Using an instrumented bicycle to explore the responses of cyclists to pavement characteristics and defects

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SHORT SUMMARY

Cycling offers great advantages in terms of space consumption, health and environmental sustainability, but is plagued by a poor road safety record, which has yet to be properly addressed due to a lack of understanding of the behavioural traits and responses of cyclists that would enable the design of suitable interventions. The aim of this study is to offer some insight into cyclist behaviour by investigating its relationship with the road environment, and specifically with pavement features and defects, such as High Friction Surfacing, cracks and utility covers. Using an instrumented bicycle, quantitative measurements of speed, steering angle and roll angle in response to different pavement features were taken from cyclists riding along a pre-determined route in Southampton, UK. The data were analysed using multiple linear regression and the findings highlighted a number of significant positive and negative effects to be considered in the design and maintenance of cyclist facilities.

Keywords: cycling, behaviour, road design, pavement defects, instrumented bicycle, field data collection

1 INTRODUCTION

Cycling is an increasingly popular travel mode in cities due to its advantages in terms of space consumption, health and environmental sustainability. It is, therefore, favoured and promoted by many city authorities, both through "heavy" infrastructure projects (such as Santander Cycles [1] and Cycleways [2] in London), and through "softer" policies (such as Southampton's cycling strategy [3]). Nevertheless, the take-up of cycling as an alternative travel mode remains well below desired levels, with countries exhibiting high cycling modal shares, like Denmark or the Netherlands, being notable exceptions rather than the norm. The main reason is the low perceived safety of cycling from the users' side, which, unfortunately, is not unjustified: according to the UK Department for Transport's latest official statistical release, and despite slight decreases in the last few years, there were as many as 91 cyclist fatalities in Britain in 2022 [4], and these were only a small part of a staggering 15,693 cyclist casualties.

The behaviour of other (mainly motorised) users is usually cited as the main reason for this trend, but another important and often overlooked reason is that of poorly designed and maintained infrastructure. Indeed, potholes, unevenness, debris and wide cracks have all been found to have a moderate to substantial effect on riding quality (particularly since they can cause loss of stability) [5-6]. Despite recent investment in cycling infrastructure, however, poorly maintained roads re-main endemic across cities and continue to pose risks to cyclists of any experience level [7]. This is because a solid understanding of the mechanics and response traits of cyclists that would enable the design of suitable interventions is currently lacking. In particular, there is a notable lack of research investigating the effect of pavement characteristics on cyclist behaviour, such as the surface type, quality (concerning defects), and features, such as utility covers.

The aim of the present study is, hence, to shed light into the under-explored topic of cyclist behaviour and its relationship with the road environment, and this is investigated by means of real-world cyclist trajectories in urban areas. Previous research by the authors explored part of this aspect, namely the effect of different road features (e.g. cycle lanes, bus stops and gradients), using trajectory data from cyclists across a number of road sites in Southampton collected with the iBike instrumented bicycle [8]. The objective of the present study is to expand on the findings by exploring the impact of pavement characteristics and defects. These include: different surface materials in use; the occurrence of cracks, potholes, etc.; and the presence of other potentially disruptive features, such as utility covers and drains.

2 METHODOLOGY

The iBike instrumented bicycle

The iBike instrumented bicycle (Figure 1) is a research facility capable of monitoring several key variables related to cycling, such as speed, steering and acceleration, through an on-board bespoke measuring and logging system [9]. The housing of the handlebar sensors includes a GY80 Inertial Measurement Unit, which incorporates a three-axis accelerometer, three-axis gyroscope, three-axis magnetometer, temperature and pressure sensors. The seat tube enclosure houses another set of accelerometer and gyroscope configuration, used to monitor the rear frame acceleration and angular rate respectively. Hall Effect and absolute encoder sensors are used to measure the revolutions of the rear wheel and the steering angle respectively, while a main control box contains an Arduino Mega 2560 board along with various electronic components and a memory card. A GoPro camera is also installed for visual confirmation.

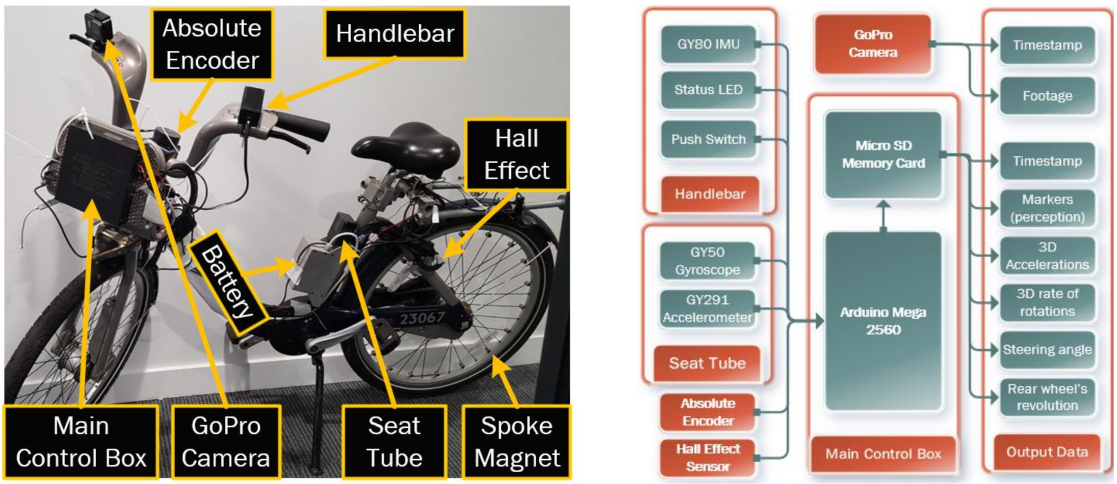


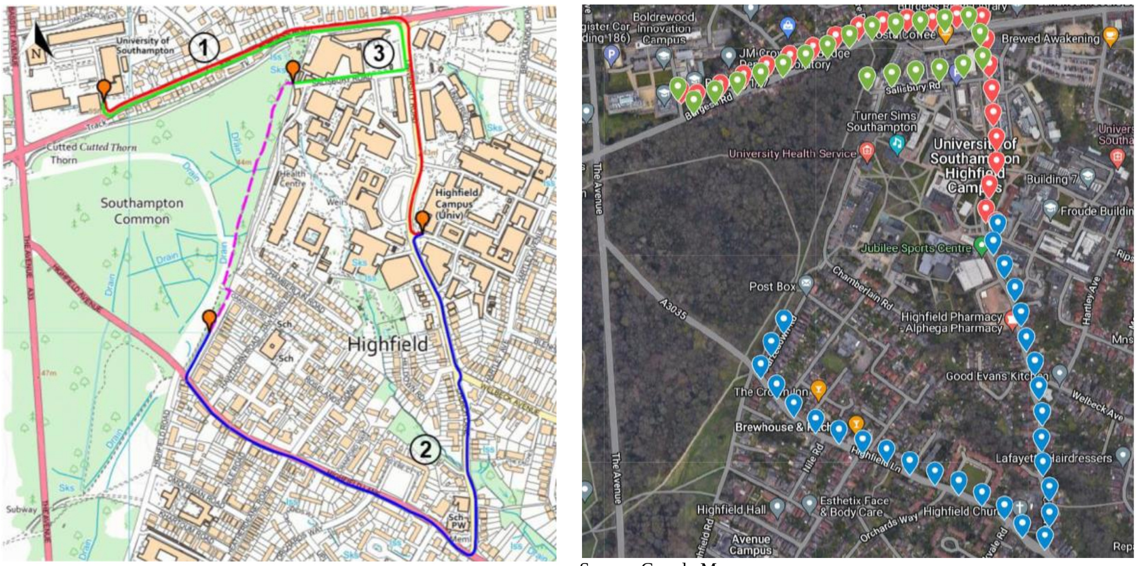
Figure 1: The instrumented bicycle (iBike) and its measurement architecture

The iBike was originally developed to enhance the positioning accuracy of cyclists. However, its measurements can also be employed to monitor cyclist behaviour in different environments (e.g. speed and course changes), and have previously also been used to measure riding comfort [10].

Study site

The surrounding area of the University of Southampton's Highfield and Boldrewood campuses in Southampton, Hampshire, UK, was used as a case study. The campuses are located 600 m apart in the Highfield suburb, a mainly residential area located to the north of the city centre.

For the purposes of the data collection, and as part of previous work [8], a 3.2 km long route to be cycled using the iBike was determined. This consisted of a sequence of 70 road links/sections or roughly equal length (~45 m), each containing different road features, whose impact on cyclist behaviour was explored. The full route, illustrated in Figure 2, was broken down into three stages. No data were collected along the stretch between the end of Stage 2 and the start of Stage 3, as it was a shared footpath with no relevant features.



Source: Ordinance Survey Source: Google Maps

Figure 2: Left: Selected route, with stages 1(red), 2 (blue) and 3 (green). Right: constituent links/sections

Classification of pavement surfaces and defects

The route was also ideal for investigating the effect of pavement characteristics on cyclist behaviour, as the constituent road sections comprise a good mix of main and residential roads with various surfaces, defects and features, some of which are shown in Figure 3. A detailed visual survey was carried out, and the following surface materials that were identified: Hot Rolled Asphalt (HRA), Stone Mastic Asphalt (SMA), stone pavers, and short segments of block paving. High Friction Surfacing (HFS) was also identified on several of the pavement surfaces, and especially in lanes approaching junctions and on cycle lanes. Of these, only HRA, SMA and HFS (Figure 4) were recorded and matched onto the route's sections. This was because block paving and stone pavers have limited presence in the site.

The visual survey also identified several pavement defects, including rutting, cracking, fretting and ravelling of varying severity. However, the majority of the defects identified were minor and would, likely, not be classed by many local authorities as severe enough to warrant repair. Previous studies into pavement defects and cyclists largely focused on the most severe defects, such as potholes [11-13], with less severe defects and features, such as patching, trench reinstatement, and cracking around maintenance holes, having rarely been investigated. All of these defects were present along the sampled route, and this research investigated the extent to which they influence cyclist behaviour.

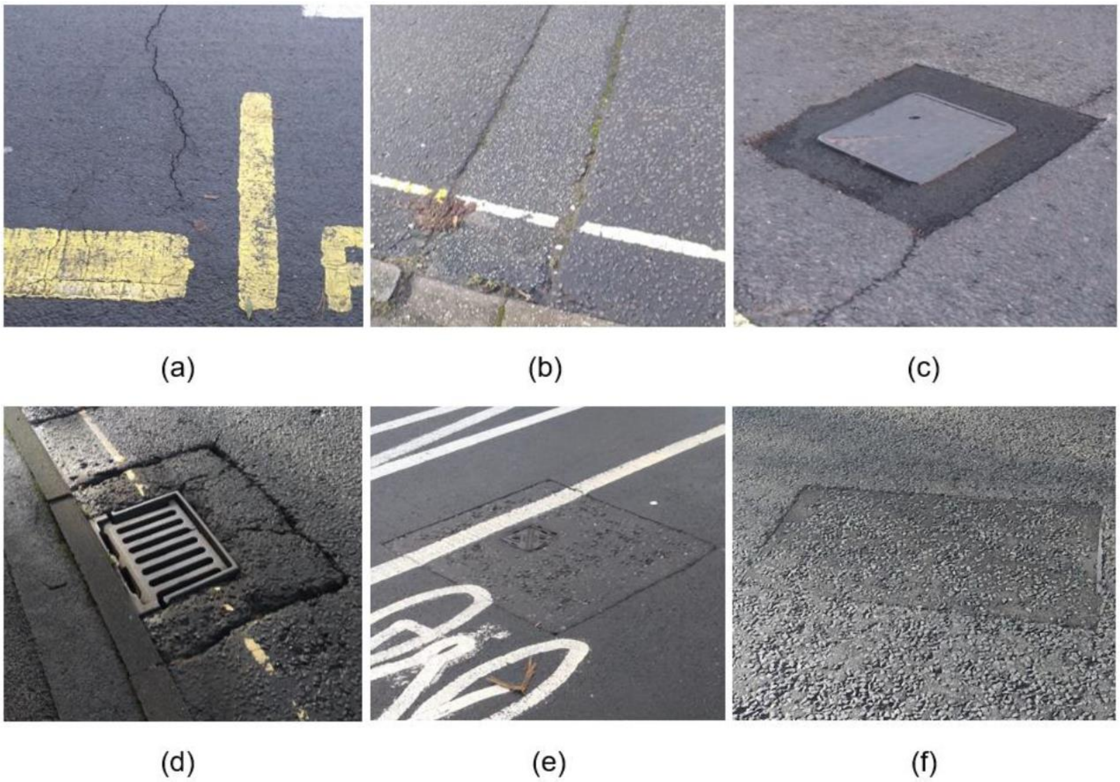


Figure 3: Some of the pavement characteristics identified, including: (a) a transverse crack; (b) a transverse trench reinstatement; (c) cracking around a maintenance hole cover; (d) cracking around a drain; (e) cracking around a small cover; and (f) patching.

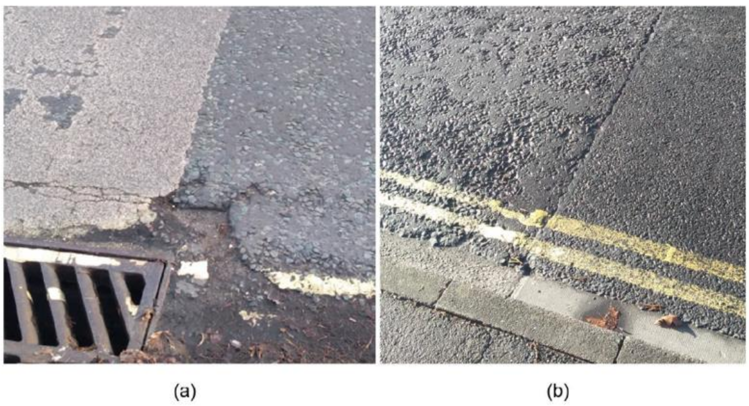


Figure 4: The surface types considered: (a) HFS (left) and HRA (right); (b) HRA (left) and SMA (right)

Various types and categories of defects were considered. Cracks were classified as transverse (perpendicular to the direction of traffic) or longitudinal (parallel), based on the way that cyclists would likely respond to them; for instance, cyclists were more likely to ride over transverse cracks, especially if they occupied a significant road width, but might avoid longitudinal cracks (which could pose a stability risk due to wheels becoming trapped in them). Cracks were further classified as minor or major based on their severity (on the basis of engineering judgement) (Figure 5), and also based on whether they were a result of a trench reinstatement; this was because cyclists would likely exercise greater caution around major cracks than minor ones. Surface cracking and patching were also recorded.

Other pavement features identified included utility covers of different sizes, and these were categorised as: drain covers; maintenance hole covers; and small covers. Cracking around such features, and in particular maintenance hole covers, was also recorded.

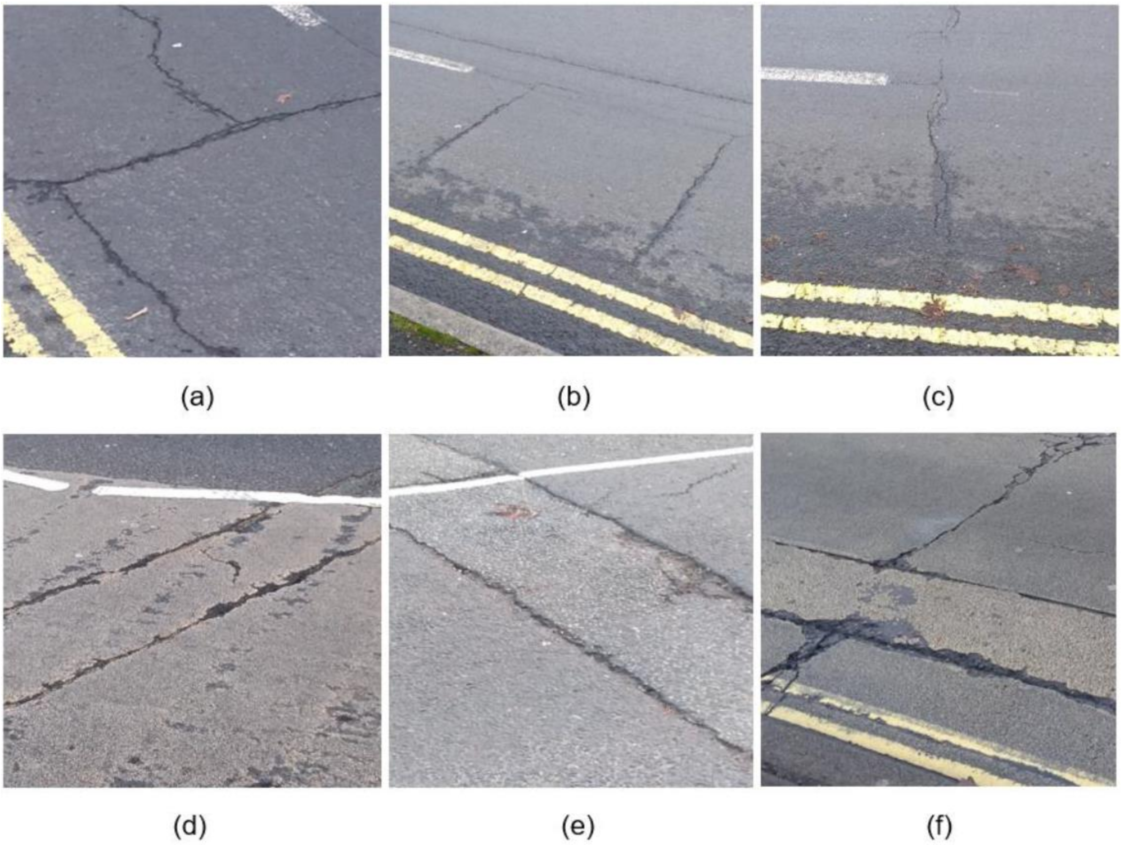


Figure 5: Examples of cracks: (a)-(c) minor; (d)-(f) major

In summary, the following pavement characteristics and defects were considered in the present study:

- Hot Rolled Asphalt (HRA);
- Stone Mastic Asphalt (SMA);
- High Friction Surfacing (HFS);
- transverse crack;
- longitudinal crack;
- minor crack;
- major crack;
- trench reinstatement;
- surface crack;
- patching;
- cracking around maintenance hole;
- maintenance hole cover;
- drain cover; and
- small cover.

Data collection and processing

As part of previous work by the authors [8], 15 test cyclists were recruited from University of Southampton staff and students and from local cycling groups. Care was taken to ensure that the sample included both male and female participants, a variety of age groups, as well different cycling experiences and typical trip purposes.

The data collection took place on selected days in February and March 2020 during daylight hours and in dry weather. Following a brief induction and the collection of some basic demographic data, each participant rode along the specified route accompanied by a member of the research team on a different bicycle. The average duration of a run across the 15 participants was 20 min.

The parameters measured by the iBike included speed, steering angle, and roll angle. Measurements were taken with a frequency of 40 per second and were, then, aggregated at the level of each of the 70 route sections for each run. The mean and standard deviation (SD) of these for each section and run (i.e. for each participant separately, rather than across the sample) were computed, which resulted in the following six variables describing cyclist behaviour:

- *mean speed*, providing a measure of confidence (with faster speeds indicating greater confidence);
- *SD of speed*, showing how smooth the ride was (with high values pointing to a jerkier ride with successive accelerations and decelerations or stops);
- *mean effective steering angle* (i.e. the angle formed by the front wheel and the frame), which expressed the bicycle's deviation from the straight line (with higher values away from junctions potentially indicating the avoidance of obstacles);
- *SD of effective steering angle*, which described how agile the ride was (with higher values indicating more agile cycling with many turns within a short distance);
- *mean roll angle*, which is another measure of cyclist confidence (with higher values indicating greater confidence, as expressed by tilting more to counteract centrifugal forces at higher speeds); and
- *SD of roll angle*, which, again measured cyclist confidence as well as ride stability (with higher values suggesting more frequent tilts, which could be an indication of a confident cyclist swerving around obstacles, but also of "wobbling").

3 ANALYSIS AND RESULTS

Data and analysis methodology

The 15 participants cycling over each of the 70 sections of the study route delivered 1050 measurements (one per participant and section). However, due to a small number of sensor malfunctions some measurements were excluded. As a result the total number of measurements considered in the analysis was 972.

The analysis used inferential statistics in order to identify formal relationships between the six dependent variables specified (namely mean and standard deviation of speed, effective steering angle and roll angle) and a set of independent variables that included the 14 pavement characteristics and defects identified in Section 2, alongside the demographic attributes and highway features identified in [8]. In order to ensure comparability between attributes and models, all categorical independent variables were converted to dummy binary ones.

The analysis proceeded by fitting six multiple linear regression models, each one having each of the six cyclist behavioural attributes as the dependent variable and all of the pavement characteristics and defects, alongside the demographic parameters and highway features explored in [8], as potential predictors. The six cyclist behavioural variables were continuous and non-negative and could be reasonably assumed to co-vary with the field data, and so multiple linear regression was an appropriate modelling candidate due to its advantage of simplicity. The suitability of the linear form was confirmed through comparison of the coefficients of determination (R^2) of each of the six models with corresponding multilayer perceptron feed-forward artificial neural networks with two hidden layers trained with the same data.

Results and interpretation

A summary of the results of the six linear regression models is shown in Table 1, whereby each column corresponds to a different model and behavioural parameter, and the signs indicate any associations (positive or negative) and their magnitude. Only the effects of the pavement defects and characteristics are reported here, as the effects of demographic attributes and road features were examined in the authors' previous work [8]. It is noted that the variables relating to HRA, transverse cracking and longitudinal cracking were dropped in all six models due to collinearity.

Table 1: Summary of models, relating behavioural parameters (across) with pavement defects (down)

	Speed (mean)	Speed (SD)	St. angle (mean)	St. angle (SD)	Roll angle (mean)	Roll angle (SD)
SMA	– – –	+ + +	·	+ + +	·	·
HFS	– –	+ +	·	·	+ +	·
Minor crack	·	·	·	·	–	·
Major crack	– –	+ + +	·	+ +	– –	·
Trench reinstatement	+ + +	– –	+	– –	+ +	+ + +
Surface crack	+	– –	+ +	·	·	·
Patching	·	–	+	·	–	+ +
Crack around maint. hole	·	+ +	·	·	·	+ + +
Maintenance hole cover	+	– –	·	·	·	·
Drain cover	·	·	– –	·	·	–
Small cover	+	– –	·	–	·	·

(+) positive association; (–) negative association; (·) no statistically significant association at the 5% level

The results are discussed next for each behavioural parameter separately.

Speed

The results of the mean speed model indicate that both SMA and HFS surfaces led to lower speeds. This may suggest that cyclists felt either less comfortable riding at greater speeds on these surfaces or were unable to due to greater surface friction. Major cracks were also associated with lower mean speeds, supporting the conjecture that cyclists generally ride slower where there is a greater potential of hazard [14-15]. This conjecture, however, was contradicted by the coefficients for trench reinstatement, maintenance hole covers, small covers and surface cracks, which correlated with higher mean speeds. This could be because cyclists may have perceived these characteristics as less hazardous than major cracks, and subsequently exercised less caution around them.

In terms of the speed SD, both SMA and HFS had positive effects. For HFS, this may be explained by its common presence before junctions, where cyclists often had to slow down. For SMA, however, this was an unexpected finding that could not be justified by the site conditions and needs to be investigated further. Furthermore, major cracks and cracking around covers were similarly associated with a greater speed SD, and this could suggest that cyclists took caution when encountering these defects by reducing their speed momentarily. Trench reinstatements, maintenance hole covers, small covers, patching and surface cracks, on the other hand, seemed to have the opposite influence. It could be argued that cyclists did not perceive these features as hazards, as was also suggested by the mean speed model, and therefore made no adjustment to their speed. In particular, the effect of maintenance hole covers is also supported by findings of previous research [11].

Steering angle

Considering the models relating to steering, it is noted that the steering angle can take both positive and negative values, depending on whether the bicycle turned left or right, respectively. This means that in the mean steering angle model, it is the magnitude of the model coefficients, rather than the sign, that determines whether an effect was positively or negatively associated with the dependent variable. High positive or low negative values suggest a positive association (i.e. more steering), with the sign indicating whether steering was more towards the left (positive) or the right (negative); values around zero, on the other hand, whether positive or negative, denote a negative, though not necessarily weaker, association.

Looking at the different associations, drain covers had a positive effect on the mean steering angle (with a negative coefficient significantly lower than zero), suggesting that cyclists may have seen drain covers as a potential source of hazard or discomfort and, therefore, actively avoided them (albeit without altering their speed). On the other hand, trench reinstatements, surface cracking and patching had negative effects (coefficient values around zero), suggesting that cyclists did not divert from their course to avoid them.

Considering the model of the steering angle SD, and according to previous research [13], cyclists were expected to steer around defects or features to avoid them, but based on this analysis, major cracks were the only pavement characteristic exhibiting this effect with a positive coefficient. On the other hand, trench reinstatements and small utility covers had negative effects, suggesting that riders maintained steady steering when encountering them, potentially to reduce the risk of their wheels getting caught in them. Finally, the significance of SMA as a predictor is consistent with the above findings regarding mean speed, whereby less steering was required to keep the bicycle stable.

Roll angle

Considering the mean roll angle model, strong positive effects by HFS, major cracks and trench reinstatements were identified. These were all associated with either higher speeds, or higher speed variability, which explains more tilting. Especially major cracks could be seen as potential hazards by cyclists, and could result in tilting while swerving around them to avoid them. On the other hand, minor cracks and patching had negative effects on tilting, which was consistent with their negative or insignificant effects on speed and steering.

Regarding the roll angle SD model (with the nature of the effects being determined by the sign, given that SD only takes positive values), significant positive effects were identified by trench reinstatements, patching and cracking around utility covers. For trench reinstatements, this can be explained by the cyclist's higher speed when avoiding them, requiring them to frequently alter their tilt. For patching and cracking around utility covers, on the other hand, the explanation lies in the low or insignificant effects of these features on the mean roll angle, which suggest that, despite their high coefficients, their actual effects on cyclist behaviour are small. Last but not least, drain covers had a negative effect on the roll angle variability; in conjunction with the strong positive effect on the mean steering angle and the insignificant effects on the other measured variables, this suggests that cyclists would have only taken last-minute and possibly spasmodic evasive actions in response to drain covers, without prolonged significant alterations to their speed or their tilt.

4 CONCLUSION

The present study analysed data collected from a number of test cyclists along a study route in Southampton using the iBike instrumented bicycle in order to explore the impact of pavement characteristics and defects on cyclist behaviour. Relevant linear regression models relating six behavioural attributes with a series of pavement features were derived. The results highlighted significant positive and negative effects, which policy-makers and stakeholders can take on board in the design of cyclist facilities and road infrastructure.

But while this study shed some light into the under-explored topic of the relationship between pavement features (and defects) and cyclist behaviour, there are limitations and work in this direction continues. Future research will concentrate on analysing the trajectory collected using data fusion and filtering in order to eliminate measurement errors and allow pinpointing the cyclist's actions to specific features rather than aggregated at the road section level. It is also planned to collect data from more cyclists and different road sites, in order to further generalise the findings. Finally, it is intended to implement the iBike approach in a smaller portable replicable device that would allow collecting data from multiple cyclists at the same time.

ACKNOWLEDGEMENTS

The authors would like to thank Southampton City Council for their support in recruiting participants and Transport for London for supplying the Santander Cycle used. Special thanks also go to Iain MacGregor for his invaluable help in the identification and classification of pavement surfaces, features and defects.

REFERENCES

[1] Transport for London. *Santander Cycles*, 2023. https://tfl.gov.uk/modes/cycling/santander-cycles.

[2] Transport for London. *Cycleways*, 2023. https://tfl.gov.uk/modes/cycling/routes-and-maps/cycleways.

[3] Southampton City Council. *Cycling Southampton – a Strategy for Our City 2017-2027*, 2017. https://transport.southampton.gov.uk/media/1071/cycle-southampton-strategy-2-page-final.pdf

[4] UK Department for Transport. *Reported road casualties in Great Britain: annual report 2022*, 2023. https://www.gov.uk/government/statistics/reported-road-casualties-great-britain-annual-report-2022/reported-road-casualties-great-britain-annual-report-2022

[5] A. Gadsby, J. Tsai, K, Watkins. “Understanding the influence of pavement conditions on cyclists’ perception of safety and comfort using surveys and eye tracking”, *Transportation Research Record*, vol. 2676(12), pp. 112-126, 2022.

[6] S. Jones. “Potholes: the true cost to cyclists”, *We are Cycling UK*, 2019. https://www.cyclinguk.org/press-release/potholes-true-cost-cyclists

[7] UK Department for Transport. *Cycle infrastructure design (LTN 1/20)*, 2020.

[8] I. Kaparias, S. Miah, S. Clegg, Y. Gao, B. Waterson, E. Milonidis. “Measuring the effect of highway design features on cyclist behavior using an instrumented bicycle”, 7th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS 2021), virtual, 2021.

[9] S. Miah, E. Milonidis, I. Kaparias, N. Karcanias, “An innovative multi-sensor fusion algorithm to enhance positioning accuracy of an instrumented bicycle”, *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, pp. 1145-1153, 2020.

[10] S. Miah, I. Kaparias, N. Ayub, E. Milonidis, W. Holmes, “Measuring cycle riding comfort in Southampton using an instrumented bicycle”, 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS 2019), Krakow, Poland, 2019.

[11] D. Walton, J. Thomas. “The influence of pathway obstacles on cyclist behaviour”, *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice*, vol. 16, p. 60-72, 2007.

[12] J. Calvey, J. Shackleton, M. Taylor, R. Llewellyn. “Engineering condition assessment of cycling infrastructure: Cyclists’ perceptions of satisfaction and comfort,” *Transportation Research Part A*, vol. 78, pp. 134-143, 2015.

[13] X. Qian, J.K. Moore, D. Niemeier, “Predicting bicycle pavement ride quality: Sensor-based statistical model”, *Journal of Infrastructure Systems*, vol. 26, p. 04020033, 2020.

[14] A. Kassim, K. Ismail, S. Woo. “Modeling cyclists speed at signalized intersections: Case study from Ottawa, Canada”, 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Naples, 2017.

[15] H. Jashami, D. Cobb, D.S. Hurwitz, E. McCormack, A. Goodchild, M. Sheth. “The impact of commercial parking utilization on cyclist behavior in urban environments”, *Transportation Research Part F*, vol. 74, pp. 67–80, 2020.