope, speed, relationship to other path users and the resulting capacity of the path. Several studies used video-based observation to determine some characteristics of bicycle flow including the point at which a path is wide enough to enable two-abreast riding, comfortable overtaking ([Yan et al., 2018](#)), and when a path becomes full.

Flow rates are of particular interest, expressed as bicycles per hour per metre of path width. The flow rate indicates the performance of bicycle transport per unit of space. Unsurprisingly, studies find that wider paths have higher flow rates but there is substantial variation in reported numbers. This variation may be a factor of cycling habits, fleet characteristics, controlled versus naturalistic experiments or the experiment itself. For example [Lee et al. \(2016\)](#) studied comfortable lateral clearance, whereas [Seriani et al. \(2015\)](#) studied how many riders it takes to reach saturation flow, above which the carrying capacity of a path diminishes. These are two approaches to study the same phenomenon. Single lane flow rates suggest some understanding – by proxy – of how much space cycling may take, and these are summarised in [Table 2](#).

One determinant of flow rates is the headway – expressed as the time (thus representing the space) between one rider and the one following

behind. It is difficult to simplify this to a number, since inter- and intra-personal variations exist such as comfort, skill, vehicle characteristics and attitude ([Hoogendoorn and Daamen, 2016](#)). Headways are of particular interest in constrained cycling conditions, but above a certain threshold are more or less the same as having no rider in front at all; this phenomenon has been observed at three ([Hoogendoorn and Daamen, 2016](#)) or five ([Mohammed et al., 2019](#)) seconds. These researchers find that at moderate speeds around 15–20 km/h, a headway time longer than these few seconds is much the same as having no rider in front at all. While bicycles are in motion and if speed is known, the headway is a more accurate spatial description than the vehicle length: these studies observe that riders leave an amount of space between themselves and the rider in front, regardless of the length of the vehicle. Vehicle static lengths are well understood ([Napper, 2020](#)) and are an important factor in queueing and parking.

Another determinant of flow is sub-lane behaviour. When riders perceive there to be enough space, they may choose to ride, and queue, next to others in the same lane; a somewhat informal arrangement but one that has been shown to work; if a path is wide enough, several flows of bicycle riders might emerge under high demand conditions. Sub-lanes enable higher flows, which accounts for the higher flow rate of wider paths ([Wierbos et al., 2019](#)). Sub-lane queueing is also found to offer faster discharge from traffic signals in a similar fashion to how sub-lane riding increases path capacity ([Kucharski et al., 2019](#)). The width of a sub-lane varies since it is a technically and socially dependent variable, but narrower sub-lanes are noted to increase headway variability ([Yuan et al., 2019](#)). Most studies on flow and headway are naturalistic or controlled experiments with Dutch bicycle riders in the Netherlands. There is limited understanding of how these results compare with other places, countries, and cultural cycling habits because comparable studies have not been carried out in other places – meaning that we poorly understand the different social norms which may contribute to sub-lane riding behaviour. We speculate that cultural and behavioural elements may be at play ([Oosterhuis, 2019](#)), and could go some way to explaining why mathematical modelling approaches return non-deterministic results ([Kucharski et al., 2019](#)).

Lateral distance between riders, obstructions and the edge of a lane or path accounts for the transverse spatial variable, and together with headway these may largely account for the sum total of flow capacity. Sub-lane riding is related to overtaking behaviour. One observational study determined an average of 1.78 m between riders in overtaking, and the average space riders leave to the edge of the path 0.86 m ([Khan and Raksuntorn, 2001](#)). While we might assume that the “balanced single track vehicle” characteristic of most cycles is well understood, few studies explicitly engage with the relationship between steering and balance that is necessary to ride a conventional bicycle. Whether for psychological comfort or the necessity of balancing, [Yan et al. \(2018\)](#) recommends a “buffer zone” of 0.5 to 1.0 m when dealing with riders adjacent to one another. The size of the bicycle, especially width of the handlebars (often the widest part of the rider and vehicle as a whole) is not studied. Width is normally assumed to be circa 0.6 m, based on the CROW manual which itself cites the statutory maximum of 0.75 m in the Netherlands ([CROW, 2016](#)). A previous Australian study by the lead author shows a range of widths from 0.39 m to 0.8 m, with the average being 0.6 m ([Napper, 2020](#)).

Our findings show that traffic flow studies tend to follow an approach that treats the bicycle and rider as a point in space. This appears to follow good reasoning: if the bicycle and rider are represented as a point in space, semi-automated data collection and modelling of complex traffic flow characteristics is made possible. The reasoning can break down at a rider level, for example not accounting for the envelope of the bicycle, and hence the possible effects of vehicle width, leaning in corners and curves, and the different balance and swept paths of cargo bikes. As such, existing studies provide a good basis for planning the width and hence capacity of bicycle infrastructure. A question remains as to how much we might learn from observing those who already cycle

**Table 1**  
High level results from critical review.

Author, Year	Location	Aim	Method	Findings
Khan et al., 2001	USA	To characterise passing and meeting maneuvers.	Naturalistic observation	Passing cyclists are 2.12 km/h faster than passed cyclists, and will increase speed if this difference is too low.
Meijaard et al., 2007	GBR, USA, NLD	To confirm canonical bicycle dynamic equations.	Mathematical study	Model confirmed and re-presented for application.
Lin et al., 2008	CHN	To determine speed differences between electric and conventional bicycles.	Naturalistic observation	Mean speed 14.8 km/h conventional, 21.9 km/h pedelec.
Johnson et al., 2010	AUS	To identify risk factors for on-road cycling.	Naturalistic observation	Sideswipe was most common event type, intersection most common event setting.
Parkin and Rotheram, 2010	GBR	To determine speed and acceleration of cyclists.	GPS data collection	85 %ile speed of 22 km/h on flat at 150 W.
Andresen et al., 2013	DEU	To investigate driving behaviour of cyclists with a Necessary-Deceleration-Model.	Mathematical simulation and controlled experiment	Speed of rider is influenced by the speed of rider in front.
Doria et al., 2014	ITA	To study the relationship between rider body and bicycle oscillations.	Bicycle simulator	Waist stiffness has low impact, arm stiffness has high impact.
Torbic et al., 2014	USA	To provide recommended lane widths.	Naturalistic observation	1.22 m bike lane width recommendation for typical conditions.
Vansteenkiste et al., 2014	BEL	To determine the affect of surface quality on the visual behaviour of cyclists.	Naturalistic observation	Low quality pavement shifts rider gaze to the closer environment.
Edelmann et al., 2015	AUT	To investigate low speed stability properties of bicycle and rider.	Mathematical model	Differentiates how riders keep stability, and exploit instability to initiate turns.
Fees et al., 2015	USA	To develop recommendations for bicycle lane widths.	Naturalistic observation	Buffered bike lane provides better service than widening bike lane.
Jin et al., 2015	CHN	To estimate cycleway capacity.	Math model with naturalistic observation	1800 and 2727 bicycles and ebikes respectively, per 1 m wide path per hour.
O'Brien et al., 2015	USA	To investigate high speed cycling near rumble strips.	Naturalistic observation	Longer gaps between rumble strips are more comfortable for cycling.
Seriani et al., 2015	CHL, GBR	To determine saturation flow, and hence maximum capacity of cycle lanes.	Naturalistic observation	Near linear relationship between width and capacity. 2070 cyc/hr/m
Hoogendoorn et al., 2016	NLD	To develop a model for bicycle headway flow.	Math model with naturalistic observation	Headway average 0.784 s, SD 0.660 s.
Lee et al., 2016	KOR	To test desirable minimum width recommendations for cycle paths.	GPS data collection	2 m minimum recommended lane width.
Ma et al., 2016	SWE	To investigate microscopic cyclist behaviour.	GPS data collection	Simple model can adequately describe most behaviour.
Twaddle and Grigoropoulos, 2016	DEU	To understand acceleration, travel and deceleration characteristics of cycling.	Naturalistic observation	Cyclists found to have different speed characteristics based on many independent variables.
Schleinitz et al., 2017	DEU	To compare speeds of conventional and electric assisted bicycles.	GPS data collection	Mean speed 15.3 km/h conventional; 17.4 km/h pedelec; 24.5 km/h S-pedelec.
Schwab and Meijaard, 2017	NED	To determine necessary path width by scientific approach.	Mathematical model	A model can describe lateral displacements and contribute to guide path widths.
O'Hern et al., 2018	AUS	To determine how bicycle lane width and features can influence rider speed and position.	Bicycle simulator	Cyclist position is affected by lane width availability.
Yan et al., 2018	CHN	To develop cycle facility width recommendations.	Naturalistic observation	1.48 m centre-centre distance between riders while overtaking.
Yu and Zhao, 2018	CHN	To study the relationship between trail geometry and low speed self-stability.	Mathematical model and prototype	Negative trail can make a bicycle self-stable at low speed.
Yuan et al., 2018	NLD	To understand cyclist interaction behaviour and develop theories and models.	Controlled experiment	Found many factors. Cyclists begin deviation maneuvers around 30 m from each other.
Kucharski et al., 2019	POL	To characterise queueing behaviour of cyclists.	Naturalistic observation	Multichannel queues discharge faster than single channel queues.
Mohammed et al., 2019	USA	To characterize cycling in following and overtaking interactions.	Naturalistic observation	Headway average 5 s.
Paulsen et al., 2019	DNK	To develop a simulation model for speed heterogeneous cyclists.	Naturalistic observation	Model developed. Faster cyclists are delayed more often than slower ones.
Wierbos et al., 2019	NLD	To describe the relationship between capacity and path width.	Controlled experiment	Saturation flow of 3996 cyclists/hr 1 m wide.
Xu et al., 2019	CHN	To analyse speeding behaviour for bicycles.	Naturalistic observation	Speeds up to 32 km/h found. Recommends speed limit of 25 km/h for heterogeneous bicycle flows.
Yuan et al., 2019	NLD	To develop improved models for headway, saturation flow and hence cycleway capacity.	Math model with naturalistic observation	Highly stochastic variables, saturation headways 1.34–1.45 s.
Arnesen et al., 2020	NOR	To model cycling speed as a function of slope and horizontal curvature.	GPS data collection	Reliable model developed however notes independent variables such as desired speed.
Bohe et al., 2020	BEL	To develop a crowdsensing method for monitoring path quality.	Crowdsensing, GPS	That smartphones can be used to monitor path quality.
Ul-Abdin et al., 2020	BEL	To develop a classification system for bicycle paths.	GPS data analysis	Curvature and lane width important in classifying cycle infrastructure.
Guo et al., 2021	CHN	To investigate bicycle flow dynamics on wide roads.	Controlled experiment	Flow rate decreases when bicycles exceed 0.5 per sq. m.
Kaths et al., 2021	DEU	To investigate how path width effects following and passing behaviours.	Bicycle simulator	The quantity and duration of following events reduces when width is increased.
Mackenzie et al., 2021	AUS	To study passing distance of motor vehicles.	Naturalistic observation	12.3 % and 2.3 % of passing was non compliant with law in high and low speed settings, respectively.

(continued on next page)

Table 1 (continued)

Author, Year	Location	Aim	Method	Findings
Twisk et al., 2021	NLD	To investigate riding characteristics of bicycles, pedelecs and speed-pedelecs.	Naturalistic observation	Speed pedelecs vary speed and undertook harsh braking more frequently than other types.
Flakveld et al., 2021	NLD	To investigate traffic conflicts involving speed-pedelecs.	Naturalistic observation	Conflict amount is higher if speed-pedelec users share bike facilities rather than car facilities.
Wierbos et al., 2021	NLD, USA	To understand the effect of queue density on discharge rate.	Controlled experiment	Dense queueing leads to 40 % efficiency gain in discharge.
Hess et al., 2023	DEU	To investigate the role of path maintenance as a barrier to cycle use.	Survey	Path maintenance is second only to the quality of cycle infrastructure in affect on cycling.
Lyubenov et al., 2023	BGR	To determine speed characteristics in a high fatal crash prevalence area.	GPS data analysis	Mean speed 9.6 km/h when crossing many junctions.
Pazdan and Kiec, 2023	POL	To determine speed characteristics of different cycling cohorts.	GPS data analysis	Share bikes 17.4 % slower, and Strava users 23.1 % faster than regular cyclists.

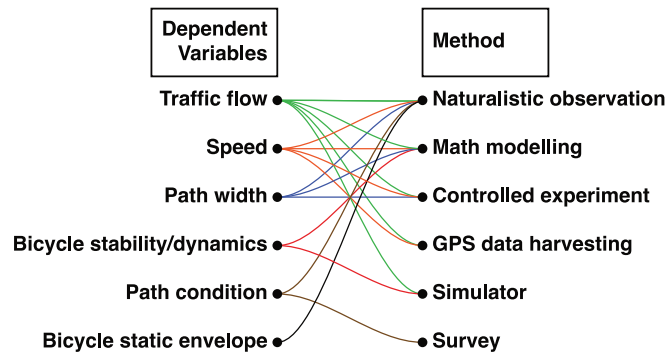


Fig. 2. Cross-referencing bicycle envelope topics with experimental methods.

Table 2

Maximum or observed flow rates expressed in cyclists per hour per metre width of path.

Author, Year	Loc.	Method	Flow rate riders/hour/width		Notes
			1 m wide	2 m wide	
Seriani et al., 2015	CHL	Naturalistic observation	2070	4657	Saturation flow
	GBR		4320	n/a	
Jin et al., 2015	CHN	Math model with naturalistic observation	1800 2727	n/a n/a	All bicycles All e-bikes
Yan et al., 2018	CHN	Naturalistic observation	n/a	1075	
Wierbos et al., 2019	NLD	Controlled experiment	3996	n/a	Inferred from 1.11cyc/sec/m

if our intent is to encourage and facilitate more non-bicycle using people to take up this mode. Studies of learner bike riders of any age were not returned in the search but are known to be understood in some high-cycling contexts (CROW, 2010). The traffic flow research provides us with a fundamental understanding of space for cycling, including some aspects of the bicycle and rider’s static width, and how much space is comfortable between riders in some (not all) places.

3.1.2. Path and lane width

Many studies examined path width, with the intention of providing policy advice for absolute minimum and “comfortable” widths. Studies of width in this review are engaged with understanding the effects of how much or how little space is provided, rather than trying to discover an empirical basis of space needed for cycling. This seems fitting with the cultural status of bicycle transport in many low cycling places – that the space is contested. Methods for studies varied between naturalistic

observation, mathematical modelling and qualitative studies such as those asking path users how they feel about the path or lane width they are using. Non path users were not sampled in the research. Path width is a contentious issue, because it directly relates to how much space is allocated to the cycling mode of transport. Space in an urban environment is usually in short supply, and may be divided among other modes of transport and place-making. The contention comes down to making a path wide enough to encourage and facilitate bicycle riding, while not taking more space than the society in question may consider reasonable. It also relates to the trade-off between creating a cohesive cycling network and negotiating street designs around important constraints such as significant trees, waterways, or historical buildings. The social, historical and political aspects of path width were not studied in this review but are noted as important, discussed at length elsewhere (Oosterhuis, 2019).

Several studies provide results in the form of recommended widths for bicycle lanes (on road) and paths, including where studies show that narrower values result in plausible, if problematic cycling conditions, as shown in Table 3.

The studies in Table 3 above tend to base their minimums on the smallest possible space they observe some people cycling in, with the exception of Lee et al. (2016) who discover that riders will expand their dynamic envelope based on the space available. Above a minimum, many studies speculate maximum widths, but not based on what a rider may need. Rather, in maximum space conditions the width is expected to be split into informal “sub-lanes” to accommodate large quantities of riders, with a preference of riders to position themselves in the centre of a given lane, regardless of width (O’Hern et al., 2018). This indicates two possible non-exclusive ways in which lane width and the bicycle dynamic envelope relate: a rider may expand their dynamic envelope to fill the space by relaxing their steering and balancing, and/or riders may engage in sub-lane behaviour if there is sufficient space between riders such as Yan et al.’s (2018) suggested 0.5 m-1.0 m buffer discussed above in section 3.1.1. Sufficient space will be different depending on social and technical variables, with Khan et al. (2001) finding a lateral passing

Table 3

Recommended widths for paths and lanes in metres.

Author, Year	Loc.	Infra type	Width in metres minimum or problematic	preferred or comfortable
Torbic et al., 2014	USA	Painted lane on road	1.2	1.5
Fees et al., 2015	USA	Painted lane on road	1.2	1.5–1.8
Lee et al., 2016	KOR	Lane on road	1.2	2
Yan et al., 2018	CHN	Grade separated lane on road	2	n/a
Ul-Abdin et al., 2020	BEL	Single direction path	1.5	n/a
		Two direction path	2	n/a

range of 0.03 m–1.45 m in a naturalistic study. This same study found that riders travelled an average of 0.86 m from the edge of the 3.0 m wide bi-directional cyclepath. Minimum lane width figures tend more towards a lower threshold, under which cycling is difficult or impossible, but this is poorly understood and methodologically fraught, since observational approaches cannot measure those who aren't cycling, and we can only speculate that people are not using bicycles because of a lack of comfortable space. Maximum and minimum figures should be interpreted and compared with this difference in mind – that minimums describe basic functionality whereas maximums are driven by path capacity. As discussed above, sub-lane riding and queuing are of interest from a traffic capacity and flow perspective.

Few studies examined the width of a single rider and the question of how much space a rider needs to accommodate balance, steering, and other activities such as obstacle avoidance while cycling. One such study finds that although the static width of a bicycle and rider is 0.75 m, the minimum and recommended widths for operating the vehicle are 1.2 and 1.5 m respectively, based on snapshots of a rider's lateral positioning on a wide road (Torbic et al., 2014). Guides consistently advise that some space in addition to the rider is needed as a buffer to kerbs, walls, etc, however the question of how much buffer to insist upon is more political than technical. If a guide requires too generous a buffer it may be the case that no bike infrastructure is built at all. This political phenomenon leads to the interest in marginal minimum space for cycling – the threshold at which a path isn't viable is important to understand. Studies of path and lane width tend to agree with width values for traffic flow, indicating a consensus around 1.5 m width for comfortable cycling. However, causality is not discussed; there is little engagement with the concept that narrow paths require a user of that particular path to take less lateral space.

### 3.1.3. Speed

Speed regularly features as a variable in cycling studies. It is noted to be an influencing variable in traffic flow capacity, trip times and safety outcomes. Speed itself is influenced by other variables such as load carrying, gradient, the presence and extent of electric assist, and the attitudes and behaviours of riders.

How fast do people ride? This depends on so many variables as to be difficult to answer. Findings of the studies in this review show some similarity, while noting that their mean figures sit in fairly large standard deviations as captured in Table 4. The literature investigates conventional bicycles, pedelecs (electrically assisted bicycles with a maximum assistance speed of 25 km/h) and speed-pedelecs (electrically assisted bicycles with a maximum assistance speed of 40 km/h).

Speed is primarily of interest in the modelling of traffic flow and capacity, the effectiveness of bicycles in carrying people and goods in a timely fashion, and road safety. As electric-assisted bicycles feature more in the general bicycle fleet, the speed differences have been studied to a greater extent in recent years. While both higher speeds and wider lanes increase traffic flow, wider lanes alone will increase discharge

rates from a queue so long as sub-lane queuing behaviour occurs. A GPS-based study by Schleinitz et al. (2017) finds that pedelec and speed-pedelec riders have respectively higher average speeds than conventional bicycles, but that this is mostly determined by speeds in unencumbered places such as straight, wide open “cycle highways” found in Belgium for example. Electrically assisted riders tend to exhibit the same, or very similar minimum speeds as non-assisted riders in denser, built-up places and only reach the higher speeds when infrastructure allows it. The study also found that speeds are inversely proportional to adult rider age, with bicycle riders aged over 65 having a mean speed 2.7 km/h less than those aged under 40. Pedelec riders across the same age differential were 5.7 km/h slower.

As might be expected, bicycle traffic consisting only of electric-assisted bicycles moves faster than non-assisted, and depending on prevailing laws in any particular place, will tend to have different characteristics. Xu et al.'s (2019) observational study in Hangzhou, China suggests that wider lanes can accommodate speeds of around 30–35 km/h. In a bicycle fleet mixture of conventional and electric-assisted vehicles, the variation in speed is noted to create conflicts between riders (Vlakveld et al., 2021, Twisk et al., 2021).

The effects of pavement type on speed are poorly understood, suggesting the difficulty of isolating one variable. Urban riding in Ghent, Belgium was found to have no significant variation in speed on either good or poor surfaces (Vansteenkiste et al., 2014). Other studies on speed do not study surface, so we may take speed variation to be wide; although most studies return values around 17 km/h (see table 3 above). A Bulgarian study in Ruse returned low speed observations in an urban setting of just below 10 km/h (Lyubenov et al., 2023) as riders navigated junctions.

The behavioural aspect of speed is often mentioned, by means of explanation for the variations found in the field. While again not possible to isolate, behaviour on a “careful-correct-reckless” scale provides some understanding of this variable (Rupi et al., 2020). Ul-Abdin et al. (2020) note that the nature of the path, for example curve radii, sight distances and width are factors in speed. We find that speeds investigated in the literature are quite variable, and not easily categorised by culture, country or city. This reflects anecdotal real world observation that there are many ways and places to carry out cycling. The relationship of speed to headway (discussed above in 3.1.1 traffic flow) is poorly understood; our current understanding is that one second of headway is observed in the range of typical cycling speeds.

### 3.1.4. Bicycle stability and dynamics

One factor that determines how much space it takes to ride a bicycle is the stability of the bicycle itself. Here we are reminded of the broad spectrum of “cycles” including trikes, quadricycles (quads), cargobikes, conventional bikes, ebikes and speed pedelecs. Also combinations of these, such as e-cargo-quads. The question of stability is largely differentiated between two- and three-wheelers as two-wheelers are unstable at rest, whereas three-wheelers present their own characteristics such as

**Table 4**  
Speed averages and standard deviations.

Author, Year	Loc.	Method	Mean Speed km/h (SD)	Vehicle Type	Notes
Lin et al., 2008	CHN	Naturalistic observation	14.8 (2.9)	Bicycle	
Andresen et al., 2013	DEU	Mathematical simulation and controlled experiment	21.9 (4.7)	Pedelec	
Twaddle and Grigoropoulos, 2016	DEU	Naturalistic observation	15.5 (2.05)	All	
Schleinitz et al., 2017	DEU	GPS data collection	18.39 (4.99)	All	Calculated from mean max and min. Passing through intersection.
			15.3 (2.3)	Bicycle	Whole of trip
			17.4 (4.4)	Pedelec	
			24.5 (3.1)	S-Pedelec	
Paulsen et al., 2019	DNK	Naturalistic observation	21.6 (3.6)	All	
Ul-Abdin et al., 2020	BEL	GPS data analysis	16 (8)	All	
Lyubenov et al., 2023	BGR	GPS data analysis	9.6 (1.2)	Bicycle	Navigating junctions

being stable at rest, and with their own variety of different cornering characteristics. The stability of any individual bicycle rider is of interest when studying traffic flow, since riders of two-wheeled bicycles can sway significantly under certain circumstances such as inexperience, or slow riding.

The literature suggests that mathematical approaches to understanding and modelling bicycle stability have been developing over many years (Meijaard et al., 2007). Practical guides also touch on the topic, with a view to educating readers about the best ways to learn cycling. Ballantine (1983) provides a neat explanation of the four ways in which a bicycle can be steered, and in doing so reinforces the relationship between balancing and steering, described below.

The vehicle is comprised of a bicycle and rider(s), with the rider's connection to the bike being somewhat flexible. This is found to influence stability and the characteristic most bicycles have for self-stabilisation (Doria and Tognazzo, 2014). A related study shows that changing the bicycle's "trail" geometry (the relationship between head tube angle, fork offset and contact patch) can be reversed to create higher stability at lower speeds (Yu and Zhao, 2018).

The manner in which a rider controls the bike is well understood – although it appears that most cycling research assumes a certain level of rider control, it may be worthy of consideration given how many bicycle crashes only involve one person. Edelmann et al. (2015) identify three control "layers" from a mathematical modelling approach to be anticipatory feed-forward control where the rider makes the bike do what they want; compensatory feedback control to correct deviations from desired and actual path, and stabilisation control to keep the bike upright.

Even turning itself is not so simple. Ballantine (1983) identifies four methods of initiating turns. The first, slowest and most common is simply not correcting a fall (which all two-wheeler riders are constantly correcting, however minute this may be) and then going with the bike. Second, initiating a quick turn is a matter of pulling the bicycle out from underneath yourself and thus starting a very quick turn in the opposite direction. Often referred to as counter-steering. Third, it is possible but uncommon to lay the bike over but keep the rider's body upright. The least common is initiating a turn by leaning the body over and therefore "falling" into a turn in that direction. We have taken the time to set these out here because although they can be verified first hand by a reader they appear nowhere else in the literature within the scope of this review. Perhaps turning is too implicit a skill to get more academic attention. We speculate that a better understanding of bicycle turning may lead to better designs for cycling.

A more recent study shows that Ballantine's first method of turning appears to be the most widespread in everyday use, recommending that curves do not start abruptly but rather a transition approach is used to lead-in and lead-out of curves. This is a good example of designing paths to match the dynamic characteristics of the vehicle (Ul-Abdin et al., 2020). While this knowledge may seem too detailed for general city operations and cyclepath planning, it is at the core of what determines how someone can safely and comfortably negotiate a journey. Bicycle stability and dynamics is variable based on hard factors such as bicycle design, and human factors such as experience, skill and fatigue. The literature goes some way to explaining why a bicycle needs more than the vehicle's width to operate, and reinforces the finding that for a bicycle and rider of nominal 0.75 m width, a lane of 1.5 m may be appropriate for many riders.

### 3.1.5. Maintenance condition of paths

Experience will show any rider that surface quality and pavement type affect how we ride bicycles. Although evidence is limited, studies in our review corroborate real life experience, that path condition is important (Hess et al., 2023). There is a complex relationship between the qualities of surface (for example paved asphalt, concrete, stones and bricks, gravel, mud, water, ice and snow) and tyres, tyre design and tyre pressure (Heine, 2020) at the interface of path and vehicle. This has

knock-on effects on the rider's behaviour. At the least, bumpy paths are acknowledged as uncomfortable to ride on, if not unsafe (Bohé et al., 2020). Aside from dynamic considerations, in bumpy conditions the rider's gaze is more concentrated on the immediate path rather than the broader context, and as such poor surfaces may be connected to adverse safety outcomes, as riders strive to mitigate safety concerns from the surface (Vansteenkiste et al., 2014). The five subjects in this study cycled at speeds within 1.5 km/h across good and poor surfaces. The degree to which a rider might deviate from their planned path to avoid an obstacle is not known. We consider this to be an important gap, since surface condition is rarely mentioned in other studies about how riders use the space available to them. It appears that in an "ideal world" we can assume paths to be in "ideal condition", however back to experience, we know that this isn't always the case. The research into path condition further strengthens the claim for lane width beyond that of the bicycle – that riders will need to deviate from time to time, and it is best that this is done within the infrastructure.

### 3.1.6. Bicycle static envelope

The size of bicycles is not often studied, however some useful benchmarks are provided by authorities in this space, which are often adopted into mathematical models describing traffic flow. Foremost among these is the CROW (2016) manual which acknowledges that cycles come in many shapes and sizes, but nevertheless suggests a "standard" bicycle of 1.23 m high, 1.95 m long, and no more than 0.75 m wide. The same guide suggests a height allowance of 2.5 m to provide clear sightlines and a comfortable feel. Previous studies have found that there are bicycles outside this benchmark (Napper, 2020). As low-cycling places increase cycling rates, we may reasonably expect the bicycle fleet to exhibit traits of high-cycling places – tending towards a majority of quotidian cycles, and at the same time becoming more diverse and containing bicycles of different shapes and sizes such as more cargo bikes. Upon reviewing the literature it would appear that bicycle size is important since it is a dimensional starting point for the (at times) contentious issue of how much space cycling requires, yet comparatively little is known about bicycle vehicle size compared to other variables such as speeds. Knowing the vehicle mix, and the sizes of these bicycles may be useful as a foundation. Research into the height of bicycles and riders was not found, nor was any suggestion that 2.5 m vertical clearance is unreasonable.

## 3.2. Experimental methods found in notes

Given the great number of variables in the cycling dynamic envelope, we might well ask how are the above conclusions drawn by researchers? Noting the complexity of technical, cultural, geographical and behavioural factors in the bicycle dynamic envelope, it is unsurprising to see in the literature that a variety of methods are employed in the search for greater knowledge. Among the methods found, four common findings are reviewed below to answer sub-research question two: What methods have been used by other researchers to build knowledge answering Q1?

### 3.2.1. Naturalistic observation

Direct observation of riders was widely used in our findings (n = 20). Among these, video recording and coding of observed behaviours are frequently deployed, with naturalistic cycling studies growing to be carried out in many countries and regions. Coded observations have been paired with rider interviews to find out how people feel in certain scenarios, for example being passed by a motor vehicle (Johnson et al., 2010).

Observation is used by several studies to determine recommendations for path and lane widths, for example by measuring how much width needs to be provided for passing to occur. A potential limitation with observations such as these is that they are observing the behaviours of people who are already cycling. This might limit findings that are applicable to attract new people to cycling.

Observation in a naturalistic setting is carried out with a variety of approaches and equipment. Although video is common, the use of equipment in conjunction with video is noted, such as GPS sensors (Wierbos et al., 2019), measurement tools (Mackenzie et al., 2021), eye trackers (Vansteenkiste et al., 2014) and radar (Lin et al., 2008). While these may suggest a technical bias in these studies, the reason researchers use observation in conjunction with other equipment is to understand the behavioural and environmental factors at play from video, especially with regard to queuing and cycling in congested conditions.

### 3.2.2. Controlled experiment

Large-scale experiments in traffic flow have been carried out to study particular features of paths and lanes, and the human behaviours that result from them. The intention is to control for confounding factors such as weather, riders outside the scope of study such as children, or to create and test specific, problematic circumstances without safety concerns for participants.

A test track is commonly used to control for infrastructure differences and non-participant riders, either by separating and equipping a carefully selected public space with sensors and cameras, or by creating a simulator test track controlling for environmental conditions such as light and weather. The known limitation of a participant-bias effect is stated to be overcome by habituation – getting participants to ride their own bicycles on the test track for a period before the study, to diminish performative behaviours (Yuan et al., 2018). Very large test tracks are potentially expensive to operate, with researchers making the most of their investment by carrying out multiple tests in a day. Oval test tracks are used by several teams as the best way to study straight-line behaviour with a continuous stream of riders (Guo et al., 2021, Yuan et al., 2018).

Equipping a public space where people already ride removes some burden of cost on experiments, however does not control for as many variables. The trade-off may be that findings are more generalisable to similar conditions and the general population of bicycle riders. Public space experiments provide an opportunity to test real-world path features such as rumble strips (O'Brien et al. 2015), queuing and discharge behaviour (Wierbos et al. 2021), gradients, car parking and “buffer” space from motor vehicle traffic (Torbic et al., 2014) and to control for participants to some extent. All controlled experiments in our results used optical identification methods (e.g. coloured hats worn by riders) to feed into a machine recording of rider location as a point in space.

### 3.2.3. Simulator

A more rigid controlled experiment is the use of a simulator – enabling studies to control a greater number of variables and study some factors of cycling in greater depth, for example the effect of raised hands (i.e. off handlebars) on vibration dampening (Doria and Tognazzo, 2014). Lateral control of the bicycle is noted as difficult to simulate (Kaths et al., 2021).

### 3.2.4. GPS data harvesting

With the advent of near-ubiquitous smartphone use, a considerable amount of publicly available data has been amassed by bicycle riders recording their journeys. Data from these journeys provides location-specific insights such as speed, stopping points, route choice and to an extent, placement of the rider on the road. GPS-based studies dominate the topic of route choice and the study of cycling habits for cities. Date and time of day are of significant interest, as they can be cross-referenced to weather, events, seasons, weekends, holidays and conditions such as congestion. Precision claims for GPS location varied across studies and are poorly documented, perhaps reflecting that they are poorly understood or contained in a technology “black box” to which the researchers have no access. Perhaps because of this limitation, the most common use of GPS data harvesting are time-based factors such as speed (Schleinitz et al., 2017, Ma and Luo, 2016, Lyubenov et al., 2023,

Arnesen et al., 2020, Parkin and Rotheram, 2010) rather than precise road placement. GPS tells us where a rider is, but not how much space they need.

Researchers use GPS data as a sample of people who are riding bicycles in the real world – aiming for representative data. A known limitation of GPS data is sample bias: that it tends to be logged by keen or sporty riders, and especially in low cycling places is an over-representation of sporty, male bicycle users. To understand this limitation, a comparison of bike share, Strava and a generalised GPS rider data sets found Strava app users were 23.1 % faster than regular riders, and bike share users 17.4 % slower than regular riders (Pazdan and Kiec, 2023). None of the authors in the scope of this review indicated how or to what extent they anonymised data to prevent individuals being identified by their bicycle trips, however the data in all cases appears to be free of identifying characteristics.

### 3.2.4. Mathematical modelling

Modelling bicycle stability with mathematical methods has been carried out for almost as long as bicycles, and bicycle-like vehicles have existed. Contemporary research in our results tended to be limited to studies which describe and predict traffic flow via modelling, although a body of work exists on the dynamics of bicycles. Authors of these studies create models to represent reality, and then validate the models against data such as observations. They provide good insight into the limitations of their models, for example limits to how they can describe actual human behaviour (Edelmann et al., 2015), or account for heterogeneity of rider fitness and type of bike (Paulsen et al., 2019). Mathematical modelling approaches tend to be defined in the scope of technical variables, acknowledging but not studying behavioural aspects. The relationship between behaviour and modelling is suggested by Ballantine's (1983) identification of ways to steer a bicycle – the experienced rider may choose from a variety of methods based on circumstances, necessity or perhaps just personal preference. A distinction is drawn between studies which report instantaneous road position of bicycle and rider at a specific point (Torbic et al., 2014), compared to those studies which investigate the amount of weaving, balancing or wobble in bicycle and rider position over a sample distance. These latter are important because they account for “The inherent lateral instability of the bicycle...” and “unavoidable lateral contact point displacements...” (Schwab and Meijaard, 2017); that is to say, only some guidance accounts for the fact that when ridden, a bicycle will sway to some extent. Terms such as sway, wobble and weaving are used interchangeably throughout the literature to describe how single-track vehicles such as bicycles are balanced.

## 4. Discussion

### 4.1. Factors of space to ride

Returning to the central question of how much space riding a bicycle takes. One of the more prevalent perspectives in the literature is traffic flow, providing evidence for how many bike riders might be carried on a lane or path. Representing riders as points in space gives us a clear idea of how much interpersonal space is needed, as well as space around boundaries and obstructions. From this we might infer the dynamic envelope of a bike and rider to some extent. The extent to which we understand the characteristics of an individual bike and rider combination is however limited – for example a point in space does not describe how much a rider might sway while maintaining balance, or the closely related matter of how they might execute cornering.

Studies reviewed tend to be from high cycling places and study samples of volunteers or the general public – in both cases seeming to cover those people who are already cycling. We speculate as to how much space a learner rider may need, a limitation in settings where policy aims to get new people cycling. A further limitation may be the broad generalisability of these results. Authors note that they are studying one population – often from a high cycling place, and that

samples from these places may not have the same characteristics as others. Readers who have observed or participated in cycling across different cultures may have shared the observation that people in different settings have varied capacity, comfort levels, and necessity for close proximity riding.

These limitations point towards a gap in knowledge; that we have a poor understanding of the dynamic envelope of cycling across a range of variables, including but not limited to geographical location, type of vehicle, rider experience, or trip purpose. A better understanding of these rider characteristics could strengthen the interpretation of cycling guidance from one culture to another.

The relationship between rider preference and necessity is not well understood. While the many observational and naturalistic studies in this review show that people can successfully ride in narrow spaces, it is poorly understood how comfortable someone may be in doing so. Would a rider choose a detour or to endure a narrow space? Clearly this is dependent on the individual and their circumstances, as well as for how long a distance the narrow or sub-optimal space exists. Naturalistic studies show that many people can ride on fairly narrow paths, however we don't know if they are comfortable doing so. There may be many other potential riders choosing other routes and modes. While the assumption of "comfort" may be a limitation, an understanding of how much space someone riding a bike occupies when unimpeded by other riders or infrastructure may be worth gaining. Such information might help us set benchmarks to attract new people to this sustainable mode.

The review does not show that higher cycling places have higher flow rates per metre of path width. We cannot separate flow-rate findings from low and high cycling places, as the data collection locations and methods vary to the extent that generalising them by country would be making too many assumptions. The British results in [Table 2](#) for example, are the highest in the literature review, whereas the general British rate for cycling is lower than in other places also studied.

Studies concerned with space, in particular lateral space and lane width, tend to use instantaneous samples to determine rider preferences. A point in space and time represents where a rider was at that particular moment, however it does not give us a clear understanding of their balancing and steering. As [Edelmann et al. \(2015\)](#) point out, there are various states that a rider might be in at a particular point in time, and when we compare this knowledge to instantaneous data we have no way of knowing how they relate. A rider's point in space may be at the apex of a balancing manoeuvre and thus not represent the centreline of their trajectory. This is all the more evident considering the lack of study on curved paths in the literature. Long standing guidance ([CROW, 2016](#)) on curves gives a relationship to speed and navigable radii; what trajectory a rider may take through a curve is not well understood.

Although measurable, it is difficult to fully understand the determinants of rider speed. If the aim is to build functional cycling paths, speed will determine the space to ride on curves since riders must lean more into curves as speed increases and radii decrease, in order to maintain bike balance. The observational and controlled experiment methods tend to study behaviour in straight sections more than curves. As in many situations, guidance from high cycling places exists but we don't know if it applies in low cycling places. The line a bicycle and rider might take through a curve is poorly understood, for example whether their path through the curve has similar characteristics to their straight line preferences, or perhaps whether something akin to a "racing line" is taken.

Studies on pavement and surface quality provide a detailed understanding of the impact on rider behaviour. The related topic of surface obstacles was not found in our search results. This might highlight a knowledge gap around how much space riders need to navigate around surface obstacles, with flow on effects to the space required for riding. Path and lane dimensions are proposed based on factors above such as capacity and speed, but if we consider the space needed to steer around an obstacle, more space may be required.

The study found a variety of answers to the first research question,

which fall into a relatively cohesive "answer", but with many caveats. We venture the summary answer that the research agrees with guidance; it takes at least 1.5 m of width and 1 s of headway for most existing bike riders to functionally cycle, however to this mechanical minimum, our findings suggest that we add additional social space in the creation of pleasant, low-stress conditions, and note that height was not studied. It is this additional space which may be contentious beyond the basic dynamic envelope. It is difficult to separate answers to the question "How much space does it take to ride a bicycle?" with how politically palatable it may be to declare a minimum lane or path width, minimum passing distance for other vehicles, a crowding threshold, or overhead obstruction height. The regulatory context of space adds further complexity. A related but separate question might be "How much space should be provided for a bicycle transport system?"

Search and review results found little to do with social characteristics of cycling. The manner in which people behave when riding a bicycle could be a determinant of whether other riders feel comfortable. These characteristics may be determined by technical characteristics as much as social ones, for example whether a person is riding for fun, perhaps with a boisterous spirit and style. In addition, the manner in which one person rides may determine their own compatibility with a path, and a given space. Someone learning to ride a longjohn or bakfiets cargobike for the first time may not feel confident on narrow paths yet. We might imagine that this limits their cycling choices and habits – however there's little evidence in the literature on this matter.

#### 4.2. Methods found in the literature

Naturalistic observation is widely used, and provides reliable real world data. A common formula is for research to use video observation plus one other method such as GPS. This complementary-methods approach provides data with context. We suggest that a primary limitation of these studies is that they don't account for people who are not yet using bicycles.

The prevalence of smartphone GPS and attendant apps such as Strava has led to a vast array of data being available for study. Location and time can be used to glean many insights, however these do not tell us much about a rider's spatial envelope beyond how fast they are travelling and perhaps, how fast they're cornering. GPS data gives us plenty of information about the bicycle transport system at an aggregate level. Controlled experiments and naturalistic observations seem better at the granular, individual rider level.

Several studies look at a rider's instantaneous road position rather than the behaviour over a distance. Knowing where a rider is can help describe behaviours, however is at odds with the knowledge that balancing a bicycle requires some amount of sway. Road position at any point is a dependent variable of many independent ones, such as preference, experience, habit, lane width, speed, congestion, surface condition, obstacles, skill, and vehicle type to name a few. Controlled experiments can eliminate some of this variance, as can specific screening and recruitment for such experiments. The methodological question arises as to whether it is more accurate or accessible to carry out research controlling for these factors, or instead to account for these limitations during a naturalistic approach.

The intent of the research studied in this review tends to be deep studies of particular aspects of cycling. These are enhancing our understanding of how bicycle mobility works, and contributing to the stock of knowledge. At the same time, researchers acknowledge limitations of their methods and as reviewers we acknowledge that these studies are somewhat bound in particular places. While riding a bicycle is a globally recognised form of mobility, regional variations are not strongly accounted for, outside of the fact that some places have more bicycle riders than others. There appears to be room for a more holistic study of bicycle riding behaviour with regard to space.

#### 4.3. Future work

Clearly a wide range of cycling research has been carried out in the last decade. The body of work reviewed for this paper tends to answer specific, isolated questions on the technical aspects of bicycle riding, with some connection to social aspects such as comfortable space between riders. For example, the contentious issue of path width is studied to determine how people behave in a given width, rather than setting out to determine empirically how much width may be needed. We speculate that a more holistic study of cycling could contribute to this space if it contains the following characteristics: collecting social and technical data and analysing for correlation or causality; studying lane placement over time rather than at a selected instantaneous point; understanding the height of bicycle and rider; and the ability to note local conditions to the extent that they could be understood as factors, rather than removed in experimental controls. An understanding of how much space is required to get people to consider or start cycling, among the many other factors in that choice, would be valuable to study from a behaviour change perspective.

#### Conclusion

This scoping review of 42 papers aimed to understand the current state of knowledge regarding how much space it takes to ride a bicycle, and the methods used in such studies. We find that isolated elements of space such as road placement, speed, and traffic flow are well understood, but that results vary across cultures and methods. This calls into question the application of guidance from one place to another – in particular the use of high cycling place guidance into low cycling places. The review highlights particular gaps around non-cycling populations who are the target of policies to increase cycling; as well as holistic studies which can combine variables to understand their impact on spatial needs for riding a bicycle. Naturalistic and observational studies of people who already ride bicycles suggest that it takes around 1.5 m of width, 1 s of headway, and for lack of competing ideas some 2.5 m of height in which to technically ride a bicycle, with evidence suggesting that more space in addition to this is welcome from a social and behavioural perspective if cycling is to be encouraged.

#### CRedit authorship contribution statement

**Robbie Napper:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Tyrell Siew:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Yi Jing Ang:** Writing – review & editing, Writing – original draft.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data presented in table one of this paper.

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