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DOI

[10.1016/j.jtrangeo.2020.102932](https://doi.org/10.1016/j.jtrangeo.2020.102932)

Publication date

2021

Document Version

Final published version

Published in

Journal of Transport Geography

Citation (APA)

Gadsby, A., Hagenzieker, M., & Watkins, K. (2021). An international comparison of the self-reported causes of cyclist stress using quasi-naturalistic cycling. *Journal of Transport Geography*, 91, 1-10. [102932]. <https://doi.org/10.1016/j.jtrangeo.2020.102932>

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An international comparison of the self-reported causes of cyclist stress using quasi-naturalistic cycling

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ABSTRACT

This study explores the influences of attitudes and setting on cyclists' stated causes of stress using survey techniques and quasi-naturalistic cycling in both Delft, The Netherlands and Atlanta, Georgia, USA. The study recruited 28 participants in Delft and 41 in Atlanta. Participants cycled approximately 30 min on specified routes in both cities on an instrumented bicycle. Prior to cycling, the participants filled in a written survey about their cycling habits, attitudes, and demographics. At specified points during and after the ride, participants were interviewed about their stress levels throughout the ride and the causes of those stress levels. Thematic analysis and statistical methods are used to understand the interactions of setting (country), attitudes, stated stress, and sensor data. The top three stressors were motor vehicles, pavement, and poor infrastructure; 83% of participants mentioned a motor vehicle causing stress, 64% mentioned road surface, and 58% mentioned infrastructure. The results confirm the importance of motor vehicle interaction to cyclist stress, but also highlight some new insights on stress such as the importance of pavement condition. Speed differentials between cyclists and vehicles were also shown to be important and suggested cyclists in Delft felt comfortable to travel their ideal speed. This speed preference was supported by GPS data that showed the cyclists in Delft were cycling at speeds about half (12 kph) that of the cyclists in Atlanta (24 kph). Review of close-pass events demonstrated that cyclists in Delft were more comfortable with closer passes which could be associated with their belief that motorists notice them and/or speed differences between the vehicle and bicycle. The results also suggest that number of vehicle travel lanes can have mixed impacts on cyclist stress. These findings can be taken into consideration when designing bicycle facilities to create low-stress cycling networks.

1. Introduction

Designing a low-stress cycling network is critical to encouraging cycling. There have been many studies on the causes of cyclist stress and stress/comfort-based rating systems, but there is still room for improvement in our understanding of cyclist stress. This study uses a new combination of quasi-naturalistic cycling, instrumented bicycles, and near real-time interviews to add to the existing body of knowledge on the causes of cyclist stress.

One major component of the existing literature on cyclist stress is stress/comfort-based rating systems for projects and road segments. The most widely known are Bicycle Level of Service (BLOS), Bicycle Compatibility Index (BCI) and Level of Traffic Stress (LTS). The designers of BLOS used cyclists' comfort ratings on roads with a variety of characteristics to develop their rating system. Significant variables include traffic volumes, number of through lanes, lane width, speed limit, volume of heavy vehicles, and road surface condition, among others (Landis et al., 1997). BCI was a parallel effort that used video clips to identify roadway characteristics' compatibility with cycling. BCI includes bicycle facility presence, width, vehicular volumes, speed, and

presence of parking (Harkey et al., n.d.). Both BLOS and BCI require intensive data collection and complicated equations that do not easily show the relationships between each component and the result. This makes them challenging to calculate network wide. LTS (Mekuria et al., 2012) was an attempt to make a rating system that was more user-oriented and applicable across a network. The designers based the classification levels on a system similar to Geller's four types of cyclists (Geller, 2006), and the distinction between categories are based on Dutch design practice rather than through experiment (Furth et al., 2016). LTS variables include bicycle facility presence and width, parking presence, speed limit, bicycle lane blockage, and number of lanes (Mekuria et al., 2012). These rating systems suggest that road lane width, presence of parking, vehicle speeds, vehicle volumes, number of vehicle lanes, and bicycle facility presence are important factors in cyclist stress. However, these scales were developed based on post-ride video review, surveys about comfort, and assumptions from the literature, rather than data collected on real-time stressors identified by participants.

Additional studies have further explored causes of cyclist stress. These studies have found that time of day (Nuñez et al., 2018),

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separation from motor vehicles (Caviedes and Figliozzi, 2018), dedicated bicycle infrastructure (Pikora et al., 2003; Heesch et al., 2012; Chataway et al., 2014), and traffic volumes (Vandenbulcke et al., 2011) are important influences on cyclist stress. Studies on cyclist stress are often exclusively survey or interview-based (Harkey et al., n.d.; Pikora et al., 2003; Heesch et al., 2012; Chataway et al., 2014). By choosing to conduct interviews and surveys outside of the cycling experience, studies become dependent on recall which diminishes with time, can require prompting, and may be less specific than surveying in real-time (Sudman and Bradburn, 1973; Reitman, 1974; Bahrick, 1969). Although there is some evidence that surveys in combination with a video can provide similar results for comfort and safety ratings as an in-person experience (Fitch and Handy, 2018), there is not yet evidence that cyclists would identify the same stressors without the additional cues an in-person riding experience offers.

Some studies combine quasi-naturalistic cycling methods with a rider characteristics focused survey, including demographics and transportation attitudes (Nuñez et al., 2018; Caviedes and Figliozzi, 2018; Vandenbulcke et al., 2011; Feizi et al., 2019; Fitch et al., 2020). Naturalistic cycling studies allow participants to cycle as they normally would without any set routes. Quasi-naturalistic studies put some limitations on naturalistic cycling, typically in the form of a specified route (Gadsby and Watkins, 2020). Both Yamanaka et al. (Yamanaka et al., 2013), who developed a bicycle to measure BLOS, and the developers of the BLOS (Landis et al., 1997) did couple quasi-naturalistic cycling with short surveys identifying the participants' stress levels during the ride. However, the participants themselves did not get to define the stressors, only their level of stress. By using quasi-naturalistic cycling methods without an interview portion to inquire why the cyclist was stressed, the defining of stressors is left to the researchers. Both interviews/surveys outside of a cycling experience and stress ratings mid-ride without a participant explanation for that rating result in top-down definitions of stressors. This results in stressors defined by the assumptions of the survey designers or data analyzers, limiting the scope of potential stressors.

Therefore, this study explores what may happen if the cyclist is able to define their own stressors through the combination of quasi-naturalistic cycling with near real-time interviews to find the gaps in researchers' assumptions of what causes cyclists' stress. To broaden the study, data were collected in both Atlanta, Georgia, USA and Delft, The Netherlands to gain perspective on stressors in what is often considered traditionally high- and low-stress environments for cyclists. Through this unique study methodology that allows for cyclists themselves to define their stressors, this international comparison aims to explore what cyclists find stressful to fill methodological gaps in the literature. Ultimately, the findings can inform design choices for low-stress bicycle facilities.

2. Method

The experiment that is the subject of this paper consisted of each participant cycling 25–30 min along a specified route. The participants rode an instrumented bicycle equipped with a variety of sensors including GPS, LiDAR, and cameras and filled out a survey about their stress levels, attitudes about transportation, characteristics as a cyclist, and demographic information. The following section provides greater detail about the methods used in the study.

2.1. Locations

The experiment was conducted in Atlanta, Georgia in the United States and Delft, Zuid-Holland in the Netherlands. The city of Atlanta has a population of approximately 500,000 people with approximately 6 million people in the metro area. As of 2016, Atlanta had a bicycle modal share of 1.4% (Bottoms, K. L. CITY OF ATLANTA, 2017). Delft is a smaller city in the Netherlands with a population of approximately

100,000 people. The Netherlands has a national bicycle modal share of just over 25% (Harms and Kansen, 2018). In urbanised areas in the Netherlands, such as Delft, bicycle modal shares of almost 40% for trips between 1 and 7 km are common (Jonkeren et al., 2019). The Dutch have been improving their cycling network since a reversal from car-oriented policies in the 1970's (Pucher and Buehler, 2008). In contrast, Atlanta began to emphasize bicycles as a mode of travel with the conception of the multimodal circulator trail, the Beltline, in 2012, and has steadily increased the bicycle network since (*How Atlanta Is Gradually Becoming a Bona Fide Bike-Friendly City - Curbed Atlanta*, n.d.). Atlanta was assumed to represent a high stress cycling environment and Delft a low stress cycling environment based on their cycling traditions. These two cities were selected due to the home base of the universities in each location as part of a larger study on the influence of cyclist stress on behaviour. The contrast is expected to highlight the similarities in cyclist stress across environments. To keep some consistency in the environment for participants, the study routes within the cities were designed based on the same guidelines.

2.2. Study route design

The study routes were designed to cover a variety of infrastructure and land uses, as could be reasonably found within each city. All routes were circuitous and designed to minimize left turning movements. Four routes were chosen around Atlanta to encourage participation and allow participants to choose a familiar route, however the small city of Delft required only one route. All Atlanta routes had more vehicular interaction than the Delft route as Dutch design standards separate cyclists and motor vehicles above 30 kph and discourage car use in the inner city (de Groot, 2007). However, both locations had route segments with unprotected bicycle lanes and mixed traffic. Maps with color-coded infrastructure of the Delft route and the most frequently used Atlanta route are shown in Fig. 1. Based on the LTS rating system, the route through Delft varied from LTS 1 to LTS 2 and the Atlanta routes LTS 1 to LTS 4. Although the routes were designed using similar principles, the availability of high stress infrastructure in Delft was very low. Therefore, it is expected for stress levels to be lower in Delft.

Familiarity was surveyed in both locations. An open-ended question was used in Atlanta but changed to a Likert-scale question in Delft. Although not perfectly comparable, most cyclists were very familiar with at least a portion of the route and familiar to very familiar with the entire route. Based on the responses, the researchers feel safe assuming that route familiarity was similar across the two samples.

2.3. Recruitment/participants

In total, there were 41 participants in Atlanta and 28 in Delft. Participants were recruited via convenience sampling through e-mails and fliers. Participants were asked to cycle one time in Atlanta, but to capture within-person differences, when possible, two times (off peak and peak hour) in Delft. In Atlanta, the participants were able to choose the time that fit their schedule best, resulting in 56% of rides done during peak hours. In Delft, 52% of rides occurred during peak hours. Ten participants in Delft were given 10-euro gift cards as compensation for participation. This was added mid-way through recruitment to encourage participation.

2.4. Instruments

Similar instrumentation, both in terms of surveys and sensors, were used in Atlanta and Delft. The instrumented bicycle in Atlanta consisted of two components that attach to the participant's bicycle. The components included a variety of sensors, but those used in this study include GPS and LiDAR. The instrumented bicycle in the Netherlands had a similar sensor set-up including GPS and LiDAR, but these were affixed to one bicycle that was ridden by all participants. Images of each

Fig. 1. Infrastructure map of the Delft route (left) and an Atlanta route (right).

of the instrumented bicycle setups are shown in Fig. 2.

All survey questions used in Atlanta were also used in Delft with small adjustments to address changes in location (“Atlanta” changed to “Delft”) and structures (i.e. level of education). The familiarity question was adjusted after data collection in Atlanta from an open-ended question to a Likert-scale to be more consistent and comparable for future data collection.

The survey consisted of two parts. The first part asked questions about the cyclists’ cycling habits (frequency, time cycling, etc.) and attitudes (risk taking preferences, trust of car drivers, etc.). The second part asked demographic questions such as gender identification and education level. One of the key rider characteristic questions asked cyclists to categorize themselves by a rider type defined by interest and confidence in cycling. This scale was originally defined by Geller in Portland to categorize people by what level of infrastructure was needed for them to cycle (Geller, 2006). It included 4 categories: “Strong & Fearless,” “Enthusiased & Confident,” “Interested, but Concerned,” and “No Way, No How.” The “Strong & Fearless” cyclists would be willing to cycle on any roadway. The required infrastructure then increases up to “Interested, but Concerned” cyclists who need full separation from motor vehicles. Misra et al. (Misra et al., 2015) refined the categories to include a category in the middle called “Comfortable, but Cautious.” This refined scale was used for this study. The “No Way, No How” category was excluded because these people would not be willing participants in a study requiring cycling. The attitudinal questions were borrowed from a study that explored user preferences for bicycle

infrastructure in emerging cycling cities and the attitudes that influence those preferences (Clark et al., 2019).

During the ride, the cyclist was asked to color-code by stress level (low, moderately-low, moderately-high, and high) a map of the recently ridden segment of the route. To reduce recall error, the map was color-coded at two points during the ride and at the end. The post-ride interview inquired about the map to understand why the cyclist gave the stress ratings they gave. The data gathered in this format was the basis for the thematic analysis.

2.5. Protocol

The protocol of a data collection appointment started with consent forms, as approved by the human research ethics boards for both universities. Following consent, the written survey was filled out by each participant. Prior to the appointment, the participant was provided a map of the route, and the route was reviewed before the sensors were set up. Once the sensors were prepared and the participant was comfortable, the ride began. The participant cycled in front with the researcher behind in case of emergencies, sensor failure, and to give directions as needed. The participant was encouraged to not interact with the researcher and cycle as they normally would cycle. The participant and researcher stopped at two pre-designated locations along the route to color-code the map based on their stress levels and review the directions for the next segment of the route. Once the whole ride was complete, the researcher removed the sensors and conducted the post-ride interview.

Fig. 2. Left: Instrumented bicycle used in Delft with the sensors used in this paper identified. Right: Instrumented bicycle components used in Atlanta on the researcher’s bicycle with the sensors used in this paper identified.

2.6. Analysis method

The analysis was conducted using mixed methods. Quantitative statistical analysis primarily consisted of Mann Whitney testing of the demographic and attitudinal differences in the samples. Such quantitative analysis was limited due to the small sample size in each location. To supplement the quantitative analysis, thematic analysis was used to identify and describe attitudes and ideas in interview responses. Thematic analysis is used in the field of transportation engineering to analyze open-ended survey questions (Davison, 2016), interviews (Ashmore et al., 2018; Heinen and Handy, 2012), and focus groups (Fishman et al., 2012). Braun and Clarke's article on thematic analysis was used as a guide for this analysis (Braun and Clarke, 2006).

Braun and Clarke suggest four phases of thematic analysis: data familiarization, generating initial codes, finding themes, and reassessing themes (Braun and Clarke, 2006). To familiarize themselves with the data, the researchers repeatedly read the data. After familiarizing, initial codes were generated to describe interesting topics in the data. The participants' responses were coded as short phrases (i.e. low traffic, smooth road surface, negative response to motor vehicles, etc.). More than one code was possible per response as participants may list more than one reason for their stress rating. The codified responses were compiled by participant. In total, 43 codes were generated. Then, themes were generated from the codes by grouping and consolidating them to a list of themes. After finding the themes, they were reassessed for coherence. To ensure the analysis was performed in a systematic manner, it was checked by two other researchers and adjusted accordingly.

An inductive (bottom-up) and semantic approach was taken to identifying themes. This means the themes were identified through exploring the responses, not from theoretical, existing knowledge found in the literature. Once the thematic analysis was complete, quantitative results from the written surveys were paired with the themed interview responses to explore the relationships of cyclist characteristics and attitudes with stated causes of stress. In addition, the instrumented bicycle data (GPS and LiDAR) were used to support the findings in the quantitative and thematic analyses.

2.7. GPS and LiDAR

GPS and LiDAR were equipped to both instrumented bicycles. The GPS provided location and speed data and LiDAR provided the distance to the nearest object to the left. The LiDAR were in approximately the same position on both bicycles, as shown in Fig. 2. The GPS data were used to find cyclists' point speed to better understand riding speed in relation to stress. The LiDAR data was used to identify close-passes (a reading of under 1000 mm). Video data corresponding to these potential close-pass events were reviewed to confirm the close-pass events. Then the close-pass locations were compared with the stress maps and survey responses to explore any potential relationship between attitudes, characteristics, and stress ratings to a close-pass event.

3. Results

This section covers the results from the various analyses. First, the multiple-choice responses and reported stress levels are presented. Second, the interview responses analysed through thematic analysis are discussed. Then both analyses are combined to explore relationships between participants' multiple-choice responses and stated causes of stress. Finally, the sensor data from the instrumented bicycle are used to tie findings in the previous results subsections to objective data.

3.1. Multiple-choice responses

Although the sample in Delft primarily consisted of graduate students from TU Delft, the two samples had similar demographic

breakdowns. Mann-Whitney tests were used to find which demographic and attitudinal questions revealed a difference in the sample. Due to the small sample sizes, some true differences may not reach statistical significance. The comparisons here are meant to improve understanding of the samples, but the differences in samples and the differences in location suggest that the responses from the two samples cannot be strictly compared.

The sample was about 2/3 male and nearly all possessed the equivalent of a bachelors (25%) or graduate degree (71%). In terms of demographics, the only statistically significant difference between Atlanta and Delft was in age ($U = 21$, $p = 0.04$). The genders, tested with a Fisher's Exact test ($p = 0.57$) were not significantly different.

The Atlanta sample had a more even spread of ages with more people above 34 years old, although both samples had the largest group in the 25–34 age range (82% in Delft and 31% in Atlanta). In the Netherlands, people were asked to ride during peak and off-peak hours, making it challenging for people with day jobs and thus, attracting more student-aged participants. To ensure this age difference did not influence the results, the results in the thematic analysis were compared by age within the Atlanta sample, showing no systematic difference in themes. Based on this finding, the authors chose not to explore age further.

When questioned about rider type, the Atlanta sample had more cyclists rating themselves as "Strong & Fearless" (39%) than the Delft sample (15%) with more people selecting "Enthusied & Confident" in Delft (68%). Just under 20% in both locations chose "Comfortable, but Cautious," and none chose the "Interested, but Concerned" category. The differences did reach statistical significance ($U = 21$, $p = 0.04$). Fig. 3 displays the distribution of the responses.

The two samples had similar cycling experience ($U = 10$, $p = 0.12$) with almost all participants learning to cycle as children. The Delft sample cycled for commute purposes more frequently ($U = 21$, $p = 0.03$), but both samples primarily consisted of regular bicycle-commuters. This is an expected bias through self-selection into the experiment. The "Less than Once per Month" participants, all in Atlanta, were checked for differences in their identified themes, but no systematic difference was found.

Of the ten attitudinal questions in the survey, four showed statistically significant differences. The results for the attitudinal questions are shown in Fig. 4 with Delft on the left and Atlanta the right. The samples did not differ in their tendency towards risk-taking and their preference for alternative modes.

The questions on which they did differ were related to their motivations for cycling and their opinion of other road users. The most statistically significant difference ($U = 49$, $p = 0.008$) was that cyclists in Delft tended to disagree more with the statement "Most Drivers Don't Seem to Notice Cyclists." The importance of this difference will be explored in the next sections (3.3, 3.4). The samples also differed statistically on the importance of exercise ($U = 21$, $p = 0.03$), estimation of cyclists' regard for their own safety ($U = 21$, $p = 0.03$), and whether their friends or family cycling with them would make them more likely to cycle ($U = 45$, $p = 0.009$). These latter three could be associated with the higher cycling modal share in the Netherlands.

Overall, the samples do differ, but these demographic differences do not seem to be the primary influence on the themes stated in their interviews. Age and commute frequency were checked, and no clear systematic difference was found in their thematic analyses. The highly statistically significant difference in response to "Most Drivers Don't Seem to Notice Cyclists" will continue to be explored throughout the analysis.

3.2. Comparison of stress levels

As expected, the percentage of segments considered by cyclists as 'low stress' was higher in Delft than Atlanta. The stress ratings by percentage of segments are shown in Fig. 5.

Fig. 3. Distribution of rider type self-classification.

Fig. 4. Results of attitudinal questions for Delft and Atlanta. Asterisks indicate statistical significance level when comparing Delft and Atlanta data (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

3.3. Thematic analysis

3.3.1. Interview thematic analysis

Twelve themes were identified for causes of stress; the most frequently mentioned were motor vehicles, pavement (road surface), and infrastructure. Nine themes were identified for stress reducers; the most frequently mentioned were high quality road infrastructure, low traffic volumes (both motorists and cyclists), and familiarity of the route/environment. Due to the low sample size and sample differences,

Atlanta and Delft were not quantitatively compared, but compared qualitatively to highlight interesting results. Table 1 shows the percentage of participants who mentioned each theme in their interviews.

The top three stressors in each location were not the same. Motor vehicles were the top stressor in both locations. In Atlanta poor road infrastructure (78%) slightly outdid poor road surface (71%). It is notable that poor road infrastructure was mentioned over twice as often in Atlanta (78%) as in Delft (32%). In Delft, poor road surface (54%) was the second most common stressor. However, other cyclists were the

Fig. 5. Distribution of stress ratings by segment for Delft and Atlanta.

Table 1

Summary of the thematic analysis showing percentage of respondents mentioning each theme.

Theme	Delft	Atlanta	Total
Causes of Stress			
Motor Vehicles	68%	93%	83%
Poor Pavement	54%	71%	64%
Poor Infrastructure	32%	78%	58%
High Volume	29%	54%	43%
Anticipation	4%	46%	29%
Speed Differential	18%	34%	28%
Lane Restriction	32%	22%	26%
Surprises	32%	17%	23%
Bus/Truck	21%	22%	22%
Pedestrians	32%	15%	22%
Cyclists	36%	0%	17%
Intersections	14%	10%	12%
Reducers of Stress			
Quality Infrastructure	93%	80%	86%
Low Volume	89%	71%	78%
Familiarity	75%	29%	48%
Speed Differential	29%	41%	36%
Lack of Motor Vehicles	29%	37%	33%
Good Pavement	32%	17%	23%
Ambiance	11%	17%	14%
Lack of Pedestrians	4%	5%	4%
Lack of Intersections	7%	0%	3%

third highest stressor (36%) in Delft with pedestrians, lane restriction, and surprises tied with poor infrastructure (32%) for fourth most common. The differences in percent identifying other cyclists and pedestrians as stressors likely have to do with the relatively higher modal share of cycling and walking in Delft than in Atlanta. Another notable difference was the mention of anticipation, the fifth most common in Atlanta (46%) and least common in Delft (4%). These comments were mostly about the movements of other road users, especially motor vehicles in Atlanta. It is notable that anticipating driver movements was so different given that motor vehicles were the most mentioned stressor in both locations.

The top two stress reducers, high quality infrastructure and low volumes, were the same in both locations. The third highest in Atlanta (41%) was speed differential with familiarity (29%) as the fifth most common. However, familiarity was the third most common in Delft (75%). As mentioned, familiarity with the route was similar between both samples. Nonetheless, to check for the effect of familiarity, all participants who did not rate any segment as very familiar were temporarily removed from the dataset, leaving 30 participants in

Atlanta and 27 in Delft. In this reduced dataset, cyclists in the Netherlands still mentioned familiarity almost twice as frequently (78% in Delft and 40% in Atlanta).

Although the Atlanta participants would have encountered a far larger number of vehicles due to modal share and infrastructure differences, motor vehicles were the most mentioned stressor in both locations. 93% of participants in Atlanta mentioned motor vehicles, and fewer participants, 68%, mentioned them in Delft, which is expected due to higher stress levels and vehicle volumes in Atlanta. Overall, 83% of participants mentioned vehicles as being a cause of stress and 33% specifically mentioned the lack of motor vehicles as being a reducer of stress.

Quality infrastructure was the top stress reducer. 86% of participants mentioned something about the infrastructure as being a stress reducer, many of these mentioning “separation from motor vehicles,” the width of the road, and, in Atlanta, multi-lane roads that allowed vehicles to pass. About ¼ of the participants mentioned restriction of their lane by other road users, labelled lane restriction, such as a close-pass or wrong-way cycling, as a stressor. These results suggest that cyclists appreciate infrastructure that limits their interaction with other road users, especially motor vehicles, and when not possible, provides space to allow for comfortable passing distances.

Infrastructure was both a high-ranking stressor and stress reducer. Infrastructure consists of many components. Therefore, multiple aspects of infrastructure have been broken out in Table 2. Aspects of infrastructure chosen for detailed analysis included: width, number of travel lanes (only relevant in Atlanta), presence of bicycle facilities, and sight

Table 2

More detailed themes showing percentage of respondents mentioning sub-themes within the infrastructure and motor vehicles themes.

Theme	Delft	Atlanta	Total
Causes			
Sub-theme of Motor Vehicles			
Parked vehicles	18%	17%	17%
Sub-theme of Infrastructure			
Narrow	29%	17%	22%
Number of Travel Lanes	0%	10%	6%
No Bicycle Facility	0%	34%	20%
Sight Distance Issue	4%	7%	6%
Reducers			
Sub-theme of Infrastructure			
Wide	11%	12%	12%
Number of Travel Lanes	0%	7%	4%
Bicycle Facility	29%	39%	35%
Good Sight Distance	14%	0%	6%

distance. In addition, the impact of parked vehicles, one aspect of the motor vehicles theme, is also included in the detailed analysis.

As shown in Table 2, the lack of a bicycle facility was never a complaint in Delft but was frequently mentioned in Atlanta (34%). The high mention of narrowness in Delft (29%) was related to a narrowed section from construction along the Delft route. Width overall of the available travel space for cyclists likely varied between the two locations but was mentioned about equally as a stress reducer (~12%). The presence of a bicycle facility was appreciated by both samples and served to reduce stress. Good visibility was mentioned about 14% of the time in Delft, but never in Atlanta. In Delft, sight distance was more important than width to reducing cyclist stress. The number of travel lanes was only slightly more frequently mentioned as a stressor (10%) than as a stress reducer (7%). Common understanding is that number of lanes contributes significantly to stress, but when cycling in mixed traffic, cyclists in Atlanta appreciated that motorists were able to move to another lane to pass them. Both groups mentioned parked vehicles at about the same rates (~17%) and both routes had similar roadside parking availability. Although cyclists in Delft believe drivers notice them more frequently, they seem to have similar wariness around parked vehicles as Atlanta cyclists.

For this analysis, the speed differential theme was defined as a mention of either their own speed or the speed of other travelers. Just over ¼ of participants mentioned speed differentials as a stressor and even more (36%) mentioned it as a stress reducer. Higher speed differences were associated with higher stress. Although both sets of participants mentioned speed, Atlanta cyclists mentioned it about twice as frequently and the focus of the comments differed between the two samples. In Delft, the comments were about the cyclists being able to keep (or not keep) their preferred speed. For example, one cyclist in Delft said the reason for their low stress rating on all segments was the “chill speed so [they] had more time to analyze and anticipate.” In contrast, in Atlanta the responses were about the speed of the vehicles. For example, stress was reduced by “lots of stop signs to slow cars,” “stop and go traffic,” and “traffic flow going [participant’s] speed.” Stress was increased by “fast cars”. Both perspectives ultimately reveal that cyclists are less stressed by low speed differentials and not be pressured by speed differentials to deviate from their ideal speed.

It is also worth noting that ambiance was mentioned by 11% of cyclists in Delft and, even more, 17% in Atlanta. Ambiance included comments about their surroundings unrelated to the immediate transportation needs such as having trees along the path or a nice view.

Although not a main stress reducer, it was mentioned without prompting suggesting it is a factor in cyclist stress and could warrant future study.

3.3.2. Combining interviews with attitudes

By combining interview responses with the attitudinal questions in both locations, we examined relationships between cyclists’ attitudes or rider type to their stated stressors. The low cell frequencies do not allow for statistical testing but suggest some interesting associations that could be further investigated with larger samples.

The first relationship explored was between how people responded to “Most Drivers Don’t Seem to Notice Cyclists” and mention of motor vehicles as stressors. Fig. 6 breaks down the results by location with the bars displaying the number of people who mentioned motor vehicles as stressor in each location grouped by their response to the attitudinal question. Of those agreeing or neutral to this statement, 97% mentioned a motor vehicle. However, of those disagreeing with this statement only 64% mentioned a motor vehicle. This suggests that cyclists who disagree with “Most Drivers Don’t Seem to Notice Cyclists” may be slightly less likely to mention a motor vehicle as a stressor. However, with more cyclists in Atlanta agreeing and in Delft disagreeing, this could also be related to regional differences.

The second relationship explored was between rider type and mention of motor vehicles, including buses and trucks, as a stressor. No obvious relationship existed with about even percentages (~70–80%) in each category in both places. Ultimately, motor vehicles appear to be a stressor for most people.

The third relationship was between rider type and mention of the infrastructure as either a stressor or stress reducer. There did not seem to be any obvious trend suggesting that “Strong & Fearless” cyclists mentioned infrastructure more or less than the “Comfortable, but Cautious” riders.

Three more relationships were explored to understand why almost exclusively, cyclists in Atlanta anticipated other road users’ movements. Although in Delft cyclists were surrounded by other cyclists, they did not report anticipating cyclist movements at the rate Atlanta cyclists anticipated driver movements. This suggests Delft cyclists were confident in predicting the movements of other cyclists, but Atlanta cyclists were not confident in predicting motorists’ actions. We decided to explore what characteristics of Atlanta cyclists correlated with commenting about anticipating a driver movement. Rider type, responses to “Most drivers don’t seem to notice cyclists,” and commute frequency were compared. Rider type and the attitudinal response did not show a relationship with

Fig. 6. Number of people responding to each category of “Most Drivers Don’t Seem to Notice Cyclists” who mentioned a motor vehicle as a stressor in the interview.

anticipating driver actions, but the daily commuters mentioned this theme substantially more (14 of the 21 daily commuters) than the less frequent commuters (5 of the 30 others).

3.4. Comparison of the sensor data

LiDAR and GPS are useful sensors for measuring key components of the cycling experience including speed and proximity to motor vehicles. These data are used in this section to further explore the stress responses regarding motor vehicles and speed differentials. LiDAR data was used to measure close-pass events in which a motor vehicle passes a cyclist with less than 1 m of space. Three assumptions were checked with regard to close-passes: (Landis et al., 1997) cyclists in Delft are less likely to rate a close-pass event as high stress, (Harkey et al., n.d.) cyclists with a higher comfort rating (i.e. strong and fearless) are less likely to rate a close-pass event as high stress, and (Mekuria et al., 2012) cyclists who disagreed with the statement that “Most drivers don’t seem to notice cyclists” are less likely rate a close-pass event as high stress.

In addition, GPS sensor data were used to understand cyclist speed by taking the instantaneous speed from GPS reading to GPS reading. This speed data can be used to check the assumption that cyclists in Delft cycle slower than the cyclists in Atlanta. This hypothesis is suggested by the comments about cyclists being able to keep their own speed in Delft.

3.4.1. LiDAR

The LiDAR data were used to identify locations with close-passes, with results shown in Table 3. Only four close-pass events were found in the Atlanta data and seven in the Delft data, two during the same ride (labelled 3 and 4). 4 of the 7 close-pass events in Delft were rated low stress, two of which were within a closer distance than any of the close-pass events in Atlanta. 4 of the 7 close-pass events in Delft were with a bus, 2 of which were rated low stress. The segments where these close-pass events occurred were along one-way streets with an exception for cyclists. The cyclists were going against the flow of traffic when passed by the buses. During the other close-pass events the cyclist and motor vehicle were travelling in the same direction. The narrow one-way street, low speed limit (30 kph), and nearby pedestrian areas likely

Table 3
Close-pass events and characteristics of the pass and rider.

Delft Close-Pass	Bus	Distance	Rider Type	“Most drivers don’t seem to notice cyclists”	Stress Rating
1	No	850 mm	Strong & Fearless	Disagree	Low
2	No	720 mm	Enthusied & Confident	Disagree	Low
3	Yes	580 mm	Comfortable, but Cautious	Strongly Disagree	Moderately Low
4	No	670 mm	Comfortable, but Cautious	Strongly Disagree	Moderately Low
5	Yes	620 mm	Enthusied & Confident	Disagree	Low
6	Yes	610 mm	Comfortable, but Cautious	Strongly Disagree	Low
7	Yes	600 mm	Enthusied & Confident	Strongly Disagree	Moderately high
Atlanta Close-Pass					
1	No	710 mm	Comfortable, but Cautious	Strongly agree	Moderately high
2	No	900 mm	Enthusied & Confident	Agree	High
3	No	710 mm	Strong & Fearless	Agree	Moderately low
4	No	700 mm	Enthusied & Confident	Strongly agree	Moderately low

resulted in low speeds (lower than the speed limit) of the motor vehicles in this area. In this unique situation, it seemed that cyclists were more tolerant of a close-pass event, likely at least partially due to low speeds.

In Atlanta, the close-pass events were all rated above low stress. Most happened at a distance greater than those in Delft. The conditions of the close-pass events were such that they were always on mixed traffic segments with the motorist and cyclist moving in the same direction. The speed limit on the roads with close-pass events was 25 mph (40 kph).

The relationship between rider type and the responses to “Most drivers don’t seem to notice cyclists” to their stress rating during a close-pass event was explored and is presented in Table 3. However, there does not seem to be any link with rider type. The strong polarization of answers to “Most drivers don’t seem to notice cyclists” resulted in all cyclists experiencing a close-pass event in Delft on the disagree side and all in Atlanta on the agree side. A larger sample of close-pass events with a more diverse sample regarding this question may be necessary to determine if it is related to their belief that drivers notice them. However, it should be noted that in addition to the low speeds, the difference in stress rating of close-pass events, could be related to these different views of whether drivers notice cyclists.

3.4.2. GPS

Based on the findings that cyclists appreciated getting to travel at their ideal speed, and that the Atlanta cyclists were more frequently stressed by high speed differentials, it was assumed that cyclists in Delft would cycle slower than cyclists in Atlanta. The point speed data were plotted as boxplots in Fig. 7. The data suggest this assumption is correct. The mean speeds are substantially different with Atlanta’s mean speed (24 kph) being about twice as high as Delft’s (12 kph). When looking at the median speeds this becomes even more extreme with Delft’s at 7 kph and Atlanta at 27 kph. The differences could be exaggerated by plotting the point speed data (a slow-moving cyclist will generate more data points in the same distance). However, the data suggest that cyclists in the Netherlands without the pressure to move more quickly, are choosing to use a lower speed than in the United States where cyclists must ride mixed with vehicles. Although these differences are striking, the cyclists’ speeds were within the range of expected values for each country (Schepers et al., 2017). There may also be other factors influencing these speed differences. These differences may be more pronounced due to the differences in bicycle used, as cyclists in America will often use a faster bicycle than the typical Dutch city bicycle used for the experiment in Delft. Similar to the bicycle styles, American cyclists are also often more sporty than in the Netherlands where cycling is a casual, every day experience (Oosterhuis, 2016).

Fig. 7. Boxplots of the speed data in kilometres per hour, triangles represent the means.

4. Discussion

Overall, the main components of cyclist stress can be attributed to the presence of motor vehicles, poor pavement, and poor infrastructure. This section goes into further discussion about the individual results of the study and how, ultimately, they relate to the influence of the built environment on feelings of stress.

The two samples differed significantly in their responses to “Most drivers don’t seem to notice cyclists” with more agreeing in Atlanta and disagreeing in Delft. This is similar to previous findings that Dutch cyclists rated their tolerance and consideration for other road users higher than cyclists in the USA (de Winter et al., 2019). Strictly looking at the Dutch, Dutch cyclists also reported to be very often confident that drivers notice them (Hagenzieker et al., 2019) and both cyclists and motorists expected motorists to yield more than cyclists (Hoekstra et al., 2018). In Delft, people disagreed more with “Most drivers don’t seem to notice cyclists” and experienced lower LTS infrastructure and vehicular volumes; however, motor vehicles were still the top stressor in both Delft and Atlanta. This highlights the importance of motor vehicles to cyclists’ stress. It is well established in the literature that cyclists’ perceived safety and stress levels are negatively influenced by interaction with motor vehicles (e.g. (Fishman et al., 2012; Kaplan and Prato, 2016; O’Connor and Brown, 2010)).

However, the Delft data suggests that it is not just motor vehicles, but all other road users that are causes of stress for cyclists. In Delft, other cyclists were the third most common stressor and pedestrians were tied with three others for the fourth most common stressor. This supports building separated infrastructure to minimize interaction with other road users, although interaction with other cyclists is likely inevitable. Additionally, it is worth noting that despite pedestrians and cyclists being frequent stressors in Delft, about twice as many participants mentioned motor vehicles than either other mode.

Another difference highlighted in the thematic analysis was how cyclists mentioned speed differentials. Delft cyclists mentioned their own speed and Atlanta cyclists mentioned vehicle speeds. Both suggested that cyclists prefer to go at their ideal speed. Based on the interview responses, the Atlanta cyclists experienced higher, more stressful speed differentials which may have pressured them to go faster than their ideal speed. This was explored in the results section (3.4.2), and it was found that the Atlanta cyclists were cycling about twice as fast as the Delft cyclists. Although other factors such as typical trip lengths, cycling culture, and bike types could also influence the ideal speeds, the thematic analysis results coupled with the large speed differences suggest that cyclists’ speed is influenced by pressure from the speed differentials in shared lanes. This may reveal the importance of infrastructure separating modes by speed, as the Dutch system does.

Pavement condition was the second most common stressor in Delft and third in Atlanta. Pavement condition, included in BLOS, has been considered in terms of physical comfort (Bíl et al., 2015; Calvey et al., 2015; Thigpen et al., 2015), but is infrequently considered in stress studies. The findings of this study suggest that this is a more important factor than previously acknowledged.

A more detailed analysis was performed on the components of the infrastructure theme. It was shown that presence of bicycle facilities is the most important aspect of the infrastructure to cyclist stress. This could explain why over double the percentage of participants in Delft who identified infrastructure as a stressor did so in Atlanta. This fits with previous findings that the presence of bicycle facilities is important to reducing cyclist stress. Sight distance caused some stress in both locations but was a substantial component of reducing stress via infrastructure in Delft. This could be related to the slower speeds in Delft allowing cyclists more time to react to visual cues. Width and presence of bicycle facilities are included in all the existing infrastructure ratings systems, but sight distance, mentioned more frequently than number of lanes, has yet to be considered.

The number of travel lanes had a nearly even percentage of

participants mentioning it as a stress reducer (7%) and as a stressor (10%). It reduced stress because cyclists felt vehicles were more able to give sufficient space when passing if there were more lanes. This suggests that number of travel lanes alone may not be as simple of an inclusion to measures of cyclist stress. Instead, aspects such as speed (high speeds often associated with high lane numbers) and roadway width may be better indicators.

5. Conclusion

Previous studies have assessed stress, but variables collected to conduct the assessment have been largely defined by the researchers. In this study, participants self-identified their causes of stress through a near real-time interview. This study confirmed and at times emphasized some of what is already known, especially the importance of motor vehicle interaction to cyclist stress. This study also contradicted the idea that number of travel lanes is a key stressor, instead suggesting that it can serve as both a stressor and stress reducer and that other stressors may be more influential. In addition, this study also highlighted new insights into causes of stress. For example, pavement condition is often overlooked but came out in the top three stressors in this study. The interviews also allowed for a new perspective on speed and the identification of sight distance as a factor in stress. Finally, this study also looked at close-pass events and how attitudes impact stress during them. The results were not definitive but suggest that the Delft cyclists’ comfort with closer passes could be associated with their belief that motorists notice them and/or the low speed of vehicles.

There were several limitations to this study. First, although for studies incorporating the use of instrumented bicycles and quasi-naturalistic cycling, the sample size was reasonable, the analysis would have been stronger with a larger sample size. Second, some of the study design was not as consistent as desirable including the difference in bicycles used and the variation in the familiarity question. Finally, it could be desirable to perform the study again in more comparable cities in terms of population and transportation infrastructure.

Findings indicate that a few themes relating to cyclist stress require further research. The results suggested that there may be some interaction between cyclist speed, stress, and their ability to foresee risky situations which warrants further study. The results about pavements also suggest that studies on pavement management for cyclists should also consider their stress, not just physical comfort. In addition, ambiance was mentioned by 14% of participants and a study specifically on ambiance could be used to aid in inexpensive improvements to the streetscape that could impact people’s willingness to cycle.

Acknowledgements

The authors would like to thank Spencer Maddox, Nic Alton, Paul van Gent, and Edwin Scharp for their help with data collection and sensor management. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1650044 and the IIE Graduate International Research Experience fellowship under Grant No. 1829436.

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